CONTROLS AND COMMUNICATIONS

Inaugural lecture of the
Professor of Electrical Engineering
delivered at the College
on 30 October 1956

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TO be introduced to you as the first Professor of Electrical Engineering is an honour of which I am very proud, but electrical engineering has, of course, been taught here since the early days of the College. I have inherited a fine set of laboratories and much equipment, for which I am particularly indebted to Assistant Professors Isaacs and Cass-Beggs.

Now many of you will know that what was, until recently, a single Chair in Engineering has now branched out into four. Three of these Chairs are in the old Engineering Department, and from this the uncharitable will no doubt infer that the present crop of Professors are either narrow in outlook or weak in intellect. However, there are other possible reasons, and I should like to dwell on them for a moment. In so doing I shall not be straying too far from my main themes, for I shall be touching on the ever-important subject of teacher–student relationship, which after all is a problem of communication.

The Engineering Teacher as a Specialist

Modern scientific engineering grows more and more important to the country as our needs change and increase. These needs become more diverse and complicated and so the techniques of design and manufacture become more sophisticated and abstruse. To be working at the frontiers of engineering knowledge these days is an arduous business and usually demands specialization in some relatively narrow field of study. Furthermore, specialization of this kind uses both time and energy in large amounts. In the course of a lifetime an engineer will not usually study in detail more than a few aspects of technology, if indeed he has studied more than one. This happens to teachers of engineering science just as much as to research engineers and designers in industry. Engineering teachers therefore specialize to such an extent that it is convenient to have separate sections within the general broad field of engineering. I hasten to add that there is always scope for the reclassification of knowledge and the synthesis of more comprehensive disciplines from these subdivisions.

I am not suggesting that teachers should be ignorant of all matters outside their own narrow field. Far from it, for I believe in acquiring the widest possible background of scientific knowledge and engineering method. However, it is the students of today who are the engineers of ten to twenty years hence, so that it is they who must have this wide background to their studies. Teachers who have specialized should be that much better at selecting, in their own fields, those laws and methods of approach which are basic and most rewarding.

The problem of communication occurs not only between teacher and student but between teacher and the other members of the engineering profession. Teachers must be able to meet their opposite numbers in industry to discuss common interests at the highest levels of technological knowledge. It would be difficult to do this if teachers resisted specialization, and ultimately the resulting lack of contact would injure the professional standing of engineering teachers. These are some of the reasons for varieties of engineering professors. Nevertheless, these divisions are in a way indicative of a failure in our educational methods. The capacity of the brain is undoubtedly finite and so is the rate at which it can take in and store information, but it is doubtful if these limits are ever reached. There is a real difficulty in persuading all but a few minds to assimilate new ideas quickly, or to adopt a critical approach to them. Even university

undergraduates, reasonably intelligent by any educational test, usually try to fit new information into the system of concepts they already have acquired, and have the greatest difficulty in grasping new sets of signs or symbols. It may be that our early schooling and training leads to this condition. If new knowledge about the action of the brain can be found it may lead to methods whereby the rate of intake of information into the brain can be increased, and even as Professor J. Z. Young suggested in his Reith lectures, that a large proportion of the population should read pages of mathematical symbols as readily as they now read print!

Something like this is fast becoming necessary, for such is the advance of science, technology, and some of the social sciences that large numbers of people simply have no idea of the concepts and ideas being used by the practitioners of these subjects. It may be that one or two of the concepts evolved by electrical engineers may play some, if a small part, in leading to a better understanding of the processes of the brain—that is, of thinking. If this is so then our educational techniques may change radically. One can imagine perhaps that the brain may learn to learn, before going out to acquire other types of knowledge. It is not difficult, on the other hand, to visualize a deeper knowledge of the brain and its method being used for more sinister ends.

Without any further progress in our understanding of the functions of the brain it is certainly possible to aid thought by machines of various kinds. It may even be possible to build machines that think. I am of the opinion that if terms such as deduction, induction, and so on are defined unambiguously and in a finite number of terms then, in principle, a machine can be designed to carry them out. It may, however, with present techniques, be impossible to construct it in practice. I shall have something more to say about machines of this kind later.

My main themes concern the subjects of control and communication, both to a large extent the province of electrical engineers. They are important and affect our lives in innumerable ways and may affect them even more profoundly in the future.

