REITH LECTURES 1950: Doubt and Certainty in Science

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Lecture 2: Brains as Machines

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I have already suggested that it would be possible to conduct our affairs somewhat better if we gave more consideration to the processes in the brain that accompany speech and thought. We have a great deal of information about these matters that was not available fifty or even ten years ago. But it would be misleading to suggest that we can yet provide a complete picture of brain action. Recent discoveries have shown enough however to give us hints as to how much we could do if we knew rather more. In this lecture I shall try to give you an introduction to the ideas that scientists use to describe these discoveries about nerves and brains.

Parts that Make Up the Nervous System

In the seventeenth century people began to make comparison of living things with the machines that were then being perfected. The French philosopher Descartes compared the body with a clock. In a clock one describes each of the parts as having a function in the working of the whole. This led Descartes to an idea that was quite novel at the time, namely that one could proceed to find out how all the parts of the body interact, investigating it as if it were a machine. Comparison of living things with machines may seem at first to be a crude, even rather childish procedure, and it certainly has limitations, but it has proved to be extraordinarily useful. Machines are the products of our brains and hands. We therefore understand them thoroughly and can speak conveniently about other things by comparing them with machines. The conception of living bodies as machines, having, as we say, structures and functions, is at the basis of the whole modern development of biology and medicine. I want here to describe the parts that make up the nervous system and to show how we can speak about them by comparison with machines.

Let us consider what happens in the nervous system in a typical case, such as blinking when a hand is waved in front of the eye. Such actions involve first a stimulus, the waving hand, which activates a receptor, the eye. From this receptor, messages, known as nerve impulses, pass along the nerves to the brain and from there other impulses are reflected back to the muscles of the eyelids. Such circuits are known as reflex arcs and they ensure that the body shall do something appropriate when there is a change in its neighbourhood — the change being known as the stimulus. All the parts involved in the reflex arc are made up, like other parts of the body, of cells that can be seen with a microscope. Each cell is a separate little system, closed in, as the name implies, by a surrounding wall. This wall regulates everything that goes in to or out of the cell. The nerve cells are very long threads, drawn out to make nerve fibres that reach from, say, the toes to the spinal cord in the middle of the back. But each of them is very thin, less than a thousandth of an inch across, although of course it is several feet long. The fibres run in bundles, tens of thousands of little thin threads making up the nerves that connect the outer parts of the body, say arms or legs, with the brain. Some of them are sensory or as we may say input threads; they carry impulses from the skin upwards to the brain. Others are motor or output fibres, carrying impulses down from the brain to the muscles. Each ingoing fibre is connected at its outer end with some part of the surface of the body; it will therefore be made to carry impulses only when a certain small area, say the tip of a finger, is touched. The thousands of fibres together thus serve to bring to the brain a traffic of information about what is happening all over the surface of the body.

A great deal is known about the changes that happen in the nerve fibres when they conduct. The whole process depends on the fact that there is a difference between the inside of nerve cells and the liquid around them. It is the function of the walls of the cell to maintain the difference. Now often when different things are separated by boundaries you get the phenomena that we call electrical charges. The drops of rain in a thunder-cloud are like this, and so are the plates in an accumulator. Everyone knows that such electrical charges may be discharged, with all sorts of effects from flashes of lightning to the starting of a motor-car. The nerve fibre, because of the difference between its inside and outside, carries such an electric charge. What the stimulus does, say in the skin when a pin sticks into you, is to start a minute electrical discharge. This little discharge then makes the neighbouring part of the nerve fibre discharge, and this in its turn the next one, and so on. That is how the nerve impulse travels along the nerve fibre, at a speed of about 200 miles per hour.

All this is very interesting, but it clearly does not tell us everything about how the nervous system works. It tells us how the nerves conduct, but not what happens when these impulses reach the central nervous system. We know that there are special outgoing or motor nerves that carry similar nerve impulses to the muscles and make them act. But what decides which muscles shall act? If each ingoing nerve fibre was connected with one outgoing fibre, the body would work like your front- door bell. Once the button has been pressed only one thing can happen; if the system is in order, the bell must ring. But the body is not nearly so simple. For one thing it does not do the same thing every time it is stimulated. For example if your son has got under the table without your knowing it and tickles your leg you will draw it away. Perhaps you will do that a second and even a third time. Then you will put your hand down to find out what is wrong. At about the fourth or fifth time you will catch him at it, and your response will be quite different from the first one. Your nervous system cannot be exactly like the bell system, which always works in the same way each time the button is pressed.

