Cairo University, Egypt
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A Spiking Neural P-System

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To

Mum and Dad

Abstract

Membrane computing is a fast growing research area in the field of molecular computing; it is inspired by living biological cells. Membrane computing defines new computational models, called membrane systems or P systems, which define the biological cell as a computing device. They are constructed of membranes separated by regions, representing different compartments of a cell, and in each region there are processing rules applied on some data objects, simulating biological processes inside the cell.

Spiking Neural P Systems are a class of P systems, inspired by neural networks and how they process information. They are composed of a net of membranes hosting a multiset of objects. They use communication channels among different cells; these correspond to axons in neural cells. Information is encoded in a sequence of consecutive moments. Time here is not a computing resource, but a way of encoding information. Spiking rules deal with all spikes in a neuron; sending spikes to its synapses, a computation is called successful if it halts, if no pending data found along any axon, and no neuron contains any activated rule.

In this thesis, an introduction to some quick historical background on the origins of this new field is made, with a biological overview on the nature of living cells, and neurons, then some basics were studied in computational theory as prerequisites for the rest of the research, then a survey on different types of P Systems was made, studying some of their features. Next we get in depth with a survey and study to some Spiking Neural P Systems, with their features and properties. After that we use the power of these computational devices to propose the concept of the membrane computer with a high level architecture for it, accompanied by a proposal for a logical model to its membrane operating system. From this point we get to the core draft proposal for a new computing device (the SNP A-Machine) which is a new model inspired by the atomic SN P Systems building block, the single neuron, constructed by defining some processes into the neuron, and merged with a memory sub-system. Thereafter we coded the new model with its processing algorithms and developed simulator software, constructed a configurable simulation environment, defined four experiments to monitor and study the new machine's behavior, processing power, and efficiency. Results are analyzed and conclusions were set at the end of this thesis, with some open tracks and future work enlisted.

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Chapter 1
Introduction

1.1 Membrane Computing

P Systems

These systems introduce a parallel computing model, processing *multisets* of objects, introduced by Gheorghe P˘aun in 1998. They are inspired by concepts from the living biological cells. Cell membrane separates the insides of the cell from the outside environment. Objects reside into regions, defined by a membrane structure, and are processed with a set of rules; they are placed into regions or membranes. The rules are applied non-deterministically in a maximally parallel manner. Some operations can be applied on objects like passing through membranes; which are handled by a set of operations like creation, dissolution, division and merging.

Spiking Neural P Systems

This class of P systems is inspired by the functioning of neural networks and the ways they use to exchange signals through their specialized junctions called chemical synapses. The system, in this case, it is composed of a net of membranes hosting a multiset of objects and being in a certain state according to which objects are dealt with. The communication channels between different cells are specified in advance and correspond to axons in neural cells. The fact that most of the neural impulses are identical, using electrical signals of a certain voltage, with a main role carried out by the time, when these signals are emitted by the intervals among signals they play the basic role of the information processing. Spiking rules deal with all spikes in a neuron; after getting fired and before sending the spike to its synapses, the neuron is its refractory period, does not receive any spikes; A computation is called successful if it halts, i.e., if no pending package can be found along any axon, and no neuron contains an activated rule.

1.2 The Motivation

Natural computing is inspired by nature and its processing operations. In the course of research in computing models based on living cells, a new direction was initiated in the membrane computing. The research curve was growing very fast (in 2003, ISI put this research area as "fast emerging" in computer science, see http://esi-topics.com). These devices are inspired by the compartmental structure and the functioning of living cells. The core novelty of membrane computing, against other molecular computing areas, is that membrane systems set the idea of the whole cell as a computing device. Many different models of membrane systems have been proposed depending on certain features of the biological cell, giving many variants of non-deterministic, distributed and parallel computing models. And consequently the quest for defining new computing models inspired by neural processes has emerged, crossing concepts with the neural computing area. The neural systems and membrane systems have many features in common, furnishing the base to construct parallel and distributed processes; thus both directions can push towards new types of computational mechanics.

1.3 The Aim

The aim of this thesis is to crack into the natural computing field from the molecular and cellular computing sides, investigating the membrane computing –P Systems– area in general, along with its derivative Spiking Neural P Systems in specific, and to study the nature of these new computational devices, trying to model and derive some new types of computing machines and algorithms, to seek more efficiency and new logical modeling mechanisms for some biological processes, based on the spiking neural concepts, from the perspective of this new science, this will be a trial in pursuit of proposing a new SN P System.

