Faculty of Mathematics, Physics and Informatics
Computational Cognitive Neuroscience
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Project Spiking Neurons

Review of the Simple Model of Spiking Neurons by Eugene M. Izhikevich (2003)

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The idea of the Simple Model of Spiking Neurons of Izhikevich (2003) is to simulate the firing patterns of biological neurons by implementing a combination of the biologically plausible Hodgkin–Huxley-model and the computational efficient integrate-and-fire neurons. By using only one of the two models, we would not be able to simulate such a vast variety of firing patterns of biological neurons. This can be achieved by manipulating four different parameters.

In the first part of this project (Part A) I have reproduced the firing patterns stated in Izhikevich's work. For this I have used the MATLAB code which was generously provided by the researcher himself and can be found on the researcher's webpage [1]. In the second part (Part B) I show 1000 randomly connected neurons' ability to self-organize and synchronously fire simulating a neural network (NN) in real time. This program is also provided by Izhikevich himself, both on his webpage and in his paper [2].

$$v' = 0.04v^2 + 5v + 140 - u + I$$
$$u' = a(bv - u)$$

if $v = 30$ mV,
then $v - c, \quad u - u + d$

Figure 1. Reducing many Hodgkin–Huxley-type neuronal models to a two-dimensional (2-D) system of ordinary differential equations with the auxiliary after-spike resetting if v ≥30 mV; then v ← c/ u ← u + d (as seen in Fig.2.) [2].

Part A: Firing Patterns

According to the equations presented in Figure 1, Izhikevich [2] developed a simple model of spiking neurons. In this model, the following parameters are used:

v – membrane potential of the neuron
u – membrane recovery variable
a – time of the recovery variable *u* (typically set to 0.02)

b – sensitivity of the recovery variable *u* to the fluctuations of the subthreshold membrane potential *v* (typically set to 0.2)

c – after-spike reset value of the membrane potential *v* (typically set to -65 mV)

d – after-spike reset of the recovery variable *u* (typically set to 2)

I – step of dc-current (typically set to 10)

The resting potential depends of the value of the variable *b* and is usually between -70 and -60 mV. Most neurons do not have fixed thresholds, therefore, depending on the history of the membrane potential before the spike, the threshold can be as low as -55 and as high as -40 mV.

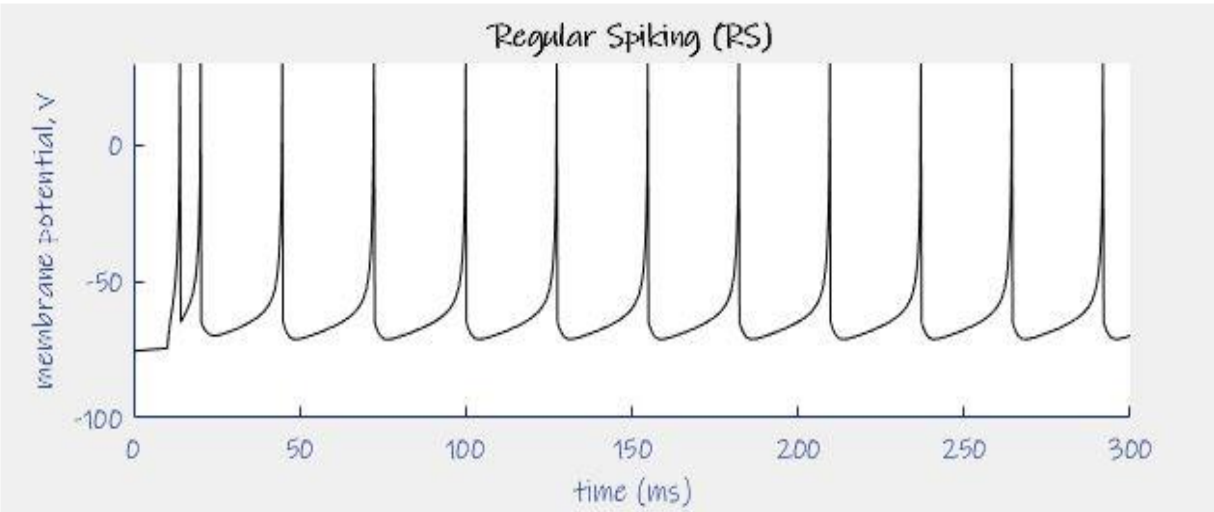
The following simulation was done using the parameters set to the values in the table (Table.1) below.

