The Massively Parallel Processor (MPP) is an ideal machine for computer experiments with simulated neural nets as well as more general cellular automata. The purpose of this paper is to describe our experiments using the MPP with a formal model neural network. Our results on problem mapping and computational efficiency apply equally well to the neural nets of Hopfield, Hinton et al., and Geman and Geman.

Keywords: Neural Network, Annealing System, Stochastic Cellular Automaton

Evolutionary Learning

An evolutionary learning system is a formal dynamical system in which the states correspond to modes of information processing, while the suitability of each state is measured by a potential function, the most desirable states possessing least potential. The dynamics of such a system are determined by an annealing process (Refs. 8-9), so that desirable modes are attained by a gradual lowering of the amount of thermal noise.

(The prototype example of an annealing process consists of a gas molecule confined in a potential well, in which the goal is the location of a global potential minimum. If the ambient temperature is lowered sufficiently slowly, the molecule will become trapped in the global minimum with a probability arbitrarily close to one. It is the random behavior of the molecule, "thermal noise," which accounts for its ability to escape from local minima during the cooling process. Simulated annealing then entails simulation of these dynamics in the solution of combinatorically large-scale minimization problems such as the "travelling salesman" problem.
problem. The essential role played by random noise in such techniques places them outside the realm of algorithmic strategies.

Further, the potential energy function depends on the environment, so that it is the environment which indirectly determines the equilibria and evolution of the system. We refer to this indirect process of control as soft programming. An evolutionary learning system may then be thought of as a dynamical system which behaves according to three principles:

- **Ergodicity** - the use of chaotic behavior to search a state space,

- **Annealing** - the regulation of thermal noise by means of (local) lowering of ambient temperature, and

- **Soft programming** - the indirect control of the evolution of the system by the environment.

More complex learning regimes were shown to follow the same basic principles (Waner and Hastings, Ref. 10). We also remark that gradualism in annealing systems is a consequence of the annealing dynamics: small changes in the starting point or the shape or potential surface usually cause small changes in the dynamics. Modification of the potential surface through feedback in learning corresponds to Conrad's modification based learning. The annealing dynamics are considered to be internal and inaccessible in detail compared to the feedback dynamics of any learning scheme.

In late 1985 and early 1986 the neural network programs were transported to the MPP. The relationship between the theoretical dynamics and the neural net models will be briefly discussed below.

The rest of this paper is divided into three main parts. The first of these summarizes our neural network models. The second part summarizes our experiments to date on the MPP, and should be understood in the context of a preliminary report. The last part describes conclusions for the application of the MPP and similar massively parallel architectures for our model and similar models. Most of our qualitative conclusions may be readily applied to other neural networks (Hopfield (Ref. 7), Hinton, Sejnowski, and Ackley (Ref. 6), Geman and Geman (Ref. 3)).
The synapses are also threshold devices. Their associated thresholds are called conduction thresholds. However, there are two important differences between the use of thresholds of synapses and those of neurons. First, the conduction threshold of a synapse determines the probability of conduction along that synapse according to the rule \( \text{prob}(\text{conduction}) = 1 - (\text{conduction threshold}) \). Second, the conduction thresholds are modified according to two rules:

**LEARNING BY REPETITION.** Thresholds of synapses which conduct (and similar synapses) are lowered. Conduction thresholds of synapses which do not conduct (and similar synapses) are raised. In the presence of suitable learning regimens, this yields Conrad's modification based learning. The threshold modification scheme must be constructed carefully to minimize the chance of positive feedback in the internal dynamics.

**LONG-TERM FORGETTING.** Most conduction thresholds (all thresholds except those very near 1 or very near 0) slowly decay to a base value. Thresholds sufficiently close to 0 or 1 do not change; this corresponds to modification-based learning.

**Annealing System**

Recall that the temperature in an annealing system corresponds to the degree of randomness. In this sense, the entropy (Shannon information) associated with random behavior at all of the synapses corresponds to the temperature. When following a learning regimen results in reducing this entropy, this corresponds to a reduction in temperature. The use of random conduction along synapses yields the underlying diffusion in an annealing system; restricting the dimension to 2 or using a wrap-around topology would guarantee ergodicity. For all practical purposes the present system appears ergodic. Differences in thresholds yield drift terms corresponding to the gradient flow part of annealing. These differences and consequent drift become more pronounced as learning via "annealing through modes of information processing" proceeds.