1.4 The Thesis Outline

This thesis is organized into 7 chapters as follows:

Chapter 1 – Introduction

This chapter introduces the Thesis with a quick overview on the research track, showing the motive, aim, and document layout.

Chapter 2 – Preliminaries

In this chapter we took an overview on the history of computing, and then we overviewed computing with cells, also introduced basic cell biology concepts. Then we visited the concept of neural networks, along with the biological neuron, in the second part of the chapter an introduction to some of the theoretical computer science concepts was made, discussing some basic entry points used in the course of the upcoming work.

Chapter 3 – P Systems

Here, a survey is made on the membrane computing and its features like information communication types, computational power, the processing rules, and membrane capabilities we also studied some of these systems variants, with their logical models, and different organized environments like neural and tissue membrane networks.

Chapter 4 – Spiking Neural P Systems

For the SN P Systems, which are natural derivatives of the P systems, we overviewed the basics of the biological neuron, and studied the SNP System formalization model, then surveyed some different variants of these systems, focusing on building a base for our upcoming work, by using some concepts like extending the spiking rules, assigning weights, defining thresholds to the systems, dividing neurons, synchronization and Asynchronization and injecting the idea of the global clock into the system.

Chapter 5 – Proposing the Membrane Computer Architecture

In this chapter a very high level architecture to the parallel membrane computer was proposed, it is seen as a logical consequence following the emergence of the cell as a computational device, we investigated some trials to simulate these systems, some were hardware based, and others were software based. We mapped some of the operating system concepts to the membrane area, and proposed a logical model of a seed for the membrane operating system (MOS), then set a bird's eye view for architecture of the computer. We also tried to utilize the SN P Systems capabilities to simulate another extended view to the operating system concepts, the (SNPOS).

Chapter 6 – Designing the SNP A-Machine

In the chapter, we tried to answer a simple question: if the neuron is a cell in the core, could it have computational model inside? We tried to think differently looking for the single neuron as more than just a logical gate or function as it is being presented in many literatures, unlike the P Systems cell that basically depend on a set of compartments and membranes for computation, the neuron could be seen as a cell with a single membrane, we thought it needs a different mechanism to process data in the single mode, then the quest was more refined: From the SN P Systems perspective, could we consider the single neuron, a computational device? We tried to merge two models of SNP systems and the dynamic arrays systems, and introduced a new SN P System with a single neuron that has a memory, we called it the SNP A-Machine (A refers to Atomic), then we went in for more details constructing structures of short and long term memories ($\mathcal{M}$), with recall and forget factors $\{r, f\}$, then proposed some learning schema for the machine, and tried to develop some algorithms for handling data and information using such computing device.

Chapter 7 – Simulation and Analysis

The chapter is divided into two main sections: 1.Simulation Software design Overview. 2. Experiments and Analysis. In first point we tried to develop some software to simulate the machine logic through the implementation of its algorithms. We used the simulator to setup a simulation environment, watch then study the machine at run time, through some experiments. Each experiment contains the setting up configurations, outputs, results analysis, and conclusions.

Chapter 8 – Conclusions and Future work.

Chapter 2

Preliminaries

Introduction

In this chapter we take an overview on the history of computing, trying to place out the origin of bio-based computation track, then we will focus on the inclusion of computing with cells, with a brief introduction to the cell biology. Then visit the concept of neural networks and the biological neuron, which will lead to the core work in this research. In the second part of the chapter an introduction to some of the theoretical computer science concepts is made, discussing some basic entry points used in the course of the upcoming work.

2.1 Historical Background

By the end of the 17th century, Gottfried W. Leibnitz put the first step in automating and formalizing human rational thinking and its steps into a new methodology called algorithms, which is executing certain job by running certain steps; and that is known as computation.

Earlier in the 20th century, Alonzo Church, Alan Turing, and others, led the track in studying and understanding of algorithms. With the efforts of Alan Turing, first computers were introduced to the world by formalizing human calculations into predefined steps. This led to the rise of computer science.

His major achievement was the Turing machine [1] [2], in his article "Intelligent Machinery", he introduced the logic of computer algorithms that can be easily utilized using Turing machine. It is an imaginary machine that uses certain set of rules defined in a table to manipulate symbols printed on tape strip. Mathematical computations limits are made clear using that machine which was also called "a-machine".

Stored program was first presented in 1945 by John von Neumann. By the help of other scientists, Neumann found basics which led to successive science development. That is when "von Neumann architecture" was looked at as the comparison grounds, and despite of their limitation in speed and amount of stored data, computers provided an important and vital contribution to the computing concept.

