Meetings

Bionics

"Can ideas gained from the analysis of biological systems be applied to the design of artificial information processing systems?" To resolve that question a first Bionics Symposium was held in Dayton, Ohio, in 1960 and a second in Ithaca, New York, in 1961. With the third symposium held again in Dayton on 19 to 21 March 1963, the answer was clearly affirmative, yet in the meantime another question had emerged to dominate the meeting: "What is the logical basis for the design and construction of biological and artificial information processing systems and of all forms of life?"

Because of interest in the latter question the meeting was expanded to include 56 contributed papers in addition to the 14 invited ones. The sponsors, the Aeronautical Systems Division and the Aerospace Medical Division of the Air Force Systems Command, are to be congratulated on making copies of the contributed papers available at the meeting.

Theory and Logic

The first group of invited speakers stressed the limitations in present methods of analyzing and designing information processing systems. The most common complaint was the lack of a suitable mathematics or formal logic for describing the behavior of such systems and the changes of information content and form which may occur. The rapid growth in this field is marked by the fact that some of the later speakers partially met this need. Thus, M. C. Goodall presented a formal description of inductive logic, which emphasized two-way communication between the observer and the outside world. (A similar description has been independently evolved by Jerome Rothstein.) The observer makes a generalization regarding the behavior of some pattern of signals he receives from the outside world. This generalization is essentially a hypothesis which predicts how that pattern of signals will change when the observer acts on the outside world in specified ways. The observer then performs these actions on the outside world; notes whether the pattern of signals received from it changes as predicted; and adjusts the hypothesis (generalization) until agreement is achieved. An uncertainty principle applies to the simultaneous precision and generality of any generalization. The precision is increased but the generality is decreased by more sharply restricting the actions of the observer with which the generalization is formed.

This formulation of inductive logic includes what has been called "the scientific method." The realization that this same process applies to all generalizations may help clear up some of the confusions in social relations by distinguishing between untested hypotheses, such as stereotypes and true generalizations. It may also lead to the design of machines that can generalize. Such machines would be able to act on the outside world in order to test and refine each generalization. This is in contrast to present "pattern-recognizing" machines which can only recognize those patterns already built into them.

Ever since it was recognized that the information theory concepts of "amount of organization" or "information content" of a system corresponded to the thermodynamic concept of "negative entropy," it has been hoped that methods could be devised for measuring the negative entropy of biological systems, such as macromolecules, intracellular organelles, cells, organisms, and societies.

Some success was reported by Heinz Von Foerster who has devised a method by which, given the energy states of a molecule, one can compute the amount of information content of each state. This enables him to predict the formation of metastable molecules in the presence of an enzyme when the energy states of the various enzyme-molecule complexes are known. Otto H. Schmitt pointed out that mitochondria and other subcellular structures are aggregates of molecules which are organized in such a way that they can produce new aggregates of increased negative entropy (at the cost of some energy being made nonusable). Von Foerster suggested designing and constructing similar or more complex structures of molecules of this subcellular size and using them to store and manipulate information. This would provide extremely compact information handling systems.

The maximum density of information which can be stored in molecules at room temperature was estimated by Jerome Rothstein from thermodynamic arguments. He found it to be 10^{21} bits per cubic centimeter within two or three orders of magnitude. (For comparison, 10^{21} bits is more than the information required to specify 50 million hours of operation of a standard television channel.) He also considered the restrictions on self-replication of molecules and concluded that self-replication can occur more readily if the atoms are arranged in a chain rather than in a sheet or a block. This argument was perfectly general and applied not only to DNA but also to any self-replicating molecule.

The information content of the chromosomes in a human cell was estimated by Hans J. Bremermann. From the number of nucleotide pairs in a human cell and the assumption that they act independently he found an upper bound of 10^{10} bits. If it is assumed that the nucleotide pairs act only in groups (genes), then from estimates of the number of human genes he estimates about 10^{5} bits as the maximum genetic information content of the human cell. This estimate implies many consequences for all studies of man and his activities. For example, even if there were only 10^{4} genes, there would be about 10^{3000} resulting genotypes. This is many times larger than the number of atoms in the universe (estimated at 10^{73}), so it would be physically impossible to label all the genotypes. Also, he calculated that to specify completely the 10^{9} to 10^{10} neurons of the human brain would require about 10^{12} bits. Since this is more than the information content of the fertilized ova from which the brain is derived, some of the neuronal connections must be repetitive in pattern or must be random. In a similar way he argued that human genetic information could not specify all antibodies if it is assumed that all antigens act independently. Therefore, antibody formation must either be an adaptive process or else the possible antigen-antibody pairs must be constrained. The essence of Bremermann's work was that from information theory arguments, the morphology of a human cannot be completely predetermined by the genes. This allows random and adaptive processes to determine some of the morphologic details.