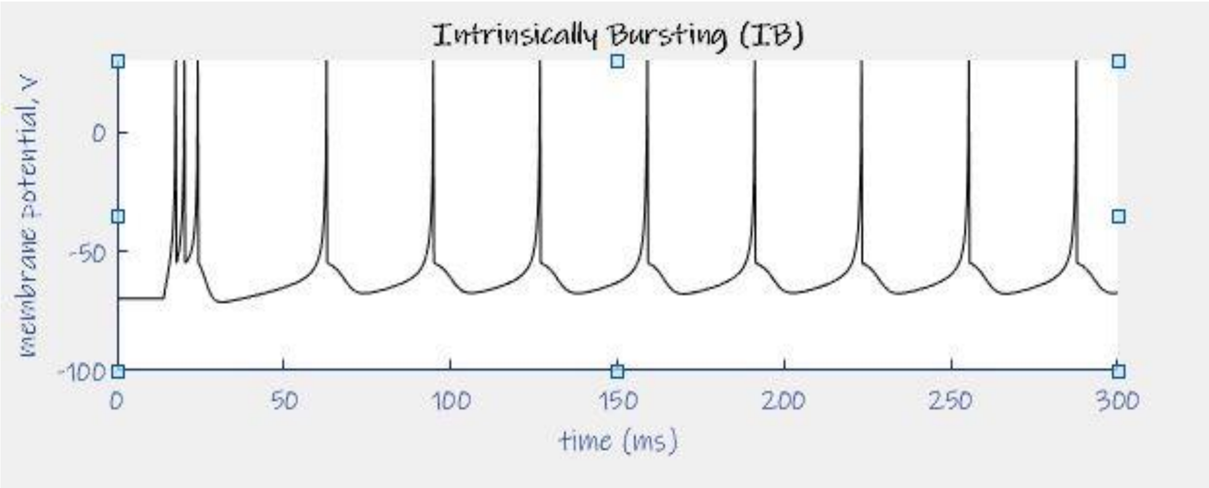
Type of Neuron	*a*	*b*	*c*	*d*	*I*	*v*
Regular Spiking (RS)	0.02	0.2	-65 mV	6	10	-70 mV
Intrinsically Bursting (IB)	0.02	0.2	-55 mV	4	10	-70 mV
Chattering (CH)	0.02	0.2	-50 mV	4	10	-70 mV
Fast Spiking (FS)	0.1	0.2	-60 mV	2	10	-70 mV
Low-threshold Spiking (LTS)	0.02	0.25	-60 mV	2	10	-70 mV
Thalamo-cortical (at rest)	0.02	0.25	-65 mV	0.05	10	-63 mV
Thalamo-cortical (Hyperpolarized)	0.02	0.25	-65 mV	0.05	10	-90 mV
Resonator (RZ)	0.1	0.26	-65 mV	2	0.5	-64 mV

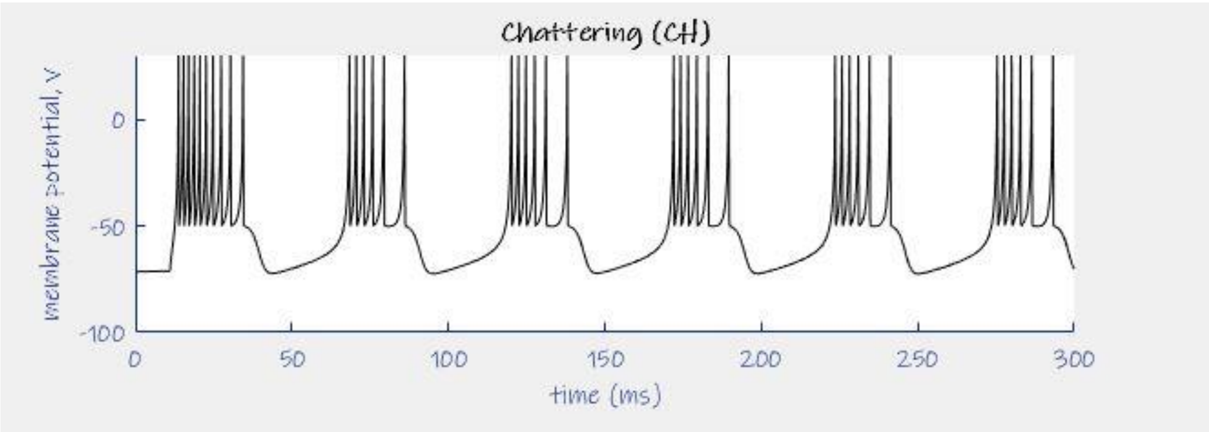
Table 1. Parameters used to simulate the different types of spiking neurons models.