The Two Functional Divisions of Electrical Engineering

The electrical engineer designs and uses apparatus in which electrical effects are of prime importance. The apparatus is mechanical in form, showing no visible signs of the quantity we call electricity. The electrical effects in fact manifest themselves as mechanical forces, chemical effects, or as heat and light, but are usually described by a special terminology, such as the flow of electric current in a wire or the propagation of radio waves through space.

Forgetting now the actual apparatus and concentrating on its functions, it will be found that there are two of great importance. The first function is to convey or transmit energy from place to place, the second is to transmit messages or signals or information from point to point.

Consider for a moment the systems in which the distribution of energy itself is of prime importance. Everyone is familiar with this and with the ease with which it is controlled. The throwing of a small switch in a house will allow energy to flow to some destination and there light a lamp or cause an electric fire to glow. With a little more elaboration it would be possible to select any brightness of the lamp or fire between being shut off and fully on. In either case it needs very little energy or force at the switch or regulator to control the flow of a much larger amount of energy at the lamp or fire. The flow of electric power is in fact very easily controlled, and in our simple

example the power at the lamp is controlled by means of a message or signal originating in the brain of the occupant of the room.

The message travelled from the brain to the switch via a nervous system and the action of the hand, but electric energy can also be used for carrying messages or signals. There is in fact a vast network of services throughout the world devoted to just that end. These services can be called, quite generally, communication systems. Communication systems include not only telegraph and telephone services but radio broadcasting, television, radar, and even devices such as the electronic computer. In these systems electrical energy is transmitted, but the amount, provided it is not too small, is not of much concern. What is of concern to the communications engineer is that the messages or signals are transmitted correctly without any loss of information.

The communications industry is built around the electronic valve, either in the form to be seen in the domestic radio, or as the transistor, as seen nowadays in deaf-aid amplifiers. Each of these devices enables one electric current, perhaps a very small one, to control the flow of another electric current, perhaps a very large one. Again, as with our lamp-switch, a larger amount of energy flow can be controlled by a smaller. Furthermore, any variations of the controlling current can be made to appear on the controlled current. If the controlled current is the larger then the variations in it, although the same in shape as those of the controlling current, are larger in scale: the variations are said to have been amplified. Now the signals or messages are sent by varying the flow of electric current or energy in some way or other. Hence the electronic valve enables signals or messages to be amplified to some higher power level. This useful higher power level is very small by the standards of the power station. The design techniques developed around the properties of this electronic valve are often called electronics or electronic engineering.

To sum this up, all electrical apparatus deals with the transmission of energy or power and all have in them a control link along which signals travel and so vary the power flow. In some types of apparatus the energy flow is large and the control signals so simple as to be almost ignored; in others the power flow is small but the signals controlling it are complex and of paramount importance.

There is yet another class of apparatus or systems in which both signals and energy flow are of equal importance, in that the energy flow is not too small and the signals are not too simple. In this class fall certain types of automatic control loop. These loops exemplify a principle, developed most fully by electrical engineers but not unique to them, called *negative feedback*, which is worth further discussion.

Negative Feedback and Automatic Control Loops

In these days of the much-publicized automation everyone has heard of automatic control and possibly of the automatic control loop. Automation itself amounts to the control of machines by machines to a large extent, and in this a particular system, the automatic control loop, will usually play its part.

The present theory of automatic control loops stems to a large extent from the studies of electrical engineers into certain types of electronic apparatus and from the development of the electrical servomechanism. That is not to say the control loop was not known long ago—it was; but a general mathematical theory appertaining to all such loops was not recognized until recently. The general feature of such a loop is that it is always trying to get

itself into *equilibrium* or a *stable state*. It is this feature that has excited so much interest in fields of study outside technology, for there are many phenomena in natural science which seem to be caused by systems seeking stability.

An example might help. Suppose we are trying to keep a pan of liquid, perhaps in cooking, at a very constant temperature, heating it on a gas burner. In the pan is an ordinary mercury-in-glass thermometer and on it is a mark denoting the required temperature. If the mercury level is not at this mark it must be above or below it. In either case there is an error between actual temperature and the desired temperature. The cook or observer will note this (he is an 'error-sensitive measuring device'!) and turn the gas-tap so as to increase the gas flow if the temperature is too low, and decrease it if it is too high. In operating the gas tap he is now a controlling device or controller. You may notice that there is a closed sequence of events or a *loop*. First the error is noticed—then the gas tap is turned—this alters the gas flow—hence the heat input to the pan is changed—the liquid temperature varies—the mercury in the thermometer moves so as to annul the error. This process is carried on again as is necessary by the cook. It is obvious that the human being forms one link of the loop and can be replaced by a mechanism which will operate the gas tap according to the measured error at the thermometer.