We remark that classical annealing problems (Ref. 9) can be readily programmed on the MPP with an analogous problem mapping of one cell per processor.

**Soft Programming**

Soft programming consists of specifying the learning goals. Three types of goals have been studied theoretically. The simplest consists of structured path learning, \( \text{learning paths from "sources to "targets."} \) The MPP program below illustrates this case. More complex cases include associative learning and more complex route-finding (only theory so far).

**Problem Mapping**

We have allocated one processor to each node. This offers the advantages of simple data flow and programming, at the expense of frequently having idle processors in simple experiments.
The Program

NEURAL NET: BEGIN

1. INITIALIZE
   Net: initialize thresholds
       initialize activities
       initialize source and
target, or learning problem

   Supervisory: initialize random
       number generator, clocks,
maximum time allowed, etc.

   Learning regimen: specify.

2. MAIN LOOP: REPEAT until timeout
   or learning occurs. Increment random
number generators as necessary
throughout loop.

   AT each neuron: IF activity is
   greater than or equal to
firing thresholds, THEN
FIRE and reset activity to 0.

   AT each synapse, IF neuron at
tail of synapse has fired, THEN
TEST for conduction:
synapse conducts if random
number is greater than
conduction threshold.

   IF synapse conducts, THEN
increment activity of
neuron at head of synapse.

   AT each synapse, modify
conduction thresholds incor-
porating learning by
repetition and short-term
forgetting.

   Did net learn? If so, then
exit loop and print results.

   Increment clock.

END MAIN LOOP

3. OUTPUT

END NEURAL NET

One should note that the net is
intrinsically parallel and
stochastic. The parallel feature of
the net allows a natural problem
mapping: one maps one formal neuron
to each processor. Other mappings are
possible; for example, one could map
each processor to one neuron in a
neighborhood of a given neuron, and
store the net in an appropriate data
structure for transversal. The
problem mapping we used was chosen for
its simplicity, and potential to
reduce the size of the program and
maximize computing speed. For
example, the MPP program is
approximately 20-30% shorter than the
VAX program, and both are programmed
in similar high-level languages.

The MPP program also ran
significantly faster than that of the
VAX. The present improvement factor
in simple experiments is about 100.
However, the MPP does not slow down as
the number of neurons firing is
increased. This combined with a
utilization factor in critical steps
of about 5% in simple experiments
suggests a relative speed increase in
complex tasks should approach 2000.

CONCLUSIONS

Massively parallel architectures
are especially appropriate and useful
for neural network and similar
simulations. In particular, the
geometry of the MPP closely parallels
the structure of our net model. This
places much of the data structure in
hardware, reducing computational
costs. In addition, much of the
computation is "strongly parallel" in
the sense that the next state
calculations must take place
simultaneously at many locations.
Failing this, data structures and data
movement must be developed to simulate
this degree of parallelism.
Furthermore, most of the VAX
computation cost apparently lies in
data movement, since no elaborate
function evaluations are needed. This contrasts sharply with both algorithms such as Gaussian elimination in which such tight parallelism is not necessary, and algorithms such as many finite element algorithms in which such parallelism is necessary (at least at a simulation level), but in which significant function evaluation costs far exceed data movement costs.

Much of our computing time is spent in random number generation. We are exploring the possibility of realizing random number generators or more general stochastic gates in VLSI hardware. Should this exploration prove successful, it would be possible to construct simple, rapid, and powerful evolutionary learning hardware.

Otherwise, the limited processor power and memory do not slow this type of modelling. In fact, the MPP architecture may well offer the best relative performance because much of the data structure and flow is already present in hardware.

FUTURE DIRECTIONS

At this point, the first part of our proposed research has been largely completed. We have largely developed the theory for applying our learning model to the route-finding problem, and should begin MPP investigations into this problem in early 1987. The extension of these models to more complex (reaction-diffusion) neurons will be done largely by M. Conrad with his former student K. Akingbehin. In a related direction, some successful ecosystem simulations have been performed with more work expected later this year.

REFERENCES