CHAPTER 8

Biological Systems

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"Wha wadna pity thae sweet dames
He fumbled at, an' a' that,
An' raised their bluid up into flames
He couldna drown, for a' that."

Robert Burns
The Merry Muses of Caledonia

A. A MIXED DIET

If electrical engineers were grandmothers and computers were simple things like eggs, then it would be presumption indeed for a biologist to offer advice. But a biologist need have no fear, for he that is low fears no fall: electrical engineers clearly prefer a mixed diet, and computers are quite incapable of turning into chickens.

One continuing source of inspiration for us all is the natural world, and it is certain that lessons for engineers will flow from biological examples for those that are willing to make the effort. The unrolling of the information stored in the sequence of building blocks of the DNA* molecule in response to the progressively developing situation in every part of a growing embryo, and the control of the chemical turnover in any living body, provide examples of information flow that are amenable to mathematical approach if they can be written down as a series of suitable relationships. A more attractive candidate for analogy with man-made mechanisms is the brain, or, in general terms, the nervous system. Here it is more obvious that communication between parts of the body occurs, and the activity has a more striking time scale.

The control of development and the control by nervous systems differ from computers in the following ways.

(i) Many thousands of parallel channels are active, i.e., they are running numerous partially interacting programs simultaneously. An embryo may have 10^8 differentiating cells, each separately unrolling its own DNA. A human eye has 10^7 nerve cells, an ear 10^4 nerve fibres to the brain, a small region of the brain or spinal cord has 10^5 nerve cells, all more or less active simultaneously. For n independent subsystems which can be either active or not active at any given moment, the number of combinations of activity in different pathways is 2^n. Because the combinations must change continuously the possible number of patterns of activity soon becomes prodigious.

(ii) Computers perform their operations many times over and such "in depth" or iterative methods make use of long waveforms as a means of building up information content; e.g., they use differences between large numbers. They must therefore be

* DNA, short for deoxyribose nucleic acid, is the chemical stuff out of which the building blocks of inheritance, genes, are made. Basically, the controlled differentiation of living structures is all coded by appropriate combinations of a few units in the long DNA molecules.

accurate to better than 1 part in 10^{12}. By contrast, nerve cells are rarely accurate to 1 part in 100, and a figure of 1 part in 10 is more realistic. Therefore, on this account alone, nervous systems must perform only "shallow" or non-iterative operations.

(iii) In computers the timing of signals is supremely important in the carrying of information: in biological systems the significant feature is the choice of labelled line or pathway.

(iv) The *state* of a biological system or of its components is never fully definable. In particular, biological systems are not digital and, therefore, every measure has a range of error. The state of a biological system is also indefinable because it contains a memory of unknown extent.

(v) Computers are systems that are built in a particular way; on the other hand biological systems are ones about which we are still *finding* things out; although a great deal is known about tracts and centres in nervous systems, only the most trivial circuit diagrams are known in terms of the single nerve cells by which the nervous system operates. Even if the computer components are thrown together at random, and include random number generators, these features are potentially *all known to be there*. This much cannot be said for any biological system.

Notwithstanding, computers are valued by biologists for:

a. doing calculations. In the past most calculations could not be done because they were too hard. Successive approximations were too time-consuming. Use of computers makes it possible to do a larger proportion of all possible calculations;
b. storing and sorting information into categories that are given. In addition, the new types of program search out likely categories first and then sort for optimum separation of previously undefined categories. In short, computers organise data to produce sophisticated summaries.
c. making mathematical working models. These are usually conceptual models within the program of the computer and they illustrate how a set of interacting parts work out in practice. But this approach is always to be viewed with suspicion. A mathematical equation summarising the relation between input and output of a black box is a contribution that biologists will not accept as an *explanation*. They may accept it as a description if they see that they are dealing with the transfer function of a single, simple interaction which is really there. The mechanism must be understood in terms of its actual components, which are not relevant in the pure mathematical model approach. One good reason for this is that the biologist always wants to say how the information is distributed among his many parallel channels of flow at any one time. Without the visualisation of the mechanism, as a collection of real biological components arranged in space (called Anatomy) the biologist will always say that he does not see how his system really works. The most meaningful models in biology are always structures, and sometimes a computer "work-out" of them will show that they are models which fit the facts quantitatively as well as in composition.

The future value of biology to computer designers has no foreseeable limit. One obvious animal mechanism to copy is pattern perception. The eye, even in simple animals, is much better designed for pattern perception by having many lines in parallel than is the one-channel scanning system of a TV camera. The abstraction of the relevant features of visual patterns is a very diverse, and interesting product of independent natural selection in many animal systems. To copy these would be fun; to make effective artificial systems would be useful for sorting mail, recognising approaching accident situations in traffic, sorting goods in a warehouse or in lieu of visual inspection on quality control. Partly in response to this need, a new type of computer is being explored. A large number of independent sensors each feed into a network of coincidence and anti-coincidence circuits which are able to pick out particular spatial patterns. But the number of possible patterns rapidly gets out of hand as the number of inputs and possible selections increases. Most lower animals have conquered this problem by restricting their attention to certain classes of pattern which occur commonly round them, and to a very limited number of choices in their behaviour. This is their *repertoire.* Therefore, it may follow that computers built with many parallel inputs must be limited to a particular repertoire. But without a memory such a system gives only a rapid answer to an immediately presented pattern. To achieve more the problem is to replace a time-sequence memory on a tape by numerous interacting memories in many locations, laid out in as many dimensions as there are input lines in parallel, and all simultaneously available. This is difficult but not impossible, for apparently many types of animal brains, e.g., bee, frog, octopus, rat and spider, manage to do it.

B. EXERCISES

1. A pattern perceiving device has n input channels which may be either On or Off at a given moment. The device has m possible outputs that it can bring into action in different combinations as a result of x different classes of patterns in the inputs.
   What is the relation between m, n and x? (A system with $n = 2, m = 4$ and $x = 4$ is easy.) Draw in terms of hardware, as relays, a system with $n = 4, m = 4$ and $x = 4$. (Clue: you now find that some patterns are not distinguished.)
2. You lead off with a random probe the electrical activity from *an unknown point* inside a digital computer, and on another occasion from inside a brain (both having a memory). In each instance how would you distinguish signal from noise?

SUGGESTED READING MATERIAL

BARLOW, H. B. "The Coding of Sensory Messages" and GREGORY, R. L. "The Brain as an Engineering Problem" in a book entitled *Current Problems in Animal Behaviour.* W. H. Thorpe and O. L. Zangwill (eds) pp.424. Cambridge University Press, 1961.

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