A common example of this is the thermostatically controlled house. Information about the temperature is fed back to the space-heater in such a way as to annul the error. This is *negative feedback*, and is a feature of automatic control loops. The system as a whole seeks equilibrium, this equilibrium being defined by the desired temperature of the house. It is sometimes called a goal-seeking system.

In this example the desired value was a static one, it did not change with time, but there is no reason why the desired value should not vary with time. The system nevertheless always tries to reach the desired value existing at any moment, but by the time it attains this the desired value will have changed so that it has to try again. With suitable design the desired value can be followed very closely. Systems attempting to achieve static equilibrium are extensively used as regulators of temperature, pressure, &c., in the chemical and process industries, but are less common at the moment in the general engineering industry. This situation is not likely to last long, for the dictum of the control engineer is that 'if you can measure it, we can control it', and this is substantially true.

In military equipment negative feedback and automatic control loops play a big part. You will all have heard of pilotless missiles chasing bombers and perhaps destroying them. A missile such as this might carry in its nose a radar set which would continuously indicate the position of the bomber relative to the missile. The missile must approach the bomber more or less directly, so that if the radar indicates that the bomber is not directly ahead then the missile's direction is in error, and it can be arranged that the fins of the missile turn it and correct this error. Equilibrium is achieved when this is so. The bomber is of course moving and perhaps changing direction, so that the missile is constantly seeking a new equilibrium—a dynamic equilibrium rather than a static one. The system of control is still error-sensitive and negative feedback closes the loop.

The essential idea is a constant comparison between what we want (the equilibrium value) and what we have, the difference setting up a train of events which will alter the existing state of affairs to the desired state of affairs. The attainment of this end may need lots of energy or

power, and it should be noted that power enters the system separately from, say, the input signal indicating the desired values. In fact, if we go back to our original example it is obvious that the cook turning the gas tap did not supply energy to heat the pan. This energy came as the chemical energy of the gas fuel. The error existed at a low level of energy but controlled or supplied information about the required high energy flow. There are always at least two separate stages in an automatic control process, usually at vastly different power levels. What passes from one stage to the next can be thought of as *information* or *data* of some kind.

Another feature of the automatic control loop or equilibrium-seeking system is that it is comparatively immune from outside disturbances. Consider our elementary example and let us assume that the heating value of the gas going to the burner is reduced. The temperature of the pan would begin to fall and so cause an error which would cause, in turn, the gas tap to open and increase the gas flow and so combat this error. Negative feedback in a system has this property of reducing the effect of disturbances on the output value, in this case the pan temperature, of the system. It is a very valuable property.

These advantages are not obtained for nothing. Apart from the cost of the apparatus involved, an automatic control loop which is damaged in some way may begin to fluctuate wildly, or oscillate, so that what we have (the output signal) would no longer bear any resemblance to what we want. This risk is well worth taking, and in any case can be guarded against to some extent.

The idea of feedback and the control loop has had a unifying effect on theories developed for such diverse systems as engine governors, radio amplifiers, and chemical-process regulators. Before these ideas were well known these systems were often described correctly, but by means of a very specialized terminology different for each case. The unifying concept of negative feedback as developed by electrical engineers has thrown new light on these systems. Take the example of the theory of governors as applied to steam and diesel engines. Before the present theory of a closed loop was developed governors were, indeed, successfully designed to control the speed of engines, but the theory was specialized. The realization that it was part of a more general theory with terminology and methods superior to its own has clarified thinking about governors, and led to their improvement. The theory, as we shall see, also has applications outside the limited field of machines, but for the moment let us consider a second important concept.

Communications and the Theory of Information

Just as negative feedback is an idea in its own right capable of being adapted to various branches of science, so recently a second idea has been developed in its present form by electrical engineers, but again implicit in the work of other scientists. This idea is concerned with the information content of a message or signal of any kind. This Theory of Information has sprung into being only since 1948 when Shannon of the Bell Telephone Laboratories, New York, published his work.