The charts show the size of the membrane voltage under the implementation of the parameters from the table 1.

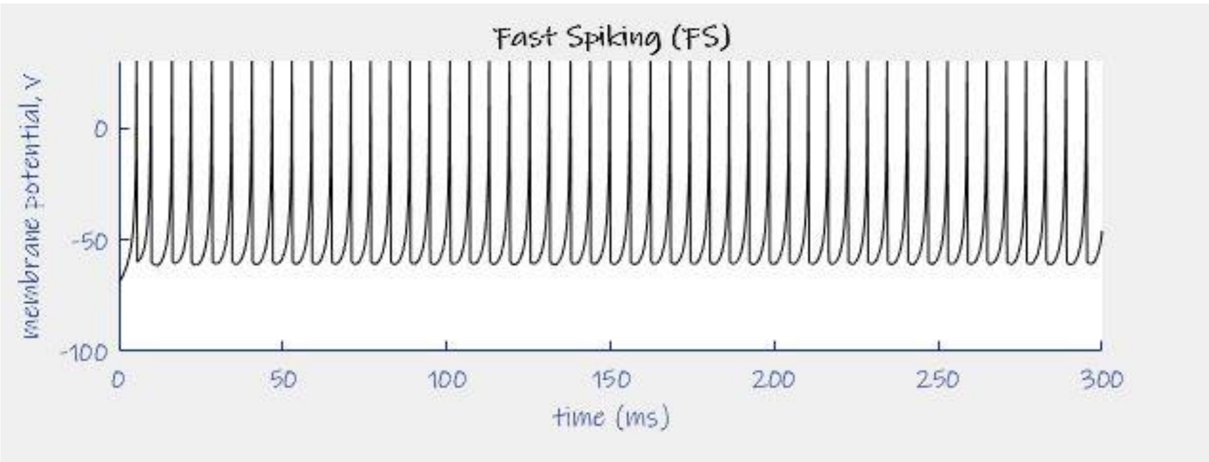
Excitatory cortical neurons:

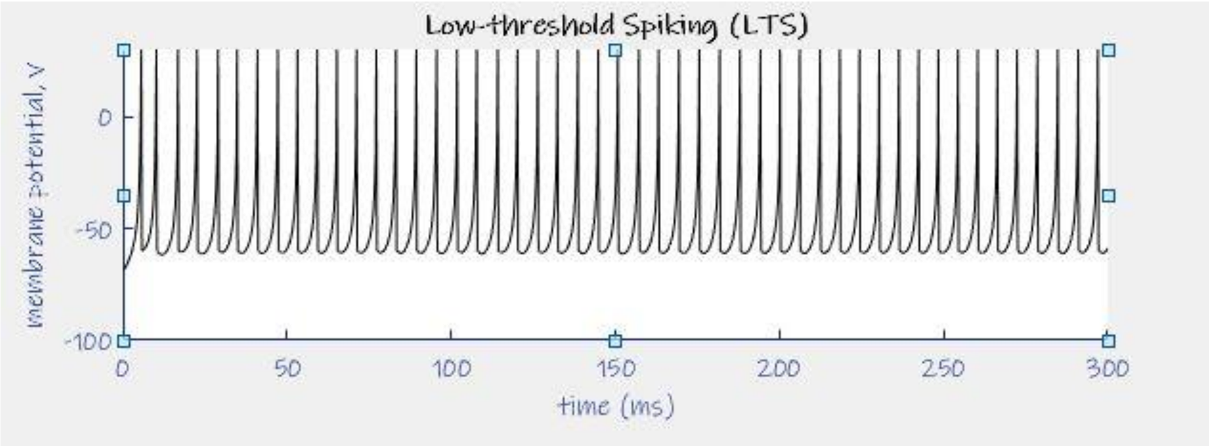






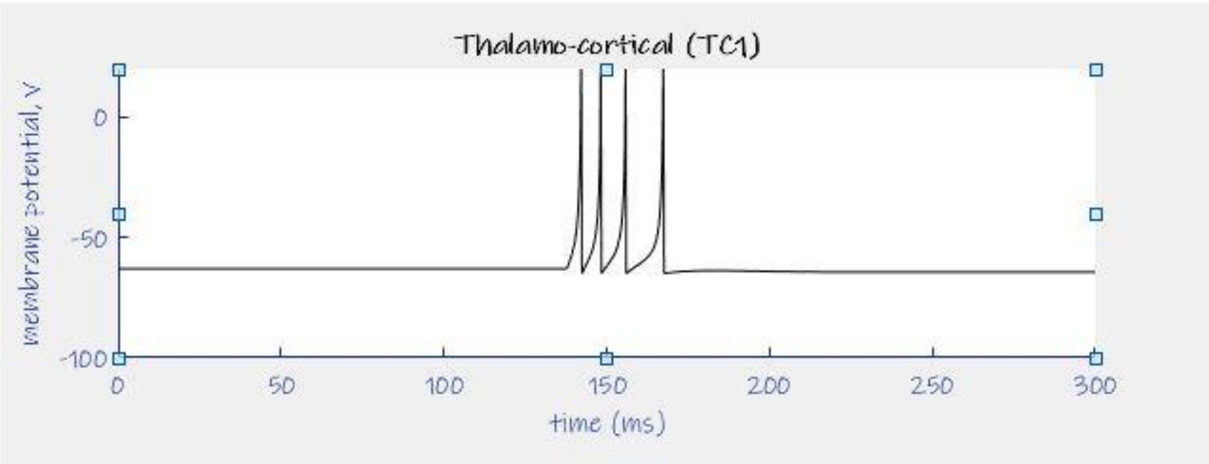
Inhibitory cortical neurons:



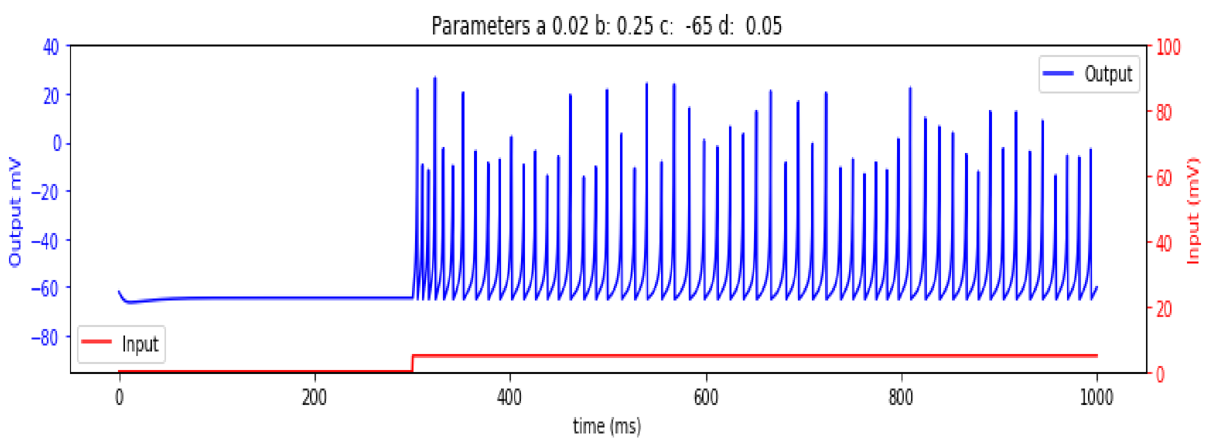


Moreover, this model can easily reproduce thalamo-cortical neurons' behavior:

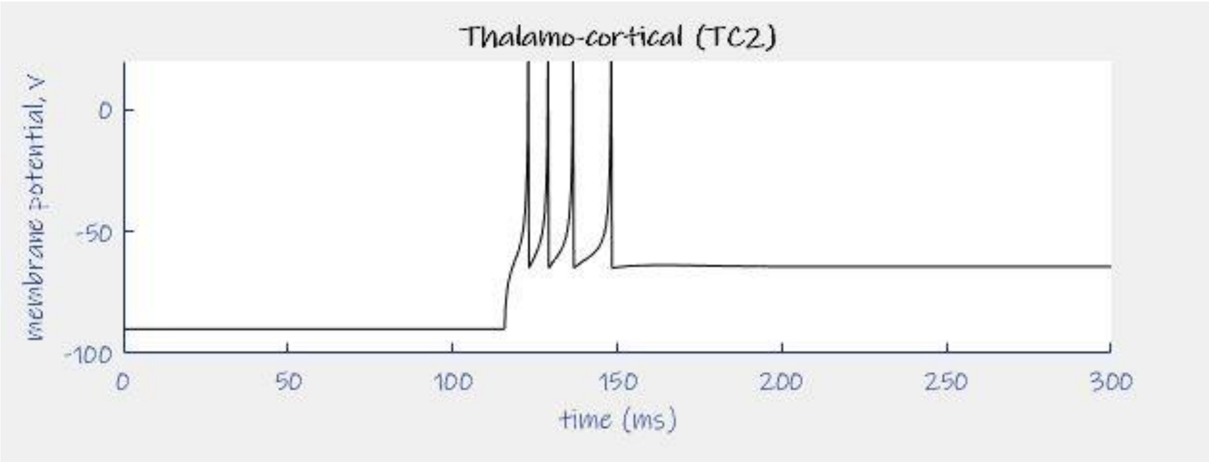
1) **In resting state (then depolarized)**



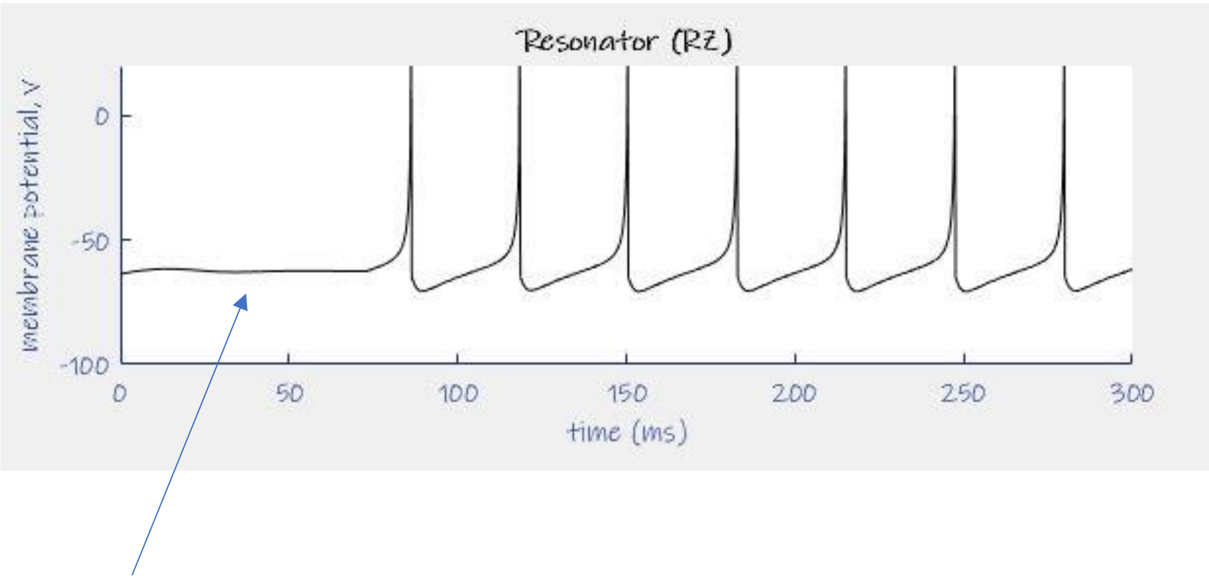
Note: This simulation did not turn out as shown by Izhikevich [2], therefore I tried another program developed by Butler, Clerkin and Kinsela [3] for Python, where I changed the voltage to -63 mV.



