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| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br><b>A brief account is given of how a neural network can store a distributed content addressable memory. Some of the properties of such a network as well as a possible site of storage of long and short term memory are discussed. Additional keywords: Army research; Synapse; information theory; parallel processing; brain.</b> |                                     |                                                                |

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### Distributed Memory

That most intriguing aspect of human memory: its persistence in spite of continual loss of individual neurons over the lifetime of the individual has led many workers<sup>(1,2)</sup> to the concept of distributed memory.

For distributed memory (more like a hologram than a photograph) possesses in a very natural way the property of relative invulnerability to the loss of storage units: individual memory sites hold superimposed information concerning many events. In order to obtain a single event, information must be gathered from many sites. Loss of individual units decreases signal to noise ratios but does not lose items of information.

Further, in contrast to modern computers that perform large numbers of sequential operations very rapidly and very accurately, the central nervous system works slowly and probably not with enormous accuracy on the level of individual units, with cycle times that cannot be shorter than a few milliseconds. However we can make complex decisions in small parts of a second. This suggests very strongly that there is much parallel processing in the brain - an idea that is almost obvious on inspection of a component such as the retina.

It is now commonly thought that the synaptic junction may be a means to store information (memory, for example) as well as to transmit it from neuron to neuron. Large networks of neurons connected to other neurons via modifiable synaptic junctions provide the physiological substrate for the distributed parallel systems discussed here.

For a distributed memory it is the simultaneous or near simultaneous activities of many different neurons (the result of external or internal stimuli) that is of interest. Thus a large spatially distributed pattern of neuron discharges, each of which might not be very far from spontaneous activity, could contain important, if hard to detect, information. Let us consider the behavior of an idealized neural network (that might be regarded as a model component of a nervous system) to illustrate some of the important features of distributed mappings.

Consider  $N$  neurons  $1, 2 \dots N$ , each of which has some spontaneous firing rate  $r_{j0}$  (This need not be the same for all of the neurons nor need it be constant in time.) We can then define an  $N$ -tuple whose components are the difference between the actual firing rate  $r_j$  of the  $j$ th neuron and the spontaneous firing rate  $r_{j0}$

$$f_j = r_j - r_{j0}. \quad (1)$$

By constructing two such banks of neurons connected to one another (or even by the use of a single bank which feeds signals back to itself), we arrive at a simplified model as illustrated in Fig. 1.

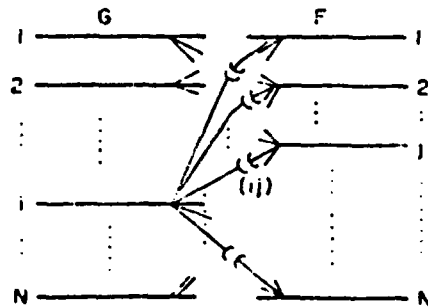


Fig. 1. An ideal distributed mapping. Each of the  $N$  input neurons in  $F$  is connected to each of the  $N$  output neurons in  $G$  by a single ideal junction. (Only the connections to  $i$  are drawn.)

The actual synaptic connections between one neuron and another are generally complex and redundant; we idealize the network by replacing this multiplicity of synapses between axons and dendrites by a single ideal junction which summarizes logically the effect of all of the synaptic contacts between the incoming axon branches from neuron  $j$  in

the F bank and the dendrites of the outgoing neuron 1 in the G bank  
(Fig. 2).

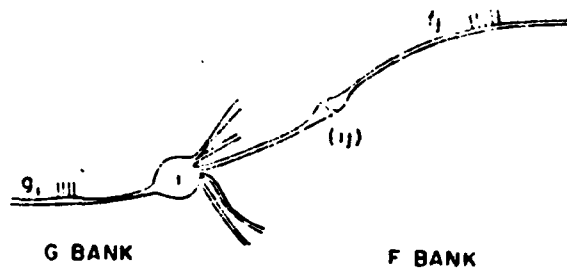


Fig. 2. An ideal synaptic junction

Although the firing rate of a neuron depends in a complex and nonlinear fashion on the presynaptic potentials, there is usually a reasonably well defined linear region in which some very interesting network properties are already evident. We therefore focus our attention on the region above threshold and below saturation for which the firing rate of neuron 1 in G,  $g_1$ , is mapped from the firing rates of all of the neurons  $f_j$ , in F by:

$$g_1 = \sum_{j=1}^N A_{1j} f_j. \quad (2)$$

In doing this we are regarding as important average firing rates, and time averages of the instantaneous signals in a neuron (or perhaps a

small population of neurons). We are further using the known integrative properties of neurons.

We may then regard  $[A_{ij}]$ , the synaptic strengths of the  $N^2$  ideal junctions, as a matrix or a mapping which takes us from a vector in the F space to one in the G space. This maps the neural activities  $f = (f_1, f_2 \dots f_N)$  in the F space into the neural activities  $g = (g_1 \dots g_N)$  in the G space and can be written in the compact form

$$g = Af. \quad (3)$$

It has been shown that the non-local mapping A can serve in a highly precise fashion as a memory that is content addressable and in which 'logic' is a result of association and an outcome of the nature of the memory itself.<sup>(2)</sup>

To illustrate with a simple example, that illuminates the content addressable properties of the mapping, write:

$$A = \sum_{\mu} g^{\mu} x f^{\mu}. \quad (4)$$

Here  $g^{\mu}$  and  $f^{\mu}$  are output and input patterns of neural activity. The symbol,  $x$ , represents the 'outer' product between the input and output

vectors. Although (4) is a well known mathematical form, its meaning as a mapping among neurons deserves some discussion. The  $ij$ th element of  $A$  gives the strength of the ideal junction between the incoming neuron  $j$  in the  $F$  bank and the outgoing neuron  $i$  in the  $G$  bank (Fig. 2).

Since

$$A_{ij} = \sum_{\mu} g_i^{\mu} f_j^{\mu}. \quad (5)$$

the  $ij$ th junction strength is composed of a sum of the entire connectivity of the system as reflected in firing rates of the neurons connected to this junction. Each association however, is stored over the entire array of  $N \times N$  junctions. This is the essential meaning of a distributed memory: Each event is stored over a large portion of the system, while at any particular local point many events are superimposed.

The fundamental problem posed by a distributed memory is the address and accuracy of recall of the stored patterns.

An arbitrary event,  $e$ , in the external world mapped by the sensory apparatus into the pattern of neural activity,  $f$ , will according to (3), generate the response,  $g = Af$ , in  $G$ .

(The pattern,  $f$ , might also be the result of some other internal pattern of neural activity.) If we equate recognition with the strength of this response, say the inner product  $(g, f)$ , and if, for illustration, we define separated events as those that map into orthogonal vectors:  $e_1 f_1, e_2 f_2 \dots e_K f_K$  where

$$(f^\alpha, f^\beta) = \begin{cases} 0 & \alpha \neq \beta \\ 1 & \alpha = \beta \end{cases} \quad (6)$$

then the mapping  $A$  will distinguish between those events it contains, the  $f^\mu$ ,  $\mu = 1, 2, \dots K$  and other events separated from these.

$$\begin{aligned} A f^\alpha &= \sum_{\mu=1}^K g^\mu \times f^\mu f^\alpha = \sum_{\mu=1}^K g^\mu (f^\mu, f^\alpha) \\ &= g^\alpha \text{ if } f^\alpha \text{ is one of the vectors } f^1 \dots f^K \\ &= 0 \text{ if } f^\alpha \text{ is not one of these vectors} \end{aligned} \quad (7)$$

In this special situation, the content addressable, parallel distributed memory is as precise as a localized memory.

$$f^1 \rightarrow g^1$$

$$f^2 \rightarrow g^2$$

$$\vdots$$

$$\vdots$$

$$f^k \rightarrow g^k$$

(8)

The properties of such a memory in more general circumstances, its ability to form associations, to map the external world, to create an 'animal logic' have been discussed elsewhere.<sup>(2)</sup>

#### Long and short-term memory

The N2 junctions,  $A_{ij}$ , contain the content of the distributed memory. It could be that a particular junction strength,  $A_{ij}$ , is composed of several different components with different lifetimes thought of as corresponding to different physiological or anatomical effects (e.g., changes in numbers of presynaptic vesicles, changes in numbers of postsynaptic receptors. Changes in  $Ca^{++}$  levels and/or availability,

anatomical changes such as might occur in growth or shrinkage of spines). We then have the possibility that the actual memory content (even in the absence of additional learning) will vary with time. For a two-component system we might have

$$A_{ij}(t) = A_{ij}^{(long)}(t) + A_{ij}^{(short)}(t). \quad (9)$$

where  $A_{ij}^{(t)}$  represents the memory at some time  $t$ , while  $A_{ij}^{(long)}$  and  $A_{ij}^{(short)}$  have long and short lifetimes. Thus in time  $A_{ij}^{(short)}$  will decay, leaving  $A_{ij}^{(t)} = A_{ij}^{(long)}$ . Whether what is in the short-term memory component is transferred to the long-term component might be determined by some global signal- depending on the interest of the information contained in the short-term component.

From this point of view the site of long and short-term memory can be essentially identical. At any given time there is a single memory. The distinction between long and short-term memory is contained in the lifetime of the different components of  $A_{ij}$ .

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