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Machines and the Brain

Mathematical logic helps design complex nets whose arrangements resemble the structure of the brain.

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There has been a great deal of work done in the last few years that is designed to place biology on the same sort of mathematical footing as physics. Physics made great progress after it had been seen just how mathematics could be used to describe physical phenomena. This was done in such a manner that deductive processes could be quickly and methodically undertaken, and these in turn led to all sorts of discoveries of physical importance.

The process of using mathematics in a science is not unlike that of discovering that a piece of territory that one wants to map is sufficiently similar in structure to a map that he already has in his possession that he can study the map and anticipate the territory accordingly. This has still not been done to any great extent in biology, in spite of the fact that many people have felt that physics and biology are essentially similar in their logical form. In some cases it has been thought that biology is *reducible to* physics. We shall not argue these matters here, but shall try to make a direct comparison between the sort of "maps" that mathematicians have produced and the biological facts. That part of biology that we shall consider is the structure and function of the brain, and especially the visual part, that is, the visual system and its cortical representation.

George Boole was the founder of modern mathematical logic. He saw that he could construct an algebra which seemed to be capable of interpretation as a practical logic. This meant that the variables, or unknowns, in the algebra were capable of being interpreted as the ordinary sentences of spoken language. He thought that this sort of mathematics rigorously represented the laws of human thought, although since then it has been felt that it actually represents something like *ideal* rather than actual thought. Nevertheless, the discovery was of the utmost importance.

Walter Pitts and Warren McCulloch took the next step quite recently, many years after Boole, when they saw that the brain is rather like a machine that can be described by a mathematical system that has values of its variables of 1 or 0, according to whether the pulses of the nerve cells (or switches) are *live* or not.

Cybernetics is now well known to have seriously proposed that the brain is a control and communication system within the sense of the definition for physical systems, and is, in effect, a complex switching device, indeed, a two-valued switching device. Thus McCulloch himself thought that propositions, or ideas, concepts, and the like, are nervous impulses "on the move," as he put it. Again, the object of this article is not to consider any of the philosophical difficulties that these ideas meet; I shall simply concentrate on describing quite quickly the idea of a logical net.

A logical net is the simple geometrical realization of mathematical logic that has a form that is similar to, and perhaps can be made identical with, the structure of the nervous system, although we cannot be sure of this until we have discovered a great deal more about the structure and function of the human nervous system.

Those people who have taken their mathematical studies up to the stage where they see that algebra is capable of being wholly mirrored in geometry, or where geometry can be made wholly algebraic—that is, after a certain stage there is no distinction between algebra and geometry since all of geometry becomes algebraic and does not demand the drawing of diagrams—those people will see the same situation here. It was Descartes who saw that by taking a sort of trellis, or mesh, and measuring an x-value along one scale and a y-value along another, all geometrical figures can be put into an algebraic form. Here we see that the actual net as a diagram has an associated equation from mathematical logic. When we bear this in mind, it is clear that the whole structure of networks can be investigated from a purely mathematical point of view, at least in this sense; they are abstract nets, and to make them, like our maps, fit any particular territory means that we must first look very hard at that territory. This is the ultimate aim in this article: to see how the territory accords with the mathematical development so far.

Logical Nets

A logical net is made up of elements and connecting fibers. These elements can be divided up into those that have both input and output fibers, those with input fibers only, and those with output fibers only. Clearly one has in mind here the neurons and their axons, and dendrites, and these are divided into internuncial, sensory, and motor neurons. However, we should be careful initially merely to describe such nets as logical rather than *neural* nets. This is important because the nets will, initially at any rate, only superficially resemble the structure of the actual nervous system.

Each element has a threshold number which represents the number of input fibers that have to be simultaneously fir-

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ing to effect a firing in the element, and thus make the output fiber fire. In this respect we should say that there are two sorts of fiber endings that impinge upon elements, and they are either excitatory or inhibitory (represented by filled-in triangles and open circles, respectively, in Fig. 1). Furthermore, we need to include elements of a certain kind that have loops on them. This means that the output fiber is also an input fiber for the same element (see Fig. 1). There are one or two further rules that say that elements can be in only one of two states, either they are *live* or they are *not live,* and an element will fire at time t if and only if another element whose output impinges on the first element fires at $t-1$. We should also notice that time is assumed, at least initially, to be in a set of equal intervals, which are the firing times of the cells in the net. This is obviously something that is untrue of the actual nervous system. However, for initial investigations, as with mathematical physics, where we talk of ideal spheres without friction, and so forth, this is a fair, and even necessary assumption. This means that differences in synaptic delays and refractory periods in nervous tissue are ignored, but this can be compensated for by introducing delay units to achieve certain patterns of nets, even though the temporal delays and patterns necessary to proper nervous activity are not yet being reproduced in these logical nets.