Bremermann showed by the same arguments that the number of stimulus-response pairs (which he called "words" of "innate language") that could be genetically determined is no more than about 1200. This is important even for computer designers, since, as Schmitt pointed out, the design of computers and their operating programs (and of any information processing system) depends ultimately on a biological system, man; and the rigorous specification of any such system makes use of genetically determined patterns of human behavior.

Another basic limitation which must be considered in the design of pattern recognition systems was discussed by W. Ross Ashby: namely, that the number of possible subsets of input signal patterns increases very rapidly with the number of input elements. Thus, a simple 20 by 20 array of input elements can have 2^{400} different pictures, and these can be arranged in $2^{2^{400}}$ ($\approx 10^{10^{120}}$) possible subsets, a number much too great to be physically enumerated. (As Albert M. Uttley pointed out, some biological systems are even more complex; the vertebrate retina has nearly a million times greater array of input elements or photoreceptors.) This large number of subsets prevents direct analysis of the whole of most pattern recognition systems. Instead, design methods are limited to: (i) breaking the system into simpler, isolated components which can be analyzed; (ii) using systems which respond to only a very limited number of built-in patterns; and (iii) using adaptive systems capable of generalizing, as described previously. Examples of all three designs can be found in biological systems.

Multistable States

Ashby pointed out that present information theory is based on the assumption of ergodic and stationary distributions of events, but that this is inappropriate for adaptive systems which permanently change their ways of behaving in order to better achieve some goal. He proposed a modified theory based on McGill and Garner's methods of uncertainty analysis, which use a table of the frequency of events over a finite time. In such a theory entropy must be redefined, but in an extreme case this theory becomes identical with the present theory of Shannon.

One such adaptive, multistable system has been examined by Malcolm R. Uffelman. This system could carry out its search for the best way of behaving by any of three procedures: (i) require total success before retaining a mode of behavior; (ii) retain those modifications which gave partial success; or (iii) search for success of a single output variable at a time. It was found that retention of partial success was the most rapid method of establishing a stable mode of behavior. For this study the adaptive memory mechanism used in the search was implemented in the form of a special purpose digital system.

The concept of multistable systems was originated to better describe the behavior of biological organisms. Its utility becomes clear when the reticular system of the vertebrate central nervous system is considered. As Warren S. McCulloch phrased it, "The reticular system is the final authority on the overall behavior of the organism. Whatever part of it receives information can, and does, take over command." An attempt to explain the operation of the reticular system in terms of a theory of iterative nets was described by William J. Kilmer. The net is made up of horizontal modules having inputs and outputs in a horizontal plane and vertically, with many of these modules stacked and connected vertically. In contradistinction to the McCulloch-Pitts system of general iterative nets, each module is connected directly only to the two adjacent modules. One question to be studied in this model is the conditions necessary for the net to be able to shift from one stable state to another without getting stuck in a cycle of indecision. Another question concerns the time required to switch from one stable state to another and the amount of the nervous system which becomes involved in making the decision to switch. For example, though the conduction time of neurons through the reticular system is less than 10 milliseconds and the firing time of a neuron is about 1 millisecond, it has been observed to take about 50 milliseconds to switch to a new stable correlation between two adjacent neurons in the reticular formation. Kilmer suggested that this time was used by the reticular system to ask the cortex to perform some computations with the available information. On the basis of the results of the computations and the incoming information the reticular system then made a decision to commit the organism to some course of action, and reset the outputs of the modules accordingly. It was his hope that study of this iterative net model would lead to experiments on the reticular system that would permit a quantitative description of its properties.

Some experiments on the reticular system's control of sensory information processing were presented by W. D. Keidel. He estimates that the output of all the sensory receptors of a human amounts to 10^9 bits per second, while from psychophysical data it would appear that only 100 bits per second are selected by the central nervous system for (simultaneous) conscious processing. (I estimate from psychophysical data that the information input rate available to "consciousness" is several orders of magnitude less than the output of the receptors, so that much selection of information must be carried out in the more peripheral portions of the central nervous system and in the sense organs.) Keidel proposed that the selection of information for conscious processing is controlled by the reticular system, and that this is done by selectively altering the information flow at every level of the sensory pathway. In support, he presented measurements of the electric potentials from the intact skull of man (presumably a measure of cerebral activity) which showed that the response to a regularly repeated stimulus is less than the response to a similar, unexpected (randomly repeated) stimulus. He also described microelectrode studies of the guinea pig's cochlea which showed that at single neural units the response to regular stimulation of that ear was decreased by irregular stimulation of the other ear. The same effect was found at the second cochlear ganglion, and the accompanying changes in frequency–sensitivity function could be interpreted as a change in the relative amounts of activity transmitted by the pathway from the inner hair cells versus the pathway from the outer hair cells.