Universal Turing machine and the common "referential model" of specifying sequential architectures were used in creating the Neumann architecture. A processing unit and a single separate storage structure used to hold both instructions and data is the main concept used in Neumann architecture computer design.

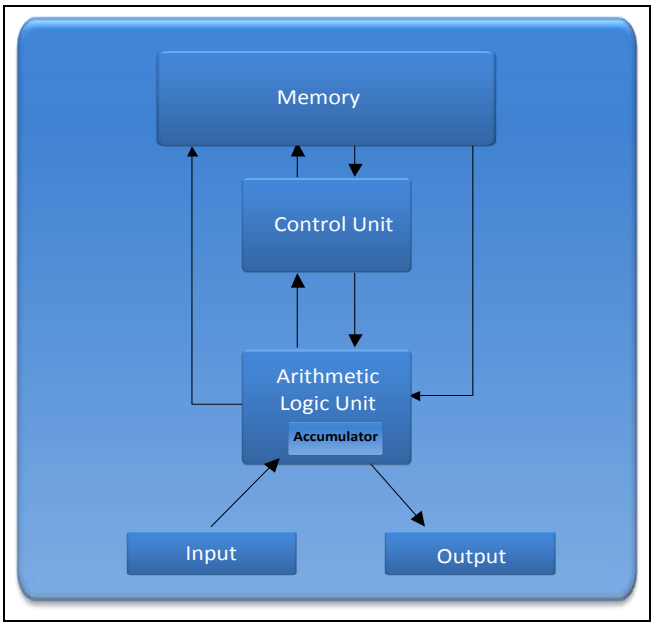

Figure 2.1: The Von Neumann Architecture.

Early computers using fixed program like calculators cannot serve other purposes, and to serve other computational directions, a specific designed computer with a fixed program should be recreated. That is where stored-program idea emerged, where programs are treated as data, and were stored in the computer as a sequence of set of instructions.

Flexibility of dynamic program changing was one of the characteristics of a stored-program, which was needed earlier to modify instruction address. But the importance of such issue was decreased when index registers and indirect addressing appeared in the machine architecture. Utilization of natural processes to establish and calculate more computing instruments is known as Natural computing, which can be used also to the revelation of computational paradigms.

By applying Natural computing concepts, many computing types can be introduced like:

- Quantum computing: Utilizes parallelism of quantum in its operation.
- Molecular and cellular computing: Simulates artificial or natural molecular processes to introduce new computing algorithms.
- Neural networks: Mimics neural structures of human brain and nervous system.
- Evolutionary computing: provides new computing strategies by utilizing mutation, recombination, and natural selection from biology.

2.2 Computing with cells

Using Cells in computing can be considered a classical track; when Automata theory appeared and Cellular model was looked at as a connection of nodes using communication channels operating over local ones and receiving data based on certain steps. This resulted in training and learning concepts among other new nodes. “Cellular automata” was introduced in by John von Neumann depending on the multicellular interactions generalizations, by abstracting biological cloning. Cellular automata provided a theoretical model for cloning equally likely devices with the same complexity.

A set of cells, having countable states and are updated by an identical interaction rule, in separate time intervals are called cellular automaton. Cellular automatons provide massive parallelism, simple components and inner interactions. Membrane system was introduced by Gheorghe P˘aun in 1998 in his “Computing with membranes” [3], as an abstracted model for cellular computing by watching the mechanisms of living cells. Chemical evolution, communication, compartmental structure and interaction functions of a living cell is the core of membrane systems base. Chemical reactions occurring in the membrane led to creating new objects from the old ones reside in the compartments of the cell that can be moved to the nearby compartments of other cells. The model of computation was named P system, is a category of biochemical distributed parallel computing devices.

Using RNA molecules as a computations physical medium was proposed in 1973, C. Bennett in molecular scale computing [4]. A theoretical modeling was introduced by Bennett to save data using RNA molecules and dealing with them with the help of motivations like “enzymes” in biochemical reactions. In 1987, Tom Head proposed a formal model of DNA molecules recombination. Restriction enzymes that classify molecules and ligases that group matched ones, perform the splicing operation. In 1994, Leonard M. Adleman used molecular biology to solve a hard computational problem, which was considered a big advance in natural computing. Practically accomplishing Feynman’s theory, he succeeded in solving Hamiltonian Path Problem using DNA strands. A huge track of research in computer science/molecular biology/biochemistry/physics was availed, but it raised another amount of problems.