We can now achieve great complexities if we take a sufficient number of these elements and string them together in very complicated networks. Such networks of elements have properties that can be stated mathematically. This is clear when we remember that every network is precisely defined in mathematical terms. There is a characteristic equation associated with each and every net. Kleene, the American logician, has shown that, by use of the propositional calculus and a little more, any of the networks that we may want are capable of being realized. The propositional calculus is simply Boole's algebra of classes where the variables are propositions and the connectives of ordinary language such as "and," "or," and "not" are to retain their ordinary meaning. The phrase "little more" refers to a small fragment of what is called the functional calculus. There is a need for functions and an existential operator, so that we can say "there exists an element such that it has been fired at some time in the past." This is a difficult matter to explain, and it is unnecessary to explain it here, except to say that this extra bit is necessary because of the loops on elements that allow them to go on firing for any length of time, once they have been fired. This mathematical system which has time suffices to define the net completely. Let us give some simple examples for Fig. 1. The element K^2 fires if and only if S^1 and S^2 fire together at the previous instant. Thus

$$K_t^2 \equiv S_{t-1}^1 \cdot S_{t-1}^2$$

where $\equiv$ is *if and only if* and $\cdot$ is *and.* Similarly, for L^1 and L^2

$$L_t^1 \equiv S_{t-1}^1 \cdot \sim S_{t-1}^2$$

$$L_t^2 \equiv \sim S_{t-1}^1 \cdot S_{t-1}^2$$

where $\sim$ means *not,* and so on for all the other elements.

Machines

We should say that logical nets are effective means of designing a machine, since we know from work on digital computers that we can realize, in electrical circuits, all the logical relations that we need to build the logical nets. This is very important, because it tells us that if we can construct a logical net with pen and ink and paper, then we have given a blueprint that could be directly translated into a hardware machine.

The machines that have been built so far are numerous, but one should especially mention Grey Walter's *Speculatrix* and *Cora,* Ross Ashby's *Homeostat,* Uttley's classification and conditional probability machine, and *Eucrates 1,* a machine recently built by Solartron for commercial purposes. All these were built in Great Britain, and many more have been built in the United States. These machines are all capable of being drawn up in logical network blueprint form, although in each case, as far as I know, they were in fact built otherwise than *from* such a plan.

The main use of logical nets is that one does not necessarily have to build the machine to know that it would work, although sometimes this is desirable and suggestive for design purposes, especially when such machines are likely to have commercial application. However, when the end is biological, and that is the only one that we are considering here, the logical nets themselves have great advantages, for it is possible to consider large aggregates of elements which involve an enormous machine, without actually having to build it. This is a method of approach to a theory, a mathematical theory, of the nervous system.

Digital and analog computers also have made contributions to ideas about how the brain works, by emphasizing the importance of methods of storage. But again the difficulty is that the methods of effecting a very similar end might, in the organism, be radically different. It is certainly one problem to build a machine that will do what a human does, and a different one to build a machine that will do what a human does by using the same *structure* and *functions.* It seems to me that the work of the engineer in building the machines of the feedback type so far built is of the greatest interest to biologists, but it must be admitted that opinions are divided in this matter. The nature of explanation in biology is still under dispute to some extent, but, even among those who favor what is called mechanistic type explanations, there are some who see no value in the suggestions of cybernetics.

Development of Nets

The next stage in the development of logical nets is simply to discover as many of their properties as possible, by mathematical and intuitive means. This has led to a sort of conceptual nervous system which has been of great use, or perhaps one should say will, it is hoped, be of great use to psychologists who wish to think of humans as machines having certain special properties that can be investigated. This can be done both for individual nets and for groups of nets. But I shall leave this matter for the time and just mention that some aspect of this subject has already been investigated under the name of *theory of games.*

It would seem necessary to outline very briefly what the present network model of a human being suggests. I shall be brief because the details have already been written up elsewhere, and I shall not pursue the question of the conceptual nervous system explicitly here, for that too has been written up elsewhere, but I shall go straight from a discussion of the properties of nervous nets and machines to a consideration of work done by neuroanatomists, electroencephalographers, and the like. This work is still too indefinite to give us any final picture, or anything even approaching a final picture, but it does at least suggest a tendency. First, though, let us take our description of logical nets a stage further.

It should be said that one lesson we

have learned from digital computer design is that sensory systems are similar to classification systems. The punched-tape or punched-card system used for filing information needs a sensing system that is fired when a hole on the tape or card passes under a wire fiber. Now, briefly, these fibers could be the fibers of the input elements of a logical net. This means that we could have a whole set of such input elements labeled *a, b, c, . . . n* which are fired or not, either individually, in twos, or threes, or any number at all, up to *n* at once. There may be vast numbers of these basic input elements that can be subdivided into sets. These sets would correspond to the different senses such as visual, auditory, and so forth. Now a physical object, which has (or *is*) a set of properties, such as being red, round, tall, and so forth, will thus be an aggregate of basic inputs firing, giving some pattern such as *acdjkrst,* say. We can now easily arrange to have logical network counters that record how often certain collections of input elements have fired together and how often they have not. Thus the machine, or organism, will be in a position to know that if *A* occurs, where *A* is some long string of basic input elements such as *acdjkrst,* then *A* is followed by *B,* some other such string, and this will be followed by *C,* and so on.

This ordering of strings of properties may be simple—that is, it may simply be a matter of observing or it may be a matter of "*A* follows *B* if and only if the machine does *A′* or *B′*," or again it may be that in either of the above two circumstances sometimes one thing follows, or again sometimes many things. These many things could be mutually exclusive or not. Thus we may say that whenever I see smoke I see a fire, *if I go and look for it.* Or perhaps if I see a shoe I sometimes see a man in it, and sometimes I don't. And so on.

The set of conjunction counters and disjunction-counters, as they are called, is shown in Fig. 1, which is a simple net capable of recording the occurrence of *a* and *b* together once or their nonoccurrence together once. The reader should trace out what happens to the net when *a* fires alone, and when *a* and *b* fire together, and when this happens in different orders. The loop will be seen to be the memory store, and thus the elements *C* and *D* are the store, which we have called the conjunction and disjunction counters, since they effectively count occurrences, although only up to one each here.

In the case of making an inference, this is possible for the machine, if it is seen that if *A* leads to *B*, and *B* leads to *D,* then, granted that the conditions of observation are adequate, it will be seen that *A* leads to *D,* contingent or otherwise on some response on the part of the machine.

Further than this, work has been undertaken showing how *consciousness* might arise in such a system, how generalizations might be made, how habits are broken suddenly as well as how activities are modified over a period of time. Indeed, much more of the behavior studied by psychologists can be mirrored in such terms. Let us assume that a great deal can be done along these lines to provide a conceptual nervous system, and let us now concentrate on the other question of how such systems fit in with neurological discoveries.

The Nervous System

We have at this stage arrived at some picture of what the cyberneticists have been talking about. We gather that they can design a machine that can classify its environment and can remember, and make inferences, and behave in many