Another biological system which exhibits multistable behavior is the system controlling "following" movements of the human eye. Its mode of operation when tracking a predictably sinusoidally moving target is different than when tracking an unpredictably moving target. Laurence R. Young and Lawrence Stark presented a model of this system which provided the two tracking modes and had an input adaptive configuration which switched the tracking modes as needed.

A somewhat different and simplified approach to the problem of multistable systems was presented by Mihajlo D. Mesarovic. He considered multi-level systems in which the first level received information from the environment and produced actions (responses) on the environment. A second-level system examined the behavior of the first level and modified that level's actions so as to achieve some particular goal. Such multi-level systems were simulated by having one person act as the second level "coordinator" of the activities of a number of persons acting as the first level systems. Some findings were that the second level has to have incomplete knowledge of the first level; that the second level can only affect the rate at which the first level converges on achievement of the goal; that second-level control could either speed up or slow down that rate. He found that, in general, such a two-level, goal-seeking system had the advantages that the goal-decider was better isolated from the environment, and that the behavior of such a system was easier to describe than that of a single-level, goal-seeking system.

Analyses of Biological Systems

The increasing willingness of communications scientists and biologists to share problems and techniques was shown by the number of papers presented which involved analysis or theory of actual biological systems—triple the number presented at the first symposium. The types of biological systems were also much more varied. For example, Adrian M. Wenner and Robert C. King presented evidence that honey bees communicate by sound and suggested that in the waggle dance, a method by which a bee informs its hivemates of the location of a food source, the information is primarily transmitted by the accompanying sound. This offers the intriguing picture of future bee hives outfitted with a sound source and a mechanical "dancing" bee so that the bee keeper could dial instructions to the bees as to which field to visit.

Experiments were described by William D. Neff which used anatomically specified lesions of the central nervous system in conjunction with behavioral testing to trace those neural paths which carry auditory information. It was found that information concerning frequency discrimination was carried along paths different from those which carry information concerning localization of a sound. He suggested that the latter information was transmitted in the form of time differences in the signals from the two ears to the superior olivary nuclei, where they were recoded in the form of place differences. He pointed out that in the medial olivary nucleus there was a type of neuron which had two large dendrites, each connecting to the path from a different ear, which seemed like an ideal unit for comparing the responses of the two ears.

A paper on peripheral neural mechanism of hearing in the monkey had been contributed by Yasuji Katsuki, Nobuo Suga, and Masahiro Nomoto, but none of the authors were at the meeting to present it. Fortunately, Keidel, in his invited talk, gave the symposium an excellent introduction to this group's fine studies of the different neural pathways from the inner and outer hair cells.

A most interesting theory of color vision was briefly outlined by J. Y. Lettvin. Starting with the known anatomy of the primate fovea, he proposed certain reasonable-appearing functional interactions of the various cellular elements so that the outputs of the ganglion cells for differing retinal illuminations would be related by the psychophysically determined laws of color matching. A basic assumption of the theory is that the response of each cone is determined only by the number of photons absorbed within its photopigment; the cone therefore is not able to distinguish changes in intensity from changes in wavelength. (In a later paper, E. L. Paulter and R. A. Wilson proposed a theory of color vision in which the rate of change of a photoreceptor's output potential was a function of the illuminating wavelength and the magnitude of the potential a function of the intensity.) In one of the neural circuits proposed by Lettvin, excitation from a foveal cone passes by means of a midget bipolar cell to a midget ganglion cell, while excitation from a surrounding annulus of cones is summed by brush bipolar cells and applied as inhibition to the dendrite of that midget ganglion cell. This inhibition acts to shunt and, therefore, to divide the amplitude of the excitatory signal reaching the output of the ganglion cell. In this way the output of that particular foveal cone is normalized with respect to the summed outputs of the neighboring cones, which include all three assumed types of foveal cones. This gives the same kind of mathematical function as Grassman's laws of color mixture. As a consequence of the basic assumption mentioned previously, such a circuit cannot distinguish a change in wavelength from certain changes in intensity distribution over the field of cones or from combinations of such changes. The uncertainty as to the meaning of the output of the midget ganglion cell can be reduced by comparing it with the outputs of the neighboring ganglion cells, thus making it possible to distinguish color and shape. Lettvin's theory is supported by the fact that it leads to the property of color constancy without additional assumptions, and by Kohler's old finding that the human visual system can learn to compensate for the colored edges of objects seen through a prism, so that the edges appear colorless.

Evidence in support of the concept that the activity of neurons is modified by the surrounding glial and other non-neuronal cells was critically reviewed by Leo E. Lipetz. He pointed out that this concept is still highly controversial and has not yet been proved. However, he concluded that, at least for the vertebrate retina, the evidence makes such non-neuronal control seem highly likely. The basis of such control is the very small space between those cells and the neuron, particularly in the brain and retina, so that those surrounding cells must act as the sources and sinks of ions during any sustained flow of ions across the neuronal membrane. This permits the amplitudes of the neuron's resting and action potentials and the propagation of potentials along the neuron to be affected by changes in the resting potential of the surrounding cells and changes in the ionic conductivity of the membranes of those cells. Some of the resting potential changes of the surrounding cells seem to be passive reflections of changes in the potentials of the neighboring neurons. But, the evidence makes it seem likely that some changes in the ionic conductivity of those non-neuronal cells are triggered and propagated through the cells by chemical processes. Lipetz proposed that retinal light adaptation could be explained in terms of such a process (for which there is some experimental evidence) propagated along the (non-neuronal) horizontal cells of the retina. He further proposed mechanisms by which certain other retinal functions, such as incomplete spatial summation and movement detection, could be explained on the same basis.

The aforementioned physiological processes of the non-neuronal surrounding cells provide modifications of neural activity which are slow compared to the responses of the neurons. It is interesting to compare this with H. D. Landahl's explorations of mathematical models of neural activity. He reported that by assuming neural elements which had two sets of time constants, one short and the other long, he was able to form neural nets whose behavior very adequately matched many known psychophysical functions. Such behavior includes flicker phenomena, apparent movement, color induction, and color constancy, and other known psychological phenomena such as conditioning and avoidance learning. However, one should note that a neural network may exhibit a long time-constant even though made up only of neurons with short time-constants. This was shown by B. G. Farley, who studied the behavior of computer-simulated networks of formal "neurons." He found that under the proper conditions, such as the presence of a few distant connections among the neurons, the overall network exhibited rhythmic waves of activity with a time constant about 15 times that of the neuron. His films of the activity of the networks in which the firing of each neuron was depicted by a light immediately called to mind Sherrington's beautiful description of the nervous system in action.

The noise limitations of information processing systems were discussed by John L. Stewart who pointed out that, especially in neural systems, there is more noise at frequencies close to zero than at higher frequencies. The system can be made more sensitive to the signal by removing this noise with a high-pass filter and time modulating the signal so that it contains higher frequency components. This technique seems to be used by a number of biological systems, for example physiological nystagmus of the eye, sniffing, and ear wiggling. Stewart described an electronic system for analyzing and specifying (recognizing) patterns of speech. He played a tape recording of some sentences of words synthesized according to those specifications and many of the words proved intelligible to the audience.

A beautiful example of the use of a new technique to illuminate an old problem was provided by the work of Patrick Wall and C. Kronacker. They investigated how the sensory nerves of an animal make the proper connections with its central nervous system. They started with the classical technique of grafting extra organs onto an amphibian and testing behaviorally which reflexes could be elicited by stimulation of the organ. For example, when the cornea of an added eye was touched, one of the normal eyes winked. Their innovation was to insert a microelectrode into the medulla at the level at which the corneal nerves terminated and to record, for 20 or more positions in that level, the electrical potentials which occurred following stimulation of the cornea. A computer was then used to convert this information into maps of the sources and sinks of current at that level for a number of time intervals after the stimulation. Large sources and sinks were found to be indicative of the terminations of large diameter nerve fibers, such as those from head skin; these were observed to be concentrated medially. Terminations of the smaller nerve fibers, primarily the fibers from the cornea, were concentrated laterally. The authors pointed out that a cut peripheral nerve which instead of regenerating, forms a neuroma, becomes smaller in diameter all the way back to its central termination.

They suggested that, similarly, the skin nerves that penetrate the bloodless cornea become smaller and change their central terminations from medial to lateral medulla. It appears that at the lateral medulla the fibers make monosynaptic connections with motor cells of the sixth nerve nucleus to stimulate the retractor bulbi muscle of the normal eye and elicit the corneal reflex. The basic hypothesis is that the tissue at the peripheral termination of a sensory nerve affects in some way both the diameter and the central termination of that nerve fiber. Additional evidence was provided by studies of normal and transplanted patches of back and belly skin of the frog. The sensory nerve fibers from all patches of back skin were small in diameter, and from all the patches of belly skin were large in diameter, and these different diameter fibers terminated at different positions in the cross-sectional plane of the spinal cord. It appears that a good start has been made toward understanding the code by which the external world is anatomically represented in the central nervous system.

In fact, it could be said that the symposium as a whole made a good start toward providing a logical basis on which to analyze and design information processing systems. For the first time it now seems possible that when the techniques of DNA alteration, molecular electronics, tissue culture, and so forth make possible the laboratory construction of new biological systems, there will exist a theory on which to base the design of the new forms of life.

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