Ever since the invention of the telegraph and telephone, but more intensively since the advent of television and radar, engineers have endeavoured to use their equipment efficiently during the transmission of signals or messages. It occurred to some of them to ask the question, 'What exactly is transmitted when a message is sent along a telegraph or telephone system?' It is not the sound of the spoken word but some electrical representation of it. This electrical representation, if all goes well, can be used to reproduce the message at the receiver, no

information having been lost. They found that it was possible to define, for their purposes, what was meant by the information content of the message and moreover give it a quantitative measure—that is, associate a number with an amount of information. Furthermore, for a real telegraph or telephone system it proved possible to define a maximum rate of transmission of information which could not be exceeded.

You may ask, 'Does the engineer's definition of information bear any resemblance to what is usually meant by the word?' The answer is 'yes', if information and knowledge are not confused. Information is the essential data of the message. Knowledge in the human brain is altered when the new data is associated with that already in the brain.

An example, although a very special example, will give some idea of the definition of information content. If you are looking out of the window watching the rain beat down and someone says 'it's raining outside', you receive no information of value, for you already know this. In other words, your uncertainty about the weather has not been altered. Now suppose you have not looked outside that day, then you have received some information, presumably of value to you. In this case an uncertainty about the state of the weather has been changed into certainty. The ratio of certainty after receiving the message to the certainty before is a measure of the information received, or, in other words, the amount of information received depends on how unexpected it was. Now certainties and uncertainties are usually expressed as probabilities as in games of chance. This being Swansea you might say that at any moment it is just as likely to be raining as not raining, so there is a one-in-two chance of rain. After the observation it became a one-in-one chance of rain. The ratio of chance after to chance before of rain is thus one divided by one over two, which is two. This number is a measure of the information. A change of uncertainty in the ratio 2 is called one *bit* of information. The word 'bit' is a contraction of 'binary digit'.

Another example might be a man asking his wife the colour of her new hat. Before she answers he probably thinks it might be one of sixteen colours: that is, each colour has a probability of one over sixteen of being the right one. After she replies he now knows the colour with probability of one, i.e. certainty. The ratio of certainty afterwards to that before is now one divided by one over sixteen, which is sixteen. Now sixteen is $2 \times 2 \times 2 \times 2$, which by definition is four bits of information. In other words, we express our ratio as a power of 2. The power index corresponds to the number of bits. The mathematically inclined will realize that the information is measured as the logarithm (to base 2) of the certainty afterwards to the certainty before.

In our first example the measure is that of *semantic information*, something to do with the meaning of the words to the recipient. Telegraph engineers are not the slightest bit interested in this but only in seeing that the language-information or selective-information is correct; for example, that all the letters of a telegram are correctly transmitted. Our definition of information is still used, or can be used, but now the uncertainties and certainties refer to the symbols and the way they are arranged. For example, 'it is raining' contains four *i*'s, one *t*, one *s*, two *n*'s, one *r*, one *a*, one *g*, and three spaces. There are thirteen symbols, some of them being repeated. Out of all these symbols numerous messages in English could be sent, but in fact only one arrived. The language-information content of this one message is measured by the total number of messages we could have received. In other words, the more uncertain we are initially the more information certainty brings.

These details of information content can be extended and refined, but the important point to grasp is that with careful definition, it can be measured. As measured and used to discuss communication systems and scientific experiment it is not concerned with *value* or *logical content* but with the separate distinguishable data which have been transmitted or received, or could have been received. This leads us to an interesting by-product of this theory.

Redundancy of Language

The written English language contains 27 symbols (26 letters plus one blank space) and if in writing a word the next letter could be equally probably any one of these 27, the information content per letter would be measured by the number 27; expressed as a logarithm this works out at 4·76 bits per letter. In actual fact any letter is not equally probable. For example, *q* is always followed by *u*, *tio* is almost certain to be followed by *n*, and so on. There are a lot of spelling rules in the language, so it turns out after some calculation that the average English word, of 5 letters, contains about 1·5 bits per letter of information only. This means that over 2 letters on average are needed to convey the same information which ideally would be conveyed by one.

What about Welsh—is this less redundant than English, does a page of Welsh words say more than a page of English? Unfortunately only a little work has been done on the Welsh language by some members of Birmingham University. On the whole the conclusion would seem to be that a given letter, and in effect there are about 32 in Welsh, contains slightly more information than a letter of printed English.

