CS 290 Paper Commentaries

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November 4, 2020

Computing with Spikes

Computing with Spikes [1] gives a quick overview of the idea behind computing models based on *spiking neurons* and the (then) current research that the author Wolfgang Maass and his colleagues were conducting. A significant portion of the paper is dedicated to describing the mechanisms of a spiking neuron.

The field that studies spiking neuron models (or spiking neural networks) is in the intersection of the field of neuroscience and the field of theoretical computer science. Unlike abstract models of computation like Turing machines and counter machines in theoretical computer science, spiking neuron models are significantly more complex since they are used to model and study the computational process of the nervous system. Spiking neuron models should be abstract enough for them to be used as models of computation that can solve abstract problems (in theoretical computer science) but they should be detailed enough so that they can be used to explain phenomena in the nervous system (in neuroscience).

Artificial neural networks are computing models that are 'inspired' biological neural network but the activation mechanism (using real functions like sigmoid and trigonometric functions) of the neuron in these models does not represent how activation occurs in a biological neuron. The activation mechanism in a spiking neuron model more closely represents the activation mechanism of a biological neuron. Aside from the difference in activation mechanism, the organization of an artificial neural network is also different to the organization of a spiking neural network.

Maass et al.'s research involves determining the computational function of *neural microcircuits*. In a spiking neuron model, these microcircuits are model using spiking neurons. The research asks how exactly does a spiking neuron work. The research involves studying actual biological neurons in order to observe how they produce and process spikes. Other aspects of their research involve the study of how the spiking neurons are organized (into networks), how memory are stored in the networks, and how learning is done by the networks.

A large part of the paper describes the spiking neuron and gives a general idea behind the spiking mechanism. The neuron has three main parts: the *soma*, the *dendritic tree*, and the *axonal tree*. The soma is the body of the neuron that produces the signal called *spikes*. The dendritic tree is the 'input' region of the neuron where it receives signals from other neurons. The axonal tree is the 'output' region of the neuron where it sends out signals to other neurons. A part of the axonal tree (output region) of one neuron can be 'connected' to a part of the dendritic tree (input region) of another neuron. This 'connection' or interface between a neuron's axonal tree and another neuron's dendritic tree is called a *synapse*.

A neuron has a *membrane potential*, a voltage value based on the difference between the charge inside and the charge outside the membrane of the neuron. A neuron has a resting membrane potential which is about -70 millivolts. The 'spike' in a spiking neuron model refers to an *action potential* in a neuron. An action potential is a sudden increase (around 40 millivolts) and then a sudden decrease of the neuron's membrane potential (happens in less than 3 milliseconds). The term 'spike' refers to that even of the membrane potential spiking.

When a neuron receives a certain combination of inputs (spikes from other neurons received by the dendritic tree), it will produce a spike. There is threshold mechanism in a neuron. If the 'combination' of input spikes passes a certain threshold, the neuron will spike. The amplitude of the spike does not change for a neuron. The input spikes can dictate if the neuron will spike or not but not how 'large' the spike is. A series of input spikes can, however, dictate the timing (i.e. frequency) in which the neuron spikes.

When a neuron spikes, the spike travels along the axon then reaches the axon terminals. The axon terminals can be connected to dendrites of other neurons. The synapse, that connects the axon terminal to dendrite of another neuron, is responsible from 'processing' the spike and then passing a 'processed' spike to the next neuron. The synapse has an internal state/configuration. This state is affected by the spikes it receives. In a sense, this is a form of memory. This state affects how the synapse processed incoming spikes.

In the biological neuron, the spiking event is a result of a combination of electrochemical activities that involve the neuron membrane, voltage-gate ion channels, potassium and sodium ions, etc. The activities in a synapse involve neurotransmitters, neurotransmitter transporters and receptors, etc. In the spiking neuron models, these electrochemical activities are abstracted and simplified in order to have manageable models of computation but they are still somewhat faithful to their biological analogues (at least much more faithful compared to artificial neural network models).

A spiking neuron can only produce a spike, a single type of signal. A neuron can not produce a 'large' spike or 'small' spike. All spikes produced are identical. Information in spiking neuron models are encoded by spiking patterns (in time) produced by a neuron. This pattern in known as a *spike train*. For example, a spike can be represented by '1' and no spike represented by '0'. A spiking neuron's activities (spiking or resting) can be represented by a string (the spike train) over the binary alphabet $\{0, 1\}$. This string is a pattern in time instead of being a pattern in space. One can only observe the spike train by looking at the activities of a neuron for a certain period of time.

Spiking Neural P Systems

References

[1] Wolfgang Maass. Computing with Spikes. *Special Issue on Foundations of Information Processingof TELEMATIK*, 2002.