SIMULATION SYSTEM FOR BRAIN MODELING

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ABSTRACT

A highly parameterized, general purpose simulation system for brain structures has been coded in FORTRAN. Detailed three-dimensional models involving up to 8,000 neurons and 80,000 synapses can be specified and simulated. Individual model elements are not enumerated. Instead the parameter scheme uses spatial lattices and intersecting probability distributions to position neurons and synapses with any desired degree of precision or randomness. The system has been used to study neural activity in a cerebellar cortex model involving 2,000 neurons and 20,000 synapses and to evaluate an integrated circuit, picture-processing array made of 2,700 logic elements and 5,400 connections.

INTRODUCTION

The Brain Organization Simulation System (BOSS) is a system of digital computer routines. It creates and simulates large models of networks of neurons interconnected as in real brain tissues. Electrical activations of individual neurons within the models are the significant simulation events.

BOSS is written in FORTRAN for batch mode operation on the UNIVAC 1108 computer. It has two major phases: an initializer to create a model from parameter specifications and a simulator to determine its electrical behavior. BOSS differs from previous nerve net programs in three ways: the size of its networks, the complexity of its elements, and the power of its parameters.

In its current version using up to 200,000 words of computer memory, BOSS can simulate networks of up to 8,000 elements (neurons), up to 80,000 connections (synapses), and up to 60 variations in element type and interconnection pattern. Parameters do not enumerate the characteristics of individual network components. Instead, from a few dozen parameters BOSS generates the hundreds of thousands of details needed to describe a large network model during simulation.

BOSS neural elements compare the continually changing sum of excitatory and inhibitory inputs to a gradually lessening threshold value. Whenever the input sum exceeds the current threshold, the neuron fires. Its threshold jumps up to a high value from which it starts decaying again. A square-wave signal pulse starts propagating down each of its axonal output connections. After delays appropriate to the lengths and diameters of each axon these pulses become dendritic inputs to the receiving neurons. They are excitatory if positive and inhibitory if negative.

SPECIFICATION OF MODELS

To be modeled by BOSS a neural structure must be regularly organized. All the neurons must be categorized into at most a few dozen classes. Neurons in each class must be uniformly distributed spatially. In a model, each neuron is represented by an instance of the idealized neuron for its class, located at the nearest grid point of a three-dimensional lattice.

Input and output processes for each neuron are assumed to fill rectilinear regions of space around the soma. Synapses are uniformly probable throughout each region. The actual number of synapses within any region depends on overlaps with the regions of neighboring neurons.

Most of the parameter values for a BOSS model define the spatial distributions, and potential connections, and firing characteristics of neurons in each class. Neuron locations are determined from the position and spacings of each class lattice and the probability of occurrence of a neuron at each lattice point. The BOSS initializer finds all cases where an output region of one neuron overlaps an input region of another. Firing pulse transmission characteristics, including propagation delays, are calculated for each synapse.

Firing parameters specify the shape of the threshold curve for neurons of each class. They give the durations, strengths, and propagation speeds of axon pulses. They determine signal transfer characteristics of dendritic synapses as a function of distance from their somas.

SIMULATION OF MODELS

Three main arrays are used by BOSS during simulation of a nerve net model. The SOMA and SYN arrays contain the details representing individual neurons and synapses during simulation. The VNT pool of future events records pulses in transit along axons and dendrites.

The SOMA entry values for each neuron tell its threshold and excitation levels; its threshold decay rate; its maximum threshold level; its neuron class identifiers; its location; its dynamic links telling when it next may fire; and its pointer to the block of SYN entries for its synapses.

The SYN entry values for each synapse tell the strength and duration of its signal pulses; its axonal and dendritic signal propagation delays; its dendritic signal attenuation factor; whether its signal strength changes with learning; and which two neurons it connects.

VNT has 256 chains, each linking events which occur during the same quantized interval, or cycle, of simulated time. VNT entries post the start and stop of synapse activity; a possible change in synapse strength because of learning; a change in excitation level in the soma; and the possible resumption of a periodic, external stimulus to the model.

The actual simulation phase is the simplest major component of BOSS. The same cycle of operations is performed during each quantum of simulated time: all events posted in the current VNT chain are executed; resulting events are added to future chains; recently excited neurons are checked for firing; neurons that fire create new axon pulse events; and a pictorial map is printed to show which neurons have just fired.

Electrical interaction in a neural network is a parallel process: many significant changes occur at the same time. The simulation algorithm is serial: computer operations are performed one at a time, although very rapidly. Each full cycle of simulator operations calculates changes in all network variables during a tiny period of simulated time. Cycle times of one millisecond or less are used for neural models.

The VNT pool and the circular ring of 256 event chain headers allow very efficient storage and retrieval of future simulated events. An increase of 1 (modulo 256) in a header index corresponds to a time delay of one quantum. Simple addition determines where to store each newly generated event. Each event is stored and retrieved from the head of its chain. No sorting of chained events, no searching for event locations, and no marking of event occurrence times are needed by BOSS.

APPLICATIONS OF BOSS

The first large information processing structure simulated with BOSS was an integrated circuit array designed for automatic picture processing. The array measured the darkened area of the centermost object in a scene full of objects. It was a 33 by 27 grid of sensor circuits. Each consisted of a light detecting threshold element, an OR-GATE, and an AND-GATE In all there were 2,700 logic elements and 5,400 precise interconnections.

Only 84 parameter values were needed to specify the BOSS model of the integrated circuit array. In all it took two days to define the model, to digitize a real photograph for input, and to produce the simulated responses of the circuit. A comparable prototype circuit would have taken several months to build from electronic components.

The cerebellum is the most regular and best understood cortical structure of the human brain. BOSS was used to simulate activity in a 3 millimeter square portion of it. The model exhibited all patterns of connections known in the cerebellar cortex, except that the densities of synapses and neurons were systematically reduced. It contained 22,000 synapses and 1,800 neurons of 12 different classes.

The simulation model was able to demonstrate how the cerebellum can learn motor reflexes, such as needed for bicycle riding and piano playing. The only requirement is that synapses from granule cells to Purkinje cells grow in strength when locally overlapping mossy fiber and climbing fiber inputs repeatedly excite Purkinje cells at the same time.

BOSS required approximately 15 minutes of UNIVAC 1108 processor time to simulate 1 second of activity in a tiny fraction of the cerebellum. Truly parallel, integrated circuit models are needed to reduce this 1000 to 1 time factor. With carefully structured electronic brain models, significant information processing feats of the brain could be simulated.