Sir Charles Sherrington has done more than anyone else to enlighten us in these matters. After prolonged study of the reflex responses of cats and other animals, he and his colleagues came to the following conception. Each muscle, say one of those that draws away the leg, is controlled by some hundreds of outgoing nerve fibres. It only exerts its full action if these are all set off together. Obviously the strength of its action will depend upon how many of the motor cells start to send out impulses at the same time. Each motor nerve cell gets connections not from ‘just one input source, like your front-door bell, but from several. Whether a given motor cell sends out its impulses or not depends simply on whether it receives impulses from a sufficient number of sources. It is like a bell that only rings if a number of buttons are pressed at the same time. Do you begin to see how the machine works? The first time your son tickles you a few impulses are sent in and they get through to the muscles that bend the knee; you draw away so that the stimulus ceases. The second time likewise. These first movements involve only a simple reflex action. All the connections can be made through the spinal cord alone. But impulses also go up to the brain each time, because there are side channels leading to it from the input fibres. Each time these inputs reach the brain they disturb it a little bit more, and at the third or fourth tickle the brain begins to send back impulses that reach to other muscles, probably muscles of the arms as well as the legs, and produce a new set of actions.

Experiment with an Octopus

Our next problem is now to try to see whether we can make out how the brain produces these more complicated actions. This is difficult in man and it may help, therefore, to describe first the case of an animal. I propose to do it for the octopus. My colleague Mr. Boycott and I have studied the octopus at Naples, where they are plentiful and can easily be kept in the tanks of the great zoological station there. An octopus in a tank always makes a home for himself in a corner, using any bricks or stones that may be lying about. If the octopus is outside its home and is stung by a sea-anemone or given a small electric shock it will retreat back into its home. It also retreats if a large object, say a dogfish, suddenly appears. On the other hand if you put a crab into the tank, the octopus will come out of its lair and hurl itself upon it, seizing it with its arms and eating it. What comparisons can we use to describe the nervous mechanism by which the octopus steers away from a dangerous object but moves towards a source of food? Descartes, you remember, compared the body with a clock, the best self-regulating system that he knew. Today we have a large range of mechanical self-regulating devices, and therefore we can make much more interesting comparisons. The ball governors of steam engines and the regulators of gas ovens and refrigerators are examples. Their value is that they keep the engine or the gas oven close to some particular state. This is obviously very much what living things do. Their whole life consists of a series of regulations tending to keep the body in a certain state, to keep it alive. When there is some change, either within the body or near it, a reflex circuit goes into action to restore the status quo. Each of the reflexes is a kind of governor. It may make the body do something faster or slower, for instance by quickening the heart-beat when we run, or it may start an action that alters the outside world so as to abolish the source of change, as when we brush away a fly.

Self-regulating Mechanical Devices

In recent years, engineers have gone a lot further in the design of self-regulating devices. They have produced a great variety of direction-finders and distance-finders, culminating in guided missiles and especially guided rockets. These devices do very much what the brain of the octopus does. They aim the missile at a target. Until not very long ago, aiming a gun involved human gunners. At first the aiming system consisted of relatively crude plans for sending back information about a target (say from a balloon), working out the appropriate ranging on paper or with a slide rule, and laying the gun by hand. But gradually calculating machines were devised that received the information, automatically computed the range, and laid the gun on the target. From this it was only one stage to placing the whole apparatus for reception, calculation and aiming in the missile itself, which is thus able to follow its target around and hit it. To be effective the machine may have to pick up information about a lot of things, not only the position of its target but also the direction and velocity of the wind and other such factors. Quite an elaborate calculating machine may then be needed in the missile, its brain as it were, to predict the correct course from all this information.

What is the value of comparing an octopus with a guided rocket of this sort? Clearly the two are identical; there is only a very limited sense in which we can say that an octopus is a guided missile. People who have not thought carefully about the use of analogies are very apt to take them too literally, and to think that by comparing something with something else you can in a subtle way grasp, as they say, what it really is. This belief in the magic of comparison and of words has indeed a certain justification because, as will become increasingly clear in these lectures, man is so much a communicating animal that when he has put his experience into words we can say that it becomes more ‘real’ for him. The point is that comparing something unknown with something already known makes it possible to talk about the unknown. The value of making the analogy is that it facilitates communication.

We still cannot describe exactly how the nervous system works in the octopus, but we find it helpful in trying to do so to speak of the actions of its brain as an engineer would describe the parts of a guided missile. When a crab moves in front of the eyes of the octopus, we say that the retina of the octopus’ eye, acting as a receiver, sends information, in the form of nerve impulses, along tens of thousands of nerve fibres. These impulses then set up activities among further thousands of cells in parts of the brain that are called the optic lobes. We know all too little about these activities, but comparison with the machinery of the guided missile is helping us to analyse them. For the process is essentially one of using the information provided by the eyes for selection of a correct response, then predicting the course of the crab and steering towards it. The most difficult part for us to understand is the selection of the right response; what makes the octopus steer towards a crab but away from a shark? Some of the most recent calculating machines come close to making such decisions. I shall show in later lectures what hints we can get from the way that they do it. It is quite possible for us to imagine that when the optic lobes have completed their calculating the appropriate muscles are set into action. The octopus turns its head so as to fix one eye on the crab and then its arms and funnel are brought into play to propel it through the water and to steer it correctly until it hits its prey.

On the other hand, when a large object comes into the field of vision of the octopus the nervous system makes a different calculation and steers the animal back to its home. If the object, say a dogfish, comes nearer still, a further calculation is made and the octopus suddenly flattens, spreads itself out, and turns white except for the edges of its arms and the area around the eyes, which go very dark. This pattern that it shows is a very striking one and would produce a retreating action by an attacking animal. Our guided missile analogy can help us to understand this too. The octopus system is such that, when a large object appears in front of its eyes, the action that is called for by the brain computer is first retreat and then the production of the startling pattern. No doubt ideas of similar systems have been in the minds of weapon designers. For in modern war one guided missile will be set to chase another. It should be possible for a rocket fired in London against an enemy rocket to act upon the attacker so as to turn it around and send it home again. This is just what the octopus does when it puts into action its device for, as we say in another idiom, frightening away the attacker.

So the guided missile analogy gives us some good ideas about how we can usefully talk about the changes in the brain which ensure that the octopus will attack a crab or frighten away a big fish. Are there other aspects of its behaviour that are even harder to describe? There is the fact that the animal may change its behaviour in the light of past experience. In other words, the octopus can learn. Boycott and I were able to show this by putting in front of the animal together with a crab also a small white square. The octopus attacked this combination quite readily, but things were so arranged that when it did so it received a small electric shock and withdrew quickly to its home. The next time that we put the crab and the square in front of it, the octopus came out much more slowly. Instead of hurling itself on the crab it put out its arms gingerly, as if to try to get the food without touching the white square. When it finally attacked, it received another electric shock. After two or three such experiences the octopus remained at home when the white square was presented to it with the crab. But it continued to come out and eat crabs put in alone, without the white square.

If we are to compare the octopus with a machine, it must therefore be with one that can change its behaviour as the result of a memory that acts, as it were, as a store of past events. In recent years there has been a great development of calculating or computing machines that can store their results, in other words remember them and use them again later on. There is nothing essentially mysterious about such machines. Indeed, storing information is really quite a familiar process. The painter does it in his picture, the writer in his book, the photographer in his photograph. A card index, again, is a store of information. Imagine a machine that can put information into a card index and later take it out again. The cards with holes punched round the edges, that are used by some businesses, are devices for doing just this. One machine punches the cards according to a plan, in order to make them carry the information. Another machine can select all the cards punched in a certain place, corresponding—shall we say?—to all names beginning with the letter A. These are the cruder sorts of information stores—only partly automatic, like the hand-laid gun. Engineers can do much better now. Photographs and cards are bulky, they take a long time to make and can only be used once. A good memory system for a machine employs units that can be used over and over again, are quickly marked and if necessary quickly erased. In modern calculating machines there are various- systems, but they mostly depend not on making any permanent physical mark but on setting up some electrical action or process.

Storing Information on a Continuous Circuit

Let me explain what I mean. You can store information just as easily by starting up some continuous process as you can by photography or by punching a card. What is needed is some arrangement which sends messages that ultimately come back to their starting point, and then sends them out again, and so on. For instance, you could store a piece of information, say your name and address, by turning it into a code of dots and dashes, like a telegram, and then arranging that it was sent on the wires from London to Bristol, Bristol to Birmingham, Birmingham to Edinburgh, Edinburgh to York, back to London and then on again to Bristol and so on round and round for days or years if necessary. All that is necessary for such storage is continual activity of the system, and a sufficient delay time, so that the sending machine has finished transmitting the message before it comes back to it. You might say ‘What an absurd method of storing—much better write it down and have done with it’. Actually, with suitably designed delay circuits (of course using other methods than sending telegrams all round the country) large amounts of information can readily be stored in this way. It has the great advantage that as soon as a piece of information is finished with it can be wiped out of the system, leaving no trace. No files of used photographs or cards remain. The apparatus is ready to store some more information.