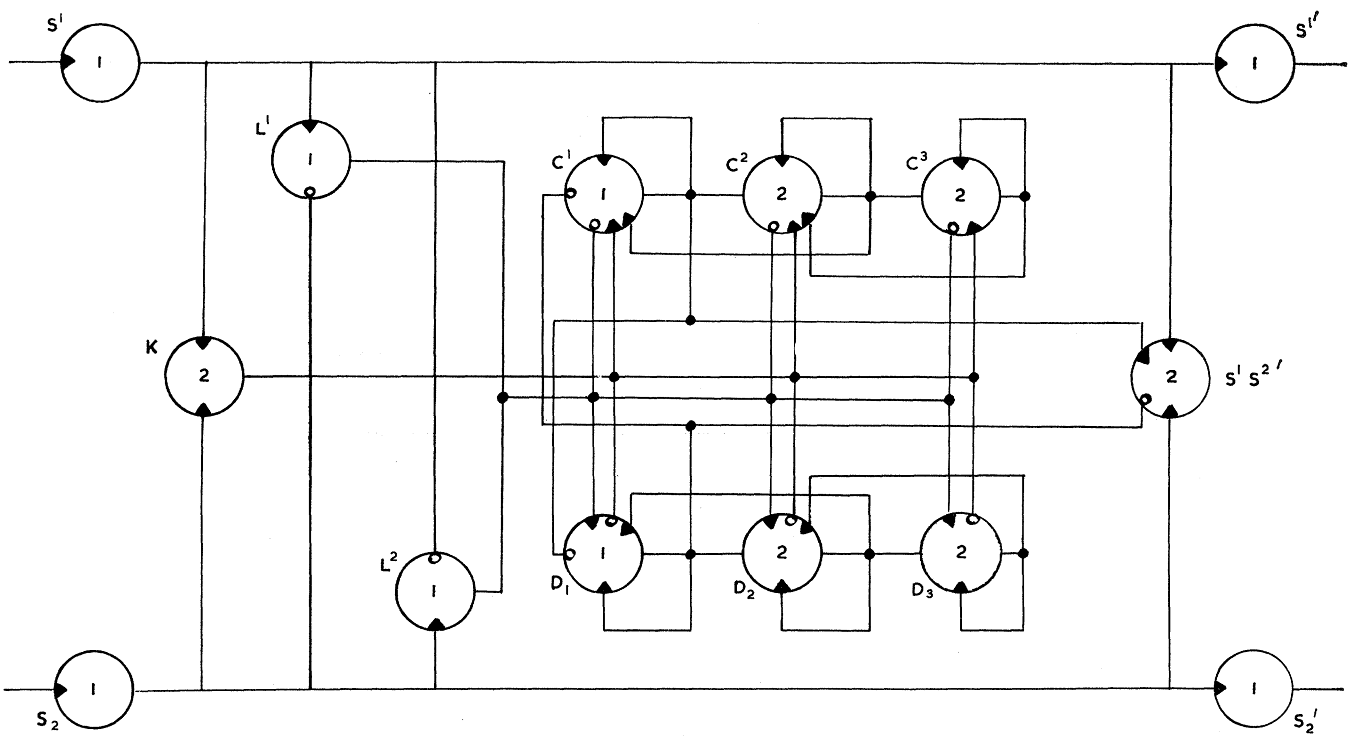

Fig. 1. Network made up of elements (large circles), with input wires (left) and output wires (right). There are two sorts of endings of the input wires on the elements. These represent excitatory (solid triangles) and inhibitory (small open circles) inputs when the input wires carry a pulse. The number written inside each element is a threshold number, and measures the sensitivity of the element by stating the preponderance of excitatory over inhibitory inputs that must be firing at any instant in order to fire the element—that is, to produce a pulse in the output wire at the next instant.

ways like an intelligent organism; now we shall compare the means which it uses with what we know of the human organism. Let us first look at the visual system, for this system is better understood than most.

We have learned a great deal about the human visual system, and I shall try to summarize very briefly what that knowledge amounts to. In the first place we know that the retinas of the eyes are the origin of the internal stimuli that travel from the periphery of the body, carrying information about the external world, to the brain. The retina itself is complicated enough, being made up of at least two kinds of nerve cells called rods and cones, and possibly also a third kind, the rod-cone. The nine layers of the retina, with their different sorts of connections and their lateral cells, are themselves a complete study, but at least we can see that the retina serves the purpose of recording two sorts of incoming sets of stimuli.

The cones and rods are separable primarily through their function in color vision and twilight vision, but also through rod areas and predominantly cone areas—those areas that are nearest the macula, a rod-free area centrally placed at the back of the eye. These areas are to some extent separable in terms of their function. They carry epicritic as opposed to protopathic fibers, which was Henry Head's functional way of distinguishing detailed from crude and generalized visual information. A more modern way of making a similar distinction is to discuss modulator and dominator curves, and this reflects the work that has been done with the help of the electroretinogram. Primarily, however, the distinction remains the same, and that is that the periphery of the retina tends to be concerned with movement and grosser visual effects, while the central parts are those of visual acuity and attention to detail. Thus the eye tends to turn in such a way that where detail is needed the object is projected onto the area with the highest ratio of cones to rods.