The redundancy of printed language is not necessarily a bad thing, for the greatly improved reliability of a written message it provides is purchased for a very reasonable cost in increased message length. For example, strings of symbols such as TXIY FGW ARV are probably not corruptions of printed English, whilst something like

> THIE FECTURE WILL FE GIWEN AN THE ASREMBLY HALT TLIGHT

would probably be

> THIS LECTURE WILL BE GIVEN IN THE ASSEMBLY HALL TONIGHT.

There are obvious advantages in redundancy if you are constantly sending telegrams in English, but I do not think this should deter any enthusiast for spelling reform.

The Electronic Computer

A well-known device, whose origin was certainly not due to the communications engineer's Theory of Information but which can be interpreted in terms of it, is the electronic computer or so-called electronic brain. This machine is usually designed to carry out long computations of a repetitive kind on all sorts of numerical data. In the machine is a store or memory in which many thousands of numbers can be accommodated. Some of these numbers in store correspond to the programme of instructions. These instructions, initially in the form of sentences, instruct the machine during the calculation. There is also an arithmetic unit whereby numbers can be added and subtracted. With the aid of these elements intricate calculations can be carried out usually at great speeds. An addition may take only three millionths of a second whilst multiplication may take only fifty millionths of a second.

The numbers operated on are represented by electrical signals of a simple kind being formed by strings of

pulses. In the primitive form a pulse represents unity and no pulse a zero. Although the initial programme may be in words it, too, is coded into numbers and then represented by electrical pulses. Once the machine has been given its instructions and initial data to work on, it carries on until it reaches some point predetermined as the end of the calculation. Some machines are able to decide between different methods of calculation according to the state of the calculation at any instant.

However, from the viewpoint of information theory these machines process data rather than create it. In fact no more information comes out than went in, for logically the input data plus the programme of instructions implicitly contains the final solution, although this solution cannot be seen directly beforehand. If we extend our definition to include semantic information then the recipient of the machine's calculation does indeed receive information, for he may value it very highly because of its novelty.

These machines are used for scientific calculations, but it may be that two of their main uses will be firstly in the processing of the vast amounts of data collected by industry and government offices, and secondly in the control of production processes in automatic factories.

Data such as sales records, inventories, overtime and pay records, census records, and so on are usually operated on in a fairly routine way by numbers of clerks, aided by small calculating machines. There is no doubt at all that this kind of work can be handled by suitable electronic computers. Somewhere between one-fifth and one-third of industrial employees are not directly connected with production, and the large firms will undoubtedly replace some of them by computers as these become cheaper. The size of the machine when installed will probably be governed by the necessity of working out weekly pay packets. Data for this could be collected up to Thursday morning and then processed to produce wages for Friday distribution. On other days the machine would be available for other purposes, such as those of sales offices and production management. The first machine of this kind, installed by a nation-wide firm of caterers about two years ago, has already made great savings and helped to reduce stocks kept in hand by more accurate forecasting of demand.

The other use of these machines will be in conjunction with negative feedback loops in controlling and guiding production in certain types of industry, most likely the chemical process and mass-production industries. Data from various parts of the plant will be correlated and examined by the computer, taking into account the demand for the factory's products and the intake of raw materials. Instructions will then be sent out to modify the rate or type of production.

In all these cases, although some workers will be displaced many others will be required, although with new skills and most likely much more rewarding jobs. There is still the problem of re-education to be tackled, and so far hardly anything is being done in this country to prepare for this eventuality. Something ought to be done.

Translation Between Languages

The work done by a digital electronic computer can be compared to that of a translator. The translator has a dictionary and the rules of grammar in both languages, and attempts to translate a passage from one language to another without loss of information. The parallel is so close that work has been going on for some time on just this problem. Some success has been achieved and more will be, for the mere possibility of machine translation has triggered off a considerable amount of new research into the structure of language, word formation, phonetics, and so on. In a way such a machine will imitate some of the mental operations of a human being and give them verbal expression.

It is of interest to note that even a word-for-word translation between European languages is of some value, providing the subject is scientific or technical, although ambiguities do occur. However, at the moment the storage capacities or dictionaries of existing computers are too small for general translation. An interesting project at Birkbeck College is to translate English into Braille. This should be possible with present machines and would be a very useful and valuable piece of work. Strictly speaking, I would not call this translation, but rather transcription.