'But', you may say, 'surely you don't expect us to compare the brain of an octopus or a man with a card index or a cycle of telegrams?' Only very roughly. Remember that it is the way of talking about things that matter, not the details. With the aid of our comparison we may be able to discover what change it is in the brain that constitutes the memory. We can look to see whether there is in the brain any sign of arrangements that could either print information or store it on continuous circuits. In the case of the octopus we have been able in our experiments to make one further step forward by finding a part of the brain that is necessary for the storing. There are two lobes on the very top of an octopus' brain, that I have not yet mentioned. A lot of nerve fibres carry impulses to them from the optic lobes, and they send impulses back to the optic lobes. You see there is here a circuit that could keep going in the way I have suggested. Boycott removed these uppermost lobes under an anaesthetic from octopuses that had learned not to attack when the white plate showed. After such an operation it was found that the animals no longer remembered the lesson. Each time that the crab and plate were shown they came dashing out from the home and received a shock. So far as we have been able to discover, removing these lobes does not produce any other defect. The octopus eats well and appears perfectly normal, except that it has lost its power of memory. It seems therefore that these lobes are essential for storing information received. How do they do it? We do not know for certain, in the octopus or in any other animal. It seems likely that the method of storing involves in some way the setting up of continuous processes such as I have suggested in the telegraph analogy.

But it really is very difficult to believe that all our memories depend only on keeping up some kind of race like this, year in year out, around our brains. If that was the method anything that stopped the cycles would destroy all memory completely. Yet we keep our memories, not only in sleep, but under anaesthetics. After severe changes in the brain action such as are produced by concussion, epileptic fits or electric shock treatment, the memory is usually disturbed, but is not completely abolished except perhaps for a short time. For such reasons, many physiologists have supposed that memory cannot depend on circles of activity and must be more like that provided by photography or punched cards in that some kind of image is left printed, as it were, on the brain tissue. Our recent research has indeed shown some basis for supposing that activity does leave its mark on the brain. There is evidence that the cells of our brains literally develop and grow bigger with use, and atrophy or waste away with disuse. It may be therefore that every action leaves some permanent print upon the nervous tissue.

So we must admit that we do not know exactly how the memory is stored, but it seems possible that both the suggested processes are involved. It can hardly be an accident that the parts of the brain concerned contain, both in octopus and man, circular chains of action. It is conceivable that such circuits serve, as it were, to carry the memory for long enough to allow slight changes in the sizes or other features of the nerve fibres to be produced, and so for the memory to be printed on the brain. To

use our analogy of the telegrams going round the country, we might imagine a teleprinter device, say in London, that made a punch card or photograph of the Morse code message, but that needed several exposures to do it. Each time the message came round to London it would 'make the record a little more definite, so that finally the message would be retained even if the circulation stopped. Perhaps it is significant, in this connection, that concussion or other shocks upset the memory of things that were going on just before the shock—the ones that were half printed, as it were, at the time. The worse the shock, the longer the time before concussion that is forgotten. Incidentally, the memory recovers also in a time sequence. If the forgetting reached back two weeks, then memory will gradually return
from that point onwards to the moment of concussion. So even if we do not yet know all about the process of learning I hope that I have at least shown that memory has some basis in the activities going on in certain particular parts of the brain. It is a fascinating problem searching out the exact details of the changes that go on as we learn.

One further point I should like to emphasise: enormous numbers of separate units, the nerve cells, are involved. All animals that show good learning powers have large numbers of short nerve cells in their brain. We do not know what the system employed for storage may be, but it seems to depend on the presence of great numbers of small cells. The latest mechanical calculator in America has 23,000 valves. But the cortex of the human brain has nearly 15,000,000,000 cells. A computer with so many parts is beyond the dreams of the engineer. A huge building would be needed to house so many valves and all the water of Niagara would not be enough to work and cool them. Yet all that such a machine can do and much more goes on gently, gently in every human head, using very little energy and generating hardly any heat.

The purpose of this whole lecture has been to make you familiar with the approach of the biologist, who tries to study animals, you remember, by finding out how they work. It has often been objected that this is only one way, a partial way and even, it is sometimes alleged, a poor way of studying them. Let me at once admit that it is certainly not the only possible way. Anyone who wishes is at liberty to start discussing the behaviour of the octopus with such phrases as 'It *wants* the food', 'It *feels* the shock', 'It *fears* the square', 'It *remembers* its pain', and so on. These may even seem to be more 'natural' ways of speaking about such matters. They make use of a method of speaking that is very ancient, and depends on the assumption that in every octopus there sits some sort of person at least vaguely like a man. This way of talking therefore depends on comparison and analogy, just as much as does the machine talk. The scientist would say that such animistic systems are primitive, and he would claim that they are inefficient. They do not tell us anything about the inner workings of the creature or how to correct them if they are out of order. It may not matter much if with talk about the mind of an octopus we are not able to cure its neuroses. But it does matter when we are talking about men.