There are various artifactual considerations about the eye that have helped us to discover the processes that different areas subserve. Among these I might mention as examples the effects of contrast (the fact that white looks whiter on a black background), the fact of figural and movement after-effects, which can be summarized as distortions of the appearance of things both static and moving that result primarily from incidental properties of the eye, such as the lag in refocusing, and the backlash of the adaptive retinal processes. Also important are eye movements that are, according to one well-know theory of visual acuity, essential to the resolution of detail in the eye. However, there is a world of detail and discussion still possible on the retinal part of the visual system alone, and I must leave that now and trace the visual pathways back to the brain proper.

At the optic chiasma, on the route back, half of the fibers from each eye cross over to the other side of the brain which, it will be remembered, is in two symmetrical sections, and half of the fibers stay on the same side. This is necessary to continuity of vision across the visual field, and it results from binocular vision in man. The optic track then courses directly to the thalamus where it terminates on successive laminae of a part of the thalamus called the lateral geniculate body. Here connections are made with the second-order neurons of the visual system. From here they radiate to the striate areas of the occipital lobe at the back of the head.

Perhaps the most interesting feature of the visual pathways is the effect of summation resulting from the fact that information is being passed through a restriction. (Something very similar is seen in the auditory pathways.)

The passing of information through a restriction is something that is characteristic of the central nervous system and makes temporal summation a necessity. It should be mentioned straightway that there is no difficulty in showing how this can be done in logical network terms.

One significant thing about the visual system is the method by which the information, passing by ordinary nervous impulses, is finally reassembled in the occipital lobe. This is not wholly verified, by any means, but the theory, primarily that of the two physiologists Marshall and Talbot, has a great deal of plausibility. It says that the firing of regions in the retina at any time is repeated in much the same form in the occipital lobe, after transmission through the restriction of the optic fiber has taken place. (This firing of the retina occurs if, apart from subtle matters of relative thresholds in the retina, something distinguishable—that is, possessing visual gradients—is projected onto the retina.) The firm contour line is represented in the occipital lobe as the statistical peaking on the area of maximal distribution.

Whether or not such a picture of the recording of the epicritic detail is correct, it is certainly fairly near to the truth. It cannot actually be said that vision ends here, since the rest of the occipital lobe is concerned with visual elaboration, and this in turn is contiguous with the rest of the cerebral cortex, with its complex activities of storing information and acting on that information, being able to generalize and make inferences, and so on. It is fairly clear that the processes are not altogether separable, and one of the characteristics of visual activity is the fact that essential processes such as recognition, when visual, depend on the registering of the necessary responses emerging from the incoming messages from the eye, but are also dependent on a comparison of some sort being made with the information already in storage.

Our main question is not whether we can build a machine, or a piece of machinery, that operates like the visual system; this much is taken for granted, provided we can give a sufficient description of the visual system. But the question is, whether we can make predictions in terms of our knowledge with respect to the human visual system.

Our picture of the visual system, it will be remembered, is of a classification system. The retina seems to be a classification system involving two sorts of information. (Compare the way one can recognize physical objects in the environment by reference not only to visual, but also to auditory and tactile, classification.) Thus the classification is divisible into subsets of independent stimuli, and these can be correlated into patterns. It is precisely such patterns that we call physical objects.

The second point we should notice is that the sort of classification system that is introduced by Uttley is one that would have to be regarded as being at a microscopic level for the purposes of direct comparison between it and the visual system. This offers no difficulties in principle, and we can regard the retina as being made up of a mosaic of points that is duplicated in area 17 of the occipital lobe. This could be, and indeed has been, regarded from the viewpoint of information theory, where the information is being transmitted from the retina to area 17. Thus our interest is that the essential classification occurs in cells in the occipital lobe.

What of the disjunction, and conjunction counters that we have postulated as necessary to counting the occurrences of certain sets of stimuli? Here, of course, in the visual system we have so much redundancy that we should not need an exact count; rather, it is clear that our general processes of recognition depend on our being able to recognize some part of the total context and to make generalizations from such a sample.

It looks as if the area in which disjunction counters and conjunction counters predominate is the temporal area of the cortex, where stimulation elicits memories in conscious humans. This does not imply that this is exclusively the place, but rather it is a place of maximum concentration. This point also raises the question of reverbatory circuits.

