University of Tehran

COMPUTER SCIENCE DEPARTMENT

COMPUTATIONAL NEUROSCIENCE

REPORT 3

NEURON POPULATION WITH IZIKEVICH MODEL

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1 Izhikevich Neuron Model

In this project we want to make some neuron populations and inject curreents to them and analyze the behavior and activities of those populations. The Izhikevich neuron model reproduces spiking and bursting behavior of known types of cortical neurons. It takes the biological plausibility of Hodgkin and Huxley neurons while being as computationally efficient as integrate-and-fire neurons. Now we review the formula and parameters used for this model:

$$\frac{dv}{dt} = 0.04v^2 + 5v + 140 - u + I \tag{1}$$

$$\frac{du}{dt} = a(bv - u) \tag{2}$$

Now we got the resetting part:

$$if\ v > 30\, mv,\ then\ [v = c\ and\ u = u + d] \tag{3}$$

Here are the parameters used in equations:

- v: Represents the membrane potential of the neuron
- u: Represents a membrane recovery variable, which accounts for the activation of k^+ ionic currents and inactivation of Na^+ ionic currents, and it provides negative feedback to v. After the spike reaches to its threshold, the membrane voltage and the recovery variable are reset according to the (3).
- I: The input current or injected dc-currents
- a: It describes the time scale of the recovery variable u. Smaller values result in slower recovery. A typical value is $a = 0.02$.
- b: It describes the sensitivity of the recovery variable u to the subthreshold fluctuations of the membrane potential v. A typical value is $b = 0.2$. Greater values couple and more strongly resulting in possible subthreshold oscillations and low-threshold spiking dynamics, because u parameter will try to decrease the neuron's potential.
- c: after-spike reset value of v. A typical value of -65 mV. It will be reset because of the fast high-threshold k^+ conductances.
- d: after-spike reset value of membrane recovery variable. A typical value of 2. It will be reset because the slow high-threshold Na^+ and K^+ conductances. It will cause to lower the membrane potential value, so the spike frequency adaption will happen and after a while the neurons will spike with bigger and distinguished inter-spike values, in other word the inter-spike period of neurons will increase. This keeps homeostasis of neurons.

We are going to make two excitatory populations and one inhibitory population. The populations are homogeneous which means the parameters of them are the same for each neuron and also neurons in one population get the same amount of current. The size of the excitatory populations is 400 and the inhibitory population size is 100. In every simulation, one current of excitatory population is stronger than the other one. The currents are from normal distribution and also the number of iteration is 300. We make some types of connection and parameters and draw the diagrams(raster plot, population activity plot and input current plot). Then we analyze the results and behavior of the populations.
Just notice we have randomness in the currents. It means all of the neurons don't get the current. Actually we added the randomness of $\frac{1}{2}$ in the currents of excitatory populations. You can see this in the code.

2 Connections and Parameters

Now we make some types of connections and parameters, then analyze the behavior of populations. Remember the current of the second excitatory population is stronger thn the first one.

2.1

The diagram of connections is:

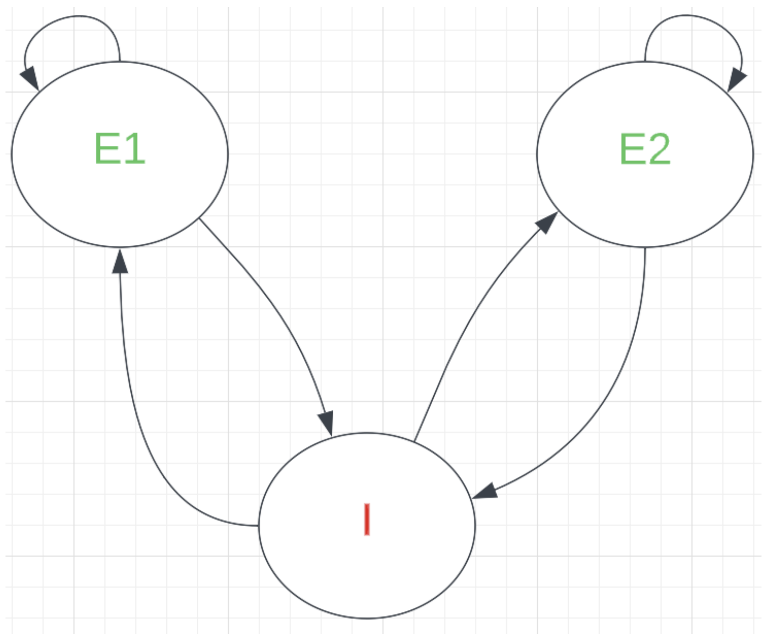


Figure 1: diagram of connections

In this type, the parameters of excitatory populations are set in a way thet both of them spike regularly. On the other hand the inhibitory population's neurons are fast spiking. the parameters of ecxitatory population is:

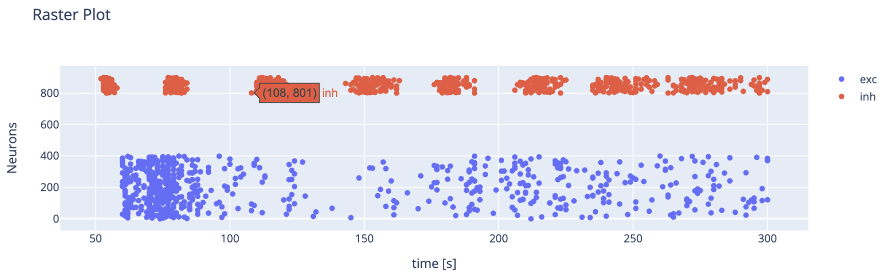
- a : 0.02
- b : 0.2

- $c : -65$
- $d : 8$

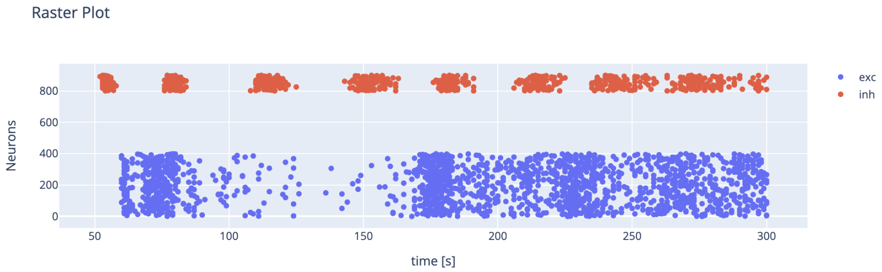
And the parameters of inhibitory population is:

- $a : 0.1$
- $b : 0.2$
- $c : -65$
- $d : 8$

We can say, this is a simulation of decision making in the brain. Instead of brain, we use these three populations and their connections. Decision making is one of the most important ability of human beings. It involves different brain areas and has conscious as well as unconscious aspects.
A network consisting of two excitatory populations interacting with a common inhibitory population. Actually the inhibitory population is shared between these two excitatory populations, so there is a competition between them. Within the two excitatory populations, neurons are randomly connected. At the end we say a populations wins if after injecting stimulus and running some iterations, the activity of that population grows further and the other one suppresses. Notice that every excitatory population indicates one of my decisions and we can have many decisions(we can add excitatory populations).
In this case, when neurons of both excitatory populations spike, the current will increase in inhibitory population. Then inhibition happens and inhibitory neurons spike to both excitatory population and the current will decrease in them. Now if one of the current is stronger than the other in excitatory populations, the inhibition won't happen in stronger one and the activities grows up, but inhibition impacts more on the other population and the activity of the other population will decrease and they'll spike less if we go further through the simulation. In this situation, we say the first population wins becuase the inhibition didn't effect on that population and the activity grows up in that. So the first decision wins.
Now let's see the diagram of raster plot for these three population:



