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Liquid State Machine Built of Hodgkin–Huxley Neurons

Wieslaw A. KAMINSKI, Grzegorz M. WOJCIK
Depatment of Theoretical Physics, Maria Curie-Sklodowska University
ul. Radziszewskiego 5, 20-031 Lublin, Poland
e-mail: gmwojcik@neuron.umcs.lublin.pl

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Abstract. Neural networks built of Hodgkin–Huxley neurons were examined. These structures behaved like Liquid State Machines (LSM). They could effectively process different input signals (i.e., Morse alphabet) into precisely defined output. It is also shown that there is a possibility of logical gates creation with use of Hodgkin–Huxley neurons and simple LSMs.

Key words: Hodgkin–Huxley, LSM, Liquid State Machine, logical gates.

1. Introduction and Problem Statement

The new idea for treating the brain as a whole was suggested by Maass and since then it has been called Liquid State Machine (LSM) (Maass, 2002). In general, the brain (or a fragment of it) is treated as a liquid. As an illustration for this approach one can consider a series of transient perturbations caused in an excitable medium (Holden, 1991) (i.e., liquid) by a sequence of external disturbances ("inputs") like sound, stones dropped into the liquid or wind. If the liquid is treated as an attractor neural network it has got the only one possible attractor – at its resting state. Nevertheless, the perturbed state of the liquid, during all this time, represents both present as well as past inputs and the information carried by it can be used for analysis of surrounding environment (Maass, 2002). Neural microcircuits appear to be very good "liquids" for computing on perturbations because of the large diversity of their elements, neurons and synapses (Gupta, 2000), and the large variety of mechanisms and time constants characterising their interactions, involving recurrent connections on multiple spatial scales (Maass, 2002). Then the "neural liquid" is under influence of different disturbances and the "observer" – or so called "readout layer" in the structure – carries the information what disturbances occurred and what happened to the "liquid" in past. Within some time after the disturbance, the liquid comes back to its fundamental state and is ready for another stimulations. In theory, such a structure can process infinite number of signals. If we treat the brain as LSM we can talk about biological computer ready to make great number of computations with the use of the same network. Like Turing machine (Holden, 1991), the model of LSM is based on strict mathematical framework that guarantees, under ideal conditions, universal computational

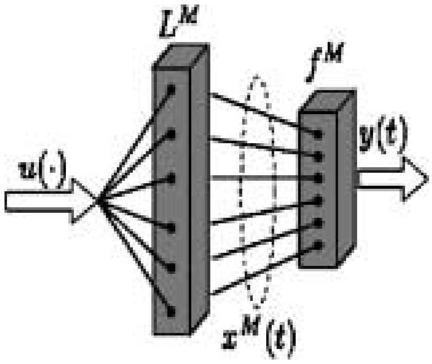

Fig. 1. Scheme of the Maass' LSM (Maass, 2002).

power. Maass proves it in (Maass, 2002). Idea of the Maass' LSM is shown in (Fig. 1). The liquid is represented by the column L^M consisting of about 100 integrate and fire neurons. Input signals u's are stimulating randomly chosen neurons of the liquid. There is a mapping function $X^M(t)$ which transforms the input into the readout layer giving the output signals y's.

In this paper we will prove that some Maass' ideas can be applied to Hodgkin–Huxley neurons. We will show that it is possible to build LSMs of such neurons that are able to give different responses to different words encrypted in Morse alphabet and to conduct some logical operations.

2. Concept of Neural Computations and Results

In referred computer experiments we simulated LSM built of Hodgkin–Huxley neurons. Our Hodgkin–Huxley LSM (HHLSM) was simulated in GENESIS. It consisted of 176 cells. Liquid was a column built of 135 cells (on the net $3 \times 3 \times 15$, the readout consisted of 40 neurons. Stimulating neuron had connections to 30% of randomly chosen neurons of the liquid. Connections in the liquid were generated with probability given by:

$$p = C \cdot \mathrm{e}^{-D(i,j)^2}, \tag{1}$$

where $I = C = 0.2$ are constants and $D(i, j)$ is the Euclidean distance of neurons i and j. The liquid and the readout were divided into slices which were connected with probability of 60% (Fig. 2). All connections in the system described above were fixed and not adaptive. More details concerning the Hodgkin–Huxley parameters of neurons one can find in Appendix 1. To the body of stimulating neuron we sent a rectangular signals with the amplitude of $A = 0.2$ mV. The network transforms the input signal into series of spike potentials. For example, if we give different words encoded in Morse's alphabet to the input we can observe different series of spikes as a result on the readout (Fig. 2).