As far as I am aware, translation by machine between two different languages on any scale, other than that where a restricted vocabulary is used, has not been achieved. Even apart from the problem of constructing a large enough store for the dictionary and basic grammar, a word-for-word translation is not enough: many words have alternative translations which must be listed, order of words in sentences differ in the two languages, and so on. What then are the prospects for machine translation? Workers in this field tend to be optimistic; but I believe that machine translation will come along, but not with present-day techniques. More knowledge of language structure is needed, and certainly more detailed investigation of the possibility of using intermediary languages or codes in the machines. Since information is conserved in a good translation this information can be coded into some other form in the machine from one language before being translated to the final language. These translations are not likely to be carried out for literary purposes, although translations of literary merit by machine are not inherently impossible, but for business and scientific purposes. Such is the growing volume of scientific literature in all languages that something of this sort is fast becoming necessary.

Perhaps a better solution after all would be to use some of the leisure automation might bring to us to learn more of the world's languages and do translations in the old-fashioned way. At least a machine would not separate us from our fellows.

Human Behaviour and Automata

One of the most fascinating problems mankind has always struggled with is how does the body carry out its functions? Much information regarding the simpler chemical and physical properties has been collected, but much remains to be known. In particular, how does the brain work? The brain, with its attendant nervous system, a vast network of communication channels reaching every part of the body, seems to control all our activities. The activity known as 'thought' seems to be connected with, or is, a product of the brain's activity. Little is known of what goes on in the brain or how its cells are organized, so that one of the main aids to speculation about the brain has been the use of analogy with machines. Descartes seems to have started this with his mechanical analogies, whilst nowadays digital computers are used.

Knowledge has increased, however, and something is known, so much so that recently the problem of designing automata is again being investigated quite seriously. Automata are machines which in some way simulate the action of the brain. There is a long history of automata, many being fakes but others being honest attempts to construct machines to play games. Edgar Allan Poe, in 1836, wrote an essay on Maelzel's Chess Player and other

automata, and incidentally mentioned Charles Babbage's computing engine, the forerunner in principle of the present-day electronic computer. None of the machines so far constructed can be said to 'think', or even to play complicated games such as chess when given the rules only.

In recent years the electronic valve has been used to construct sensitive measuring apparatus with which to investigate the nervous systems of animals and humans. It is known that the brain and the spinal cord are connected via a large network of nerve films to nearly every part of the body. Somehow along these nerves messages are sent. Some, known as sensory nerves, carry information to the spinal cord whilst others, the motor nerves, carry messages back to the muscles. These nerves can be shown to carry electrical impulses or short bursts of electrical activity which run along them at high speeds, round about 200 miles per hour. Suppose a nerve film is connected to the skin surface and is stimulated by pressure—that is, to touch. When nothing is happening few or no pulses per second are transmitted. Application of pressure causes the number of pulses per second to increase, like a slowly ticking clock suddenly starting to tick very rapidly. Information about the pressure on the skin is being coded or translated into pulses and sent off. If enough nerves in the area are stimulated a nerve cell in the spinal cord will be activated and send out pulses along a motor nerve fibre to a muscle which would remove the skin from the offending pressure. Alternatively, or as well, some of the information coming in would be side-tracked to the brain, which itself might initiate action at the muscles. There is about all this a resemblance to the way information is sent around computers and communication systems.

One part of the brain, the lower part, is closely connected with processes in the body which keep its properties constant, or in equilibrium. The human body only functions when its temperature is correct, the blood has the correct composition, and so on, so that there must exist a series of regulatory systems to do this. The principle of negative feedback and the automatic control loop, which we have discussed as an essential part of machine regulators, is also a helpful concept in discussing biological regulators. We can imagine information entering and leaving the lower part of the brain from and to all parts of the body, and it is suspected that in this part of the brain comparisons are made between what ought to happen and what is happening at any part of the body. If a discrepancy exists appropriate action is initiated. I am not a physiologist but I understand that the actual details are unknown.