2) **In hyperpolarized state**



Another interesting type of dynamics are the resonator neurons (with subthreshold oscillations):



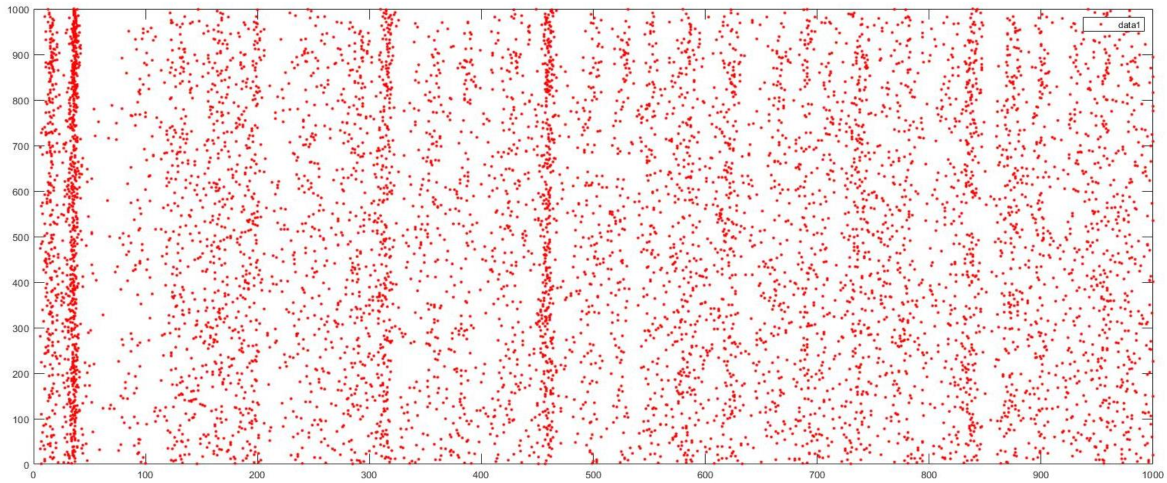
Subthreshold oscillations

Part B: Network of Neurons

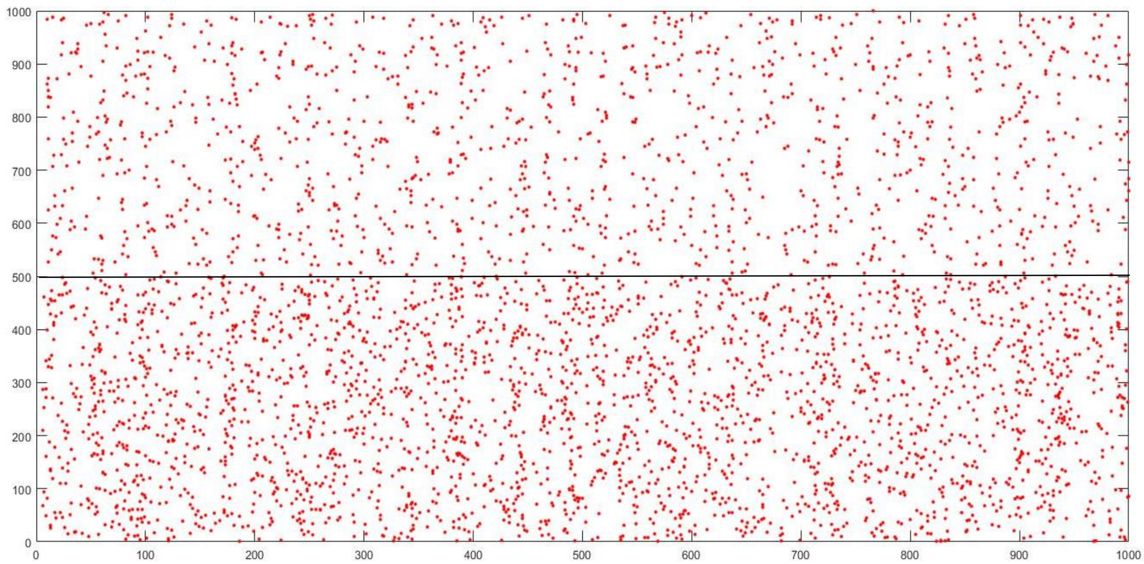
The motivation for this network was the mammalian cortex, which contains an excitatory-inhibitory neurons ratio of 4:1, where the synaptic connections of the inhibitory neurons are stronger. Additionally, each neuron received noisy thalamic input.

On the following graphs I have tried to show different synchronization of neurons' firing depending on various parameters:

1. The distribution of neurons
    - 800 Ne -200 Ni



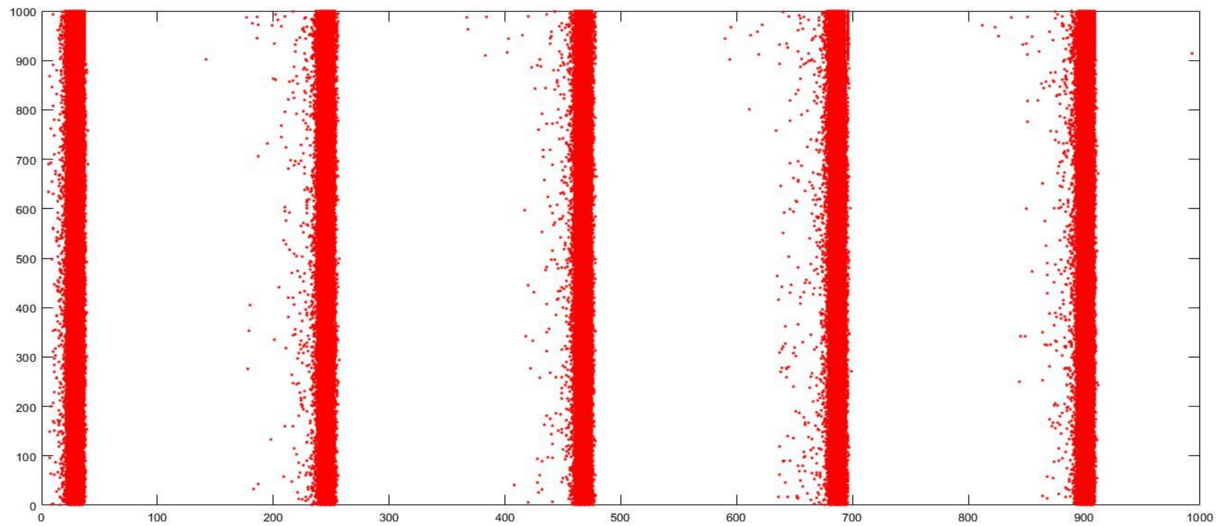
- 500 Ne – 500 Ni



Here we can see that the connections are stronger for the inhibitory neurons, but the neurons are more scattered.

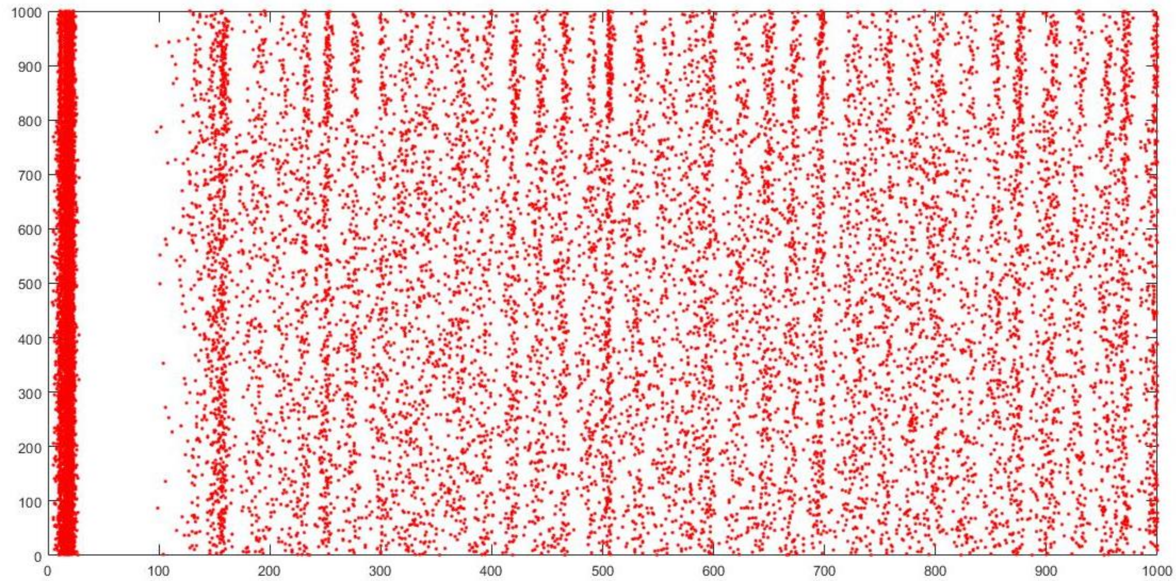
(All the lines are generated manually, as I have an older MATLAB version, which does not support the *yline* function introduced in MATLAB R2018b)

- 900 Ne- 100 Ni



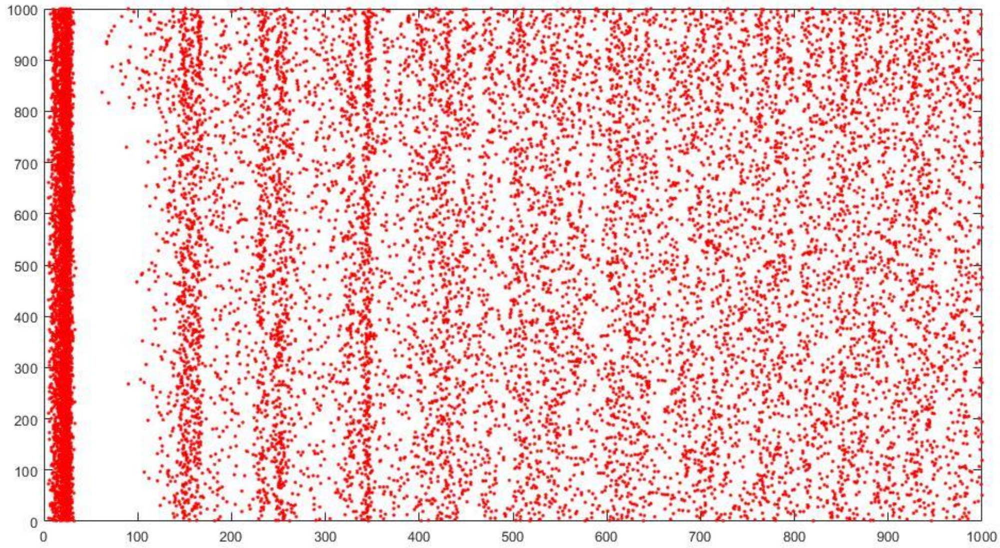
By increasing the excitatory neurons, we get a more synchronized network.

2. Different scattering of thalamic noise input
    - The initial values set in the code (thalamic noise (5,2)) (see the first plot, same as Ne – 800, Ni – 200)
    - Changed value of thalamic noise to (7,2) (only increase for excitatory neurons)



The inhibitory neurons show a better structure (upper ratio from 800 to 1000) because the noise is smaller for them.

- Thalamic noise increased for both excitatory and inhibitory neurons (7,4)



Up to t =400 (x axis), we can see more organization in the structure, although the noise has been increased. Nevertheless, the 200 inhibitory neurons (y axis 800-1000) show more scattering than excitatory ones.

1. **Under which conditions (i.e. values of which parameters) does the network show periodic synchronizations?**

The network shows periodic synchronizations when we increase the number of excitatory neurons (see plot of 900 Ne, 100 Ni).

2. **Under which conditions the spiking of neurons does NOT synchronize at all? Any other intersting behavior you can observe?**

The spiking does not synchronize under conditions of low numbers of excitatory neurons and more inhibitory neurons. Another interesting thing I observed can be seen under point 2 in the change of thalamic noise only to excitatory neurons. The synchronization still happens and seems more regulated than when the noise is smaller, but only for excitatory neurons. If the inhibitory neurons' thalamic noise gets increased the synchronizing occurs only in the first 400 ms.

References

[1] "Which Model to Use for Cortical Spiking Neurons?", *Izhikevich.org*, 2019. [Online]. Available: https://www.izhikevich.org/publications/whichmod.htm. [Accessed: 23- May- 2019].

[2] E. M. Izhikevich. "Simple model of spiking neurons", *IEEE Transactions on Neural Networks*, vol. 14, no. 6, pp. 1569–1572, November 2003. Available: 10.1109/tnn.2003.820440.

[3] "Izhikevch Model", *Maths.dit.ie*, 2019. [Online]. Available: http://www.maths.dit.ie/~johnbutler/Izhikevich/IzhikevichModel.html. [Accessed: 23- May- 2019].