We already know that there are such things as reflexes and negative feedbacks. For example, the pupillary reflex tends to keep the retinal receptors under constant excitation by adjusting the diameter of the pupil inversely with respect to the brightness. Such feedbacks are envisaged by Marshall and Talbot as being on the visual route back to the visual cortex. This damps excessive stimulation and amplifies inadequate stimulation.

It is also the case that there is a mapping of the retinal points on the midbrain which causes a reflex centering of objects seen in the peripheral visual field, already mentioned, by minimization of the polar coordinates. Of course, the translation of retinal maps to the midbrain and to the cortex may involve all the well-known transpositions of rotation, reversal, and so forth, but the topological properties of the original retinal mapping seem to be maintained.

We can go on multiplying the detail of the visual system by introducing the alpha rhythm as a scanning system that offsets the blurring and lack of sharpness due to aftereffects of the retinal stimulation. All these properties have obvious mechanical analogies that can be represented in somewhat idealized mathematical form.

We want now to go beyond these grosser feedbacks to the reverbatory circuits that have been observed in the cerebral cortex itself. These seem to be necessary to the storage of information. Or rather, they seem to be the most convenient way of storing information, and a method that is probable, in view of the evidence of such observations as those of the great American physiologist, Lorente de Nó. The frequently observed overlap of cortical function coupled with the apparent adaptation of cortical cells to repeated stimulation, suggests that the delicate timing of responses, or rather their *ordered* nature, becomes a consideration of the first importance. Thus we come to see, as indeed we should have done independently by pursuing our logical nets. We see that the ordering of the stimuli that make up the input turn out to be a vital characteristic. Thus an ordered set that is interpreted as A (and this may involve any degree of complication in the pattern of the primitive stimuli making up the stimulus A) will itself be an influence in deciding the nature of the next signal. Thus, very simply, things that have happened once are seen as more likely to happen again than those things that have not happened before. Thus a state of expectation, or set, is the weighting of contingent probabilities with respect to the ordering of signals in the nervous system. Such a state of affairs is at least consistent with what we know of cortical, or general neural, stimulation.

If we see the sensory classification system as taking up one large part of the brain, it is certainly true that a motor classification system takes up the other part. Thus we have a limited number of gross behavioral responses by action of glands, movements of muscles, and so forth, and these may be complex and intermingled. Thus we may expect that the direct responses that are associated with the sensory classification system will themselves be mapped onto some smaller subset which makes up the range of the individual's capacities.

Weighting of Events

There is now nothing essential needed between the sensory and motor classification systems except the storage system which makes up the counters. In fact, of course, there is, in the human being, more than one type of memory in that there seem to be things that are elicited on a short-term basis and those that require "digging out" from the unconscious. Here we are needlessly multiplying entities if we think of two different processes, because the same process, subject to two conditions, which are in any case necessary, will be sufficient. In the first place the organism has methods for allowing more weight to recent as well as more frequent events, for equal values. It also has a way of ascribing different values to events.

The recency factor can be taken care of in a variety of ways, the most likely being the gradual destruction of counts that occur through random firing and through various forms of interference in the very complex cortical picture, and especially where values are not high. What I mean by saying that values for the organism are high is that certain events are associated with other events that have high value for the organism in reducing a state of need, either in direct terms, by alleviating hunger, or the like, or indirectly, by contributing toward a state that will reduce a need. The extent to which the need is reduced is what we call, in self-conscious terms, the degree of feeling of satisfaction; this is what must also be recorded, and this is the value of the event.

Neurologically, the projection fibers from the hypothalamus and the lower centers, especially those concerned with the autonomic system and running to the frontal lobes, would seem to fit with the selector or motivational system of the logical net theory. It was always clear that the brain, acting as a logical machine, would not have the same efficiency as a counter for all events and their "togetherness." This is accounted for in part by the selective nature of the aggregates of input elements in the eye, in the human, which, because of the alpha rhythm, and other "errors" yet to be discussed, will not give equal weight to all external events. But even more, this bias that is placed on external events is due to the valuation that is accorded in terms of need reduction.