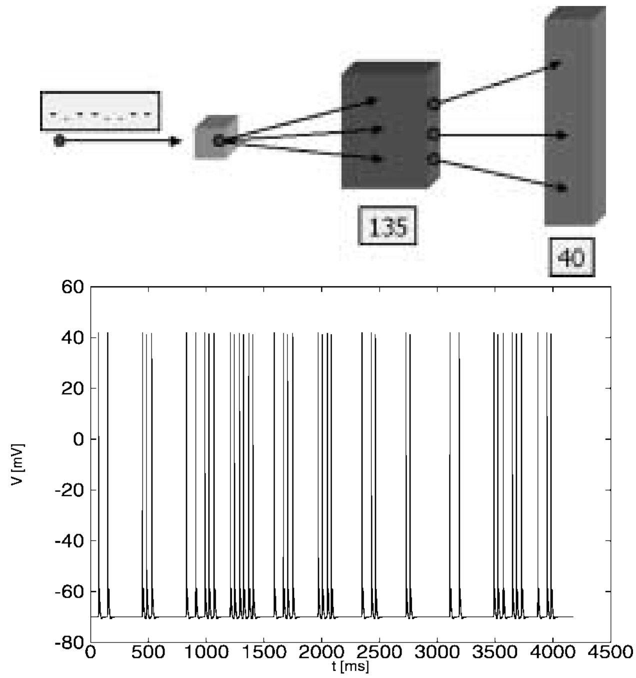

Fig. 2. Scheme of simulated LSM and readout neuron response for the word INFORMATICA.

From our research also follows that networks built of Hodgkin–Huxley neurons can process input signals like logical gates OR and AND. So it is possible to create simple logical gates with the use of HHLSMs. We built two-module HHLSM (Fig. 3). Such a structre behaves like the OR gate. The AND gate can be built on one module (Fig. 4) with the only one difference that the stimuli are given to dendrites of stimulating neuron. The amplitude of them is $A = 0.055$ mV.

3. Summary

In our work we showed that networks built of Hodgkin–Huxley neurons behave like LSMs. Such attitude allows for treating the brain (or at least some part of it) as a whole. This may also allow to simulate great structures of, i.e., cortex with better precision, but without necessity of observing and analysing every single neuron. Stimulated network transforms the input signal into output one. What's more, it is possible to convey basic logical operations by biological neural networks. So it is possible to build neurocomputer on such cells and LSM-like structures. We do not postulate that the whole brain works as similar processor, but we suppose that at least some of its parts may have created in evolution some mechanisms transforming activity in logical way. It ought to be mentioned that not only did we confirm but also expanded Maass' ideas of LSM by changing neurons from Integrate and Fire into Hodgkin–Huxley ones.

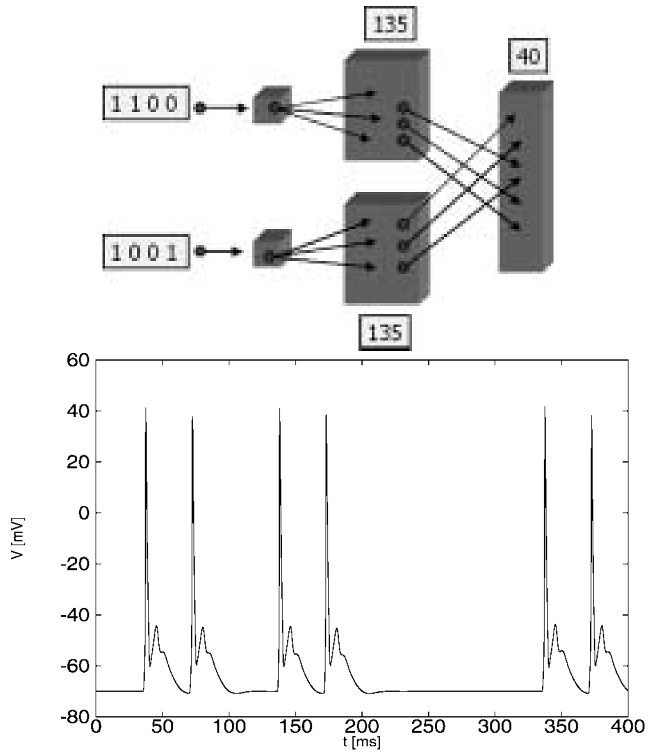

Fig. 3. Structure and response of logical gate OR built of HHLSMs.