Massively parallel searches is the key point in the inspiration of DNA computing that provides huge advantages in speed, energy consumption and stored information density. As in Adleman's model [5], a DNA computer could be 1,200,000 times faster than the fastest super-computers, and about 1010 times more energy efficient [6]. A single DNA memory could hold more words than all the computer memories ever made.

2.3 The Cell

Francis Harry Compton Crick, with the help of James Dewey Watson, revealed in 1953[7] DNA secrets. As per Crick, The cell is divided into cover and inner by a clever filter, that permits some produced molecules to move in/out the cell and block other molecules. A closer look at the content of a cell, two shapes of molecules can be found, the first is very large and long, while the other is small and thin.

The cell is considered as a factory containing multiple type of work. Small molecules being changed one into another and large molecules being built out of small ones. Inside a single cell, it can generate all these types of molecules using very primitive processes. DNA, Cell membrane, ribosomes, and cytoplasm, are the common properties of all cells, with different types, in the following Figure 2.2 a general view is shown for a cell.[8][9]

Cell division is the process responsible for reproducing cells. First a cell increases in size up to the level in which two daughter cells can be generated. For successful division, chromosomes duplication must take place first to provide daughter cells with diploid chromosomes. DNA replication is defined as the process of duplicating DNA molecules where each has identical nucleotide sequences, so it contains the same genes.

Proteins are considered as gateways for the cell, allowing certain molecules to go through the cell in both directions (in/out). Proteins exist in the cell inner layer, but the most of their hydrophilic parts branch into the cells interior and outside of the cell. The membrane's outer side is most likely rich in glycolipids, which have hydrophobic parts, are included in membrane's hydrophobic region while their heads are outside the cell.