However, engineers have discovered many ways of storing and comparing information in machines such as the computer, and many workers have seized on these ideas as being useful as models with which to discuss the design of experiments to be made on the brain. There is nothing particularly wrong in this, for the experimental scientists working on the brain are unlikely to confuse the machine model with the brain. For example, one way of storing information in a digital computer is to send off numbers, one after the other, along a circular path, somewhat like a line of railway coaches going round and round a toy railway. A new number, represented by a coach, can be put on the track whenever a vacant space comes by, or a given number taken away whenever it passes a certain point. There is a suggestion that there are circular closed paths of cells in the brain which might possibly store information, if only temporarily, by this method. Be that as it may, there is much theoretical work being done by mathematicians and engineers on the combinations of very simple elements

which might possess some of the properties of the brain. These elements might be such that they have only two states, say storing some electricity or not storing electricity. Nevertheless, if enough are combined together the combination as a whole can develop most varied properties. The object of course is to see if, perhaps only theoretically, some properties of the brain can be imitated.

It is possible, in a most general fashion, to build up a picture of the brain in terms of the flow of information from inside and outside the body and the correlation of new information with old. Processes such as 'trying to find the truth' are described in terms of electrical operations such as 'smoothing and filtering', operations whereby random elements are eliminated as much as possible. The prediction of future events from present information has also its counterpart in electrical engineering. Cognizance is taken of the various languages used in thinking—pictorial languages using representations of visual images and vocal languages using representations of sound words.

Let us now turn to the parallel problem of devising machines that 'think' rather than devising machines as models for the actual brain. It is necessary to define thinking, and A. M. Turing suggested that a machine is thinking if it answers the questions put to it by a human sufficiently well to deceive him for a reasonable time. This would have to be modified somewhat so that a machine that merely looked up answers in an encyclopaedia was disallowed. However it is defined, the machine must not merely carry out trains of mathematical or symbolic logic but must in some way generate new hypotheses and suggest new concepts. This creative process is often called induction, and in practice induction does not necessarily lead to the ultimate laws of nature. There are countless laws of science which have now been abandoned for later ones, and we should not expect any machine to do much better than man himself. The 'thinking' of a machine will be as suspect as that of anyone else. From an operational point of view it will be enough that the laws it infers from known data will be confirmed by reasonable comparison with future data. Data deviating from the law would be accounted for in some other way or, if frequent, cause the law to be abandoned.

There is also another way of regarding automata. We have problems and we need solutions. It has been suggested by W. Ross Ashby that it ought to be possible to build an intelligence amplifier, such that although built by intelligent humans it would solve problems beyond their intellectual powers. It would be based on the selection of the correct solution of its problem from a collection of random events. Equivalent, if you like, to watching a band of monkeys hammer on typewriters and suddenly noticing them typing out a well-known poem. It has been said that a random sequence of events, say letters, will if long enough contain all the answers. Now there are physical processes which seem random, occur very rapidly, and are continuous. They occur as random fluctuations of current in electric circuits, movements of molecules in a gas, and so on. Every random change in the measured quantity can be interpreted as a number and so a letter. Hence the process can be imagined as emitting a string of letters or numbers. In due course every combination possible will be written, but waiting for a particular sequence may take a long time. It is not too difficult to devise a scheme for recognizing the answer to the problem when it finally arrives; it is based on the negative feedback principle, as you might expect. It is suggested that if built its time of operation might be short enough to be worth while, but this remark is in the

non-proven class. It is an idea that is worth following up, and no doubt it will be.

There are other approaches to the problem. One being a machine which organizes itself to match in some way data fed in from outside. In carrying out this matching trials are made, which can be thought of as new hypotheses. Furthermore, the machine can use as data information about its own activities. Although this idea seems simple and almost trivial it has possibilities in theory, nothing has been done practically, of producing new and trustworthy hypotheses. The value of these can only depend on experimental tests.

If these machines are constructed there is no need to fear them. Every machine is in some way an extension of ourselves, usually of our physical powers, and there is no reason why our mental powers should not also be extended. These machines would take their place in the world, and perhaps enable us to become more a communicating animal than we have ever been before. After all, we do not necessarily exist to solve problems, just as we do not exist to work in factories, so that relieved of these tasks we could do something else: perhaps ponder on why we do exist.

To sum up, my themes have been two ideas, derived from engineering practice but scientific theories in their own right and capable of being transferred to other sciences. This in itself is an indication that the distinction between pure and applied science is now very blurred, so that it would be safe to say that very little pure science being carried out today has not been stimulated by a practical application. I have indicated their applications to human behaviour, for this is the most exciting application, useful if only for the stimulation of new thought it has caused. There are other applications in Physics, some quite fundamental, and there is no doubt that a new 'no-man's land' in science is now being charted.

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