4. Appendix A

Our HHLSMs consisted of multicompartmental neurons with a dendrite compartment, a soma, and an axon. The dendrite contained a synaptically activated channel and the soma contained voltage activated Hodgkin–Huxley sodium and potassium channels. The behaviour of each compartment followed:

$$C_m \frac{\mathrm{d}\,V_m}{\mathrm{d}\,t} = \frac{(E_m - V_m)}{R_m} + \sum_k \left[(E_k - V_m)G_k\right] + \frac{(V_m^{'} - V_m)}{R_a^{'}} + \frac{(V_m^{''} - V_m)}{R_a}. \quad (2)$$

Each sub-circuit was characterised by a group of parameters: $R_a = 0.3\Omega$, $R_m = 0.333333\Omega$, $C_m = 0.01$ F, $E_m = -0.07$ V. For the soma compartment $E_k = -0.0594$ V whilst for the dendrite $E_k = -0.07$ V. Conductance for each type of ionic channels was chosen: $G_K = 360\Omega^{-1}$ and $G_{Na} = 1200\Omega^{-1}$. The soma had a circular shape with the diameter of 30μm, the dendrite and axon were cable like with the length of 100μm. All other parameters were chosen as default and suggested by GENESIS authors as best for simulations (Bower, 1995). More details concerning Hodgkin–Huxley model one can find in (Hodgkin, 1952).

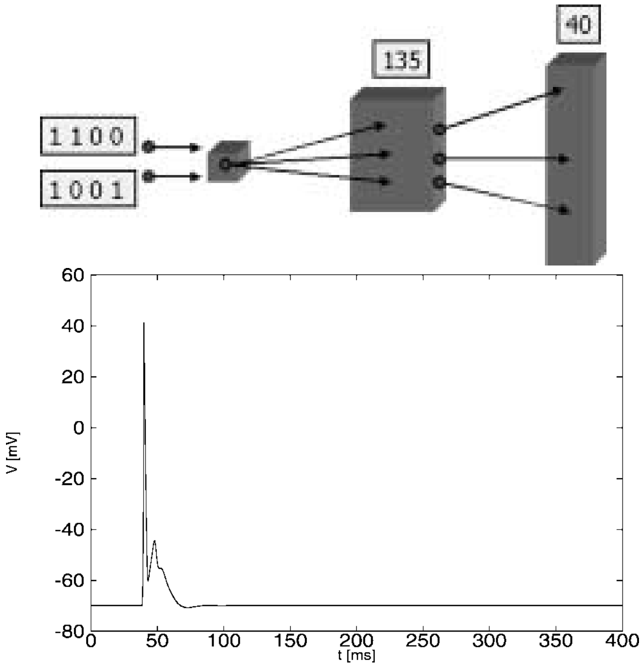

Fig. 4. Structure and response of logical gate AND built of HHLSM.

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W.A. Kaminski was awarded the master of science degree at the Maria Curie-Sklodowska University in 1972, PhD in Physics in 1977 and habilitation in 1992. He also received the professor title in 1996. At present he is a full professor at the Maria Curie-Sklodowska University. His main research interests include the computational artificial intelligence, neurocomputations and description of learning processes and other properties of neural networks using field theory and statistical physics methods. He is a head of the Complex System Physics Division at the Maria Curie Sklodowska University, Lublin, Poland.

G.M. Wojcik was awarded the master of science degree at the Maria Curie-Sklodowska University in 2000. He is PhD student at the Mathematics, Physics and Informatics Faculty of this University. He is interested in computational artificial intelligence.

Skysčio būsenų mašina sudaryta iš Hodgkin–Huxley neuronų

Wieslaw A. KAMINSKI, Grzegorz M. WOJCIK

Straipsnyje nagrinėjami neurotinklai sudaryti iš Hodgkin–Huxley neuronų, kurių struktūros elgiasi kaip skysčio būsenų mašinos pagal Maass. Parodyta galimybė sukurti loginių vartų schemas, panaudojant Hodgkin–Huxley neuronus.