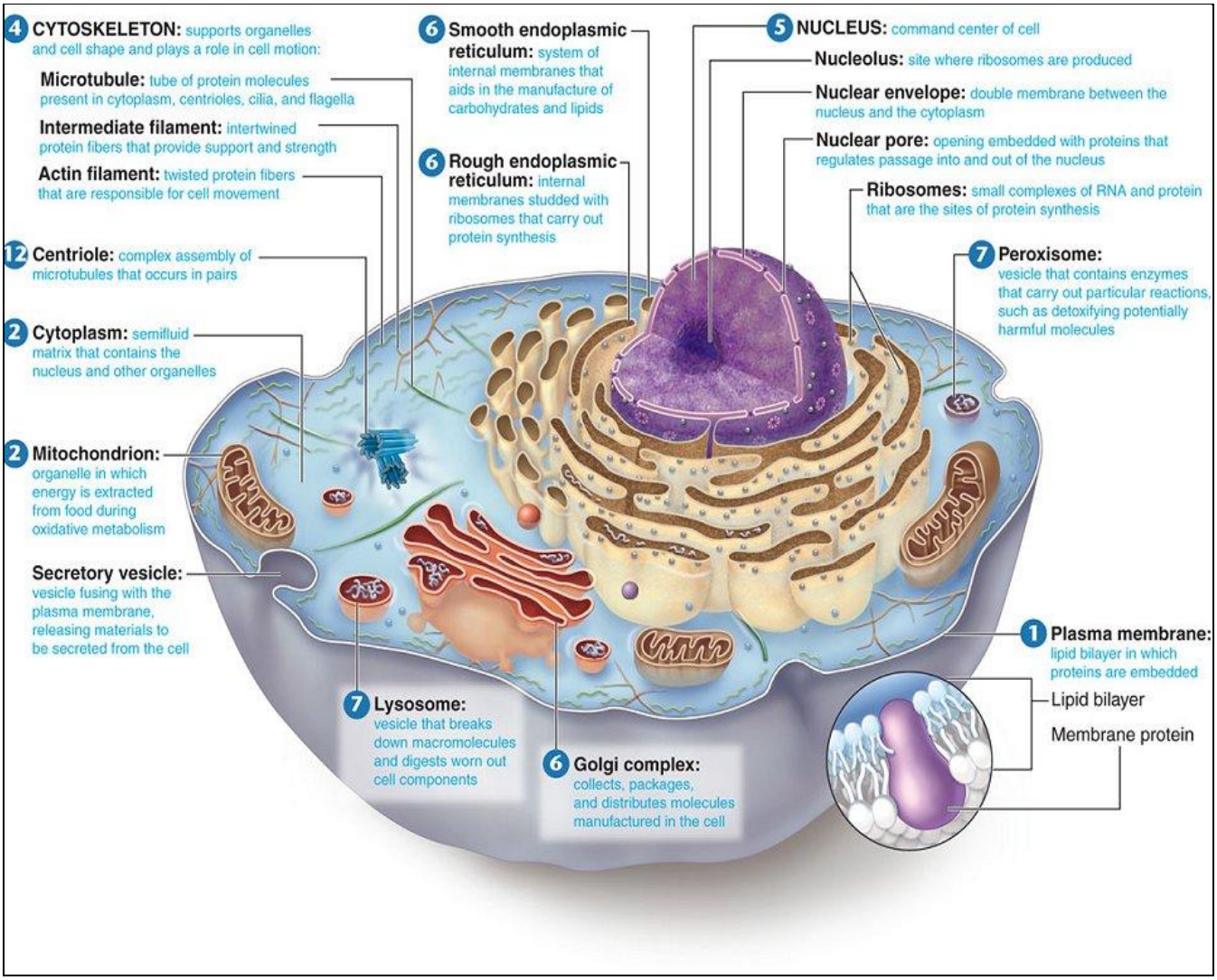

Figure 2.2: An overview of the Animal Cell. [10]

2.4 Neural Networks

A neural network is an interconnected assembly of simple processing elements, units or nodes, whose functionality is loosely based on the animal neuron. The processing capability of a network is built via learning of training patterns, this capabilities is saved in inter-unit connection strengths, or weights [11]. The human brain contains about 1011 (100 billion) nerve cells or neurons, that can be basically seen in Figure 2.2. Neurons interconnect using electrical signals

that are fast-dead impulses or "spikes" in cell wall or membrane voltage. Synapses are electrochemical junctions located on cell dendrites and responsible for interneuron connections. Thousands of connections among neurons takes place, these connections reach the cell body. When a single neuron receives connections that their summation exceeds a certain threshold, it produces an impulse as response which is propagated to other neurons via the axon.

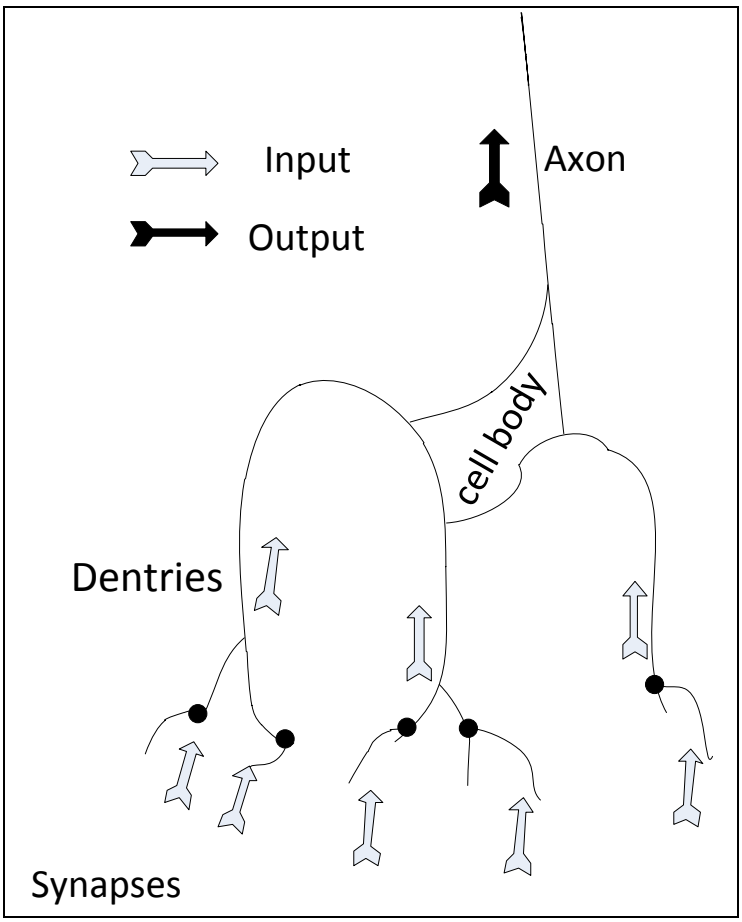

Figure 2.3: Simplified Neuron Overview. [11]

Neuron fires when a certain threshold is surpassed by output signal. Axon – the branching fiber- is then used to send the generated voltage impulse to other neurons. Part of the received signals make an excitatory effect encouraging impulse production, and the other part makes inhibitory effect. Neuron processing ability exists in the hardness of synaptic connections with its neighbors and whether it is excitatory or inhibitory.