It should perhaps be said explicitly, to avoid giving the impression of gross oversimplification, that the complexities of values are enormous and a matter of great individual differences. It is all complicated further by self-consciousness and reflection, which is the process of stimulus-response activity of a covert kind that allows the firing of the sensory classification and motor classification systems by internal means, without involving the organism's going through the actual motor responses at the muscular or glandular level. This is part of what we call imagination and thinking.

The point of the above remark is to remind the reader that it is not always the actual value of need reduction so much as the believed value of need reduction that is so vital.

At any rate, the ability of the organism to avoid unpleasant consequences and to find pleasant ones lies in the "stamping in" of certain responses and the "stamping out" of others. One soon learns *not* to put one's hand in the fire, but one soon learns to put one's hand in the chocolate box. All of this is easy enough to incorporate into machine design; the problem is to find the detailed system responsible in the human. It would seem to be primarily a matter for the autonomic system, but it is also more complicated than this suggests.

Work on electrical stimulation of the hypothalamus of cats has shown what is called "sham rage," but recent demonstrations of the cortical representation of the autonomic system, coupled with the apparent meaninglessness of sham rage (hence its name), have convinced most people that the hypothalamus is only a relay center for the "emotional" system. Ultimately emotional behavior can best be understood in the light of reasonable behavior and it must involve the storage system of memory, since clearly recognition will normally play a vital part in it. Again we can introduce counters, as has already been done for ordinary association purposes, where it is not the actual count so much as the general dimensions of the count that is important to allow the passing of information indicating which are highly satisfactory impulses and which are not. Thus a correlation will be set up between satisfactory responses and certain signs in the environment, which will in turn condition what we call the person's *choice*. Thus a selection of stimulus situations may be expected in terms of previous experience.

It is perhaps worth adding that we can now see how to model almost all the functions of the human. This means that we can mimic more or less every organismic activity, even to the extent that John von Neumann in America has shown that machines can be self-reproducing. Self-reproduction turns out to be primarily a mathematical problem, and its solution is of special genetic interest.

The interest in the attempts to solve these problems lies in the realization that we are gradually, by such methods, making biology mathematical. It is most striking when one hears that a purely mathematical solution to the question of reproduction turns out to have great interest for geneticists. The implication is that such mathematical methods are well suited to the task of such descriptions.

Lastly, we must bring ourselves down to earth to some extent. The human machine is far more complicated than logical nets may seem to suggest. In humans there are endocrine systems and other means of communication besides the nervous system alone. Moreover, the nervous system itself is made up of several millions of neurons, of varying sizes, with varying latencies, varying refractory periods, and so on. Thus we know that at best we can only hope to find out something about biological principles and in practice we shall need to reduce our definite descriptions to a probability level.

In the nervous system we could list a few of the factors that may make for difficulties of precise prediction: (i) the fact that the metabolic products of nearby cells, their concentrations, and gradients may well affect thresholds; (ii) electric fields in the nervous system, to say nothing of the five principal components of a wave caused by even an ordinary nervous stimulus; (iii) thermal changes in nervous tissue, and so on.

Even in spite of this we can talk of homogeneous random cubes of cortical tissue, where intercortical connections, and the subcortical connections, can be approximated by quite simple mathematical functions. But it is clear that our descriptions are bound to be of a probability nature.

John von Neumann developed a picture of logical nets on such a basis, where errors of firing occur but where the errors are assumed to be small. These errors will not necessarily occur through inefficiency of the neurons involved but through the synapses being blocked by "emotional" responses (to take a probable example).

What we have to do is to try to recognize more and more of the mechanisms of the central nervous system, based whenever possible on the simplest notions of excitation and inhibition, and central inhibitory and central excitatory states, as postulated by Charles Sherrington, and then to be able to supply a mathematical function that can be shown to be sufficiently similar, by experiment and by other observations that would serve as a test of what is a hypothesis.

Ultimately, though, the idea must be that we should have a detailed account of the whole of the organism, a detailed and predictive account, which would not be used in practice to its full extent because of our vague knowledge of the effective inputs for the organism. Hence, given some idea of the inputs and some idea of the internal states, we want to be able to make a predictive statement about the subsequent behavior. All we can hope for is a probability statement, but we can perhaps make such statements fairly accurate. Logical nets and the field of cybernetics are trying to do just this. The link between the sort of systems that are *actually used* by humans and the machine analogies described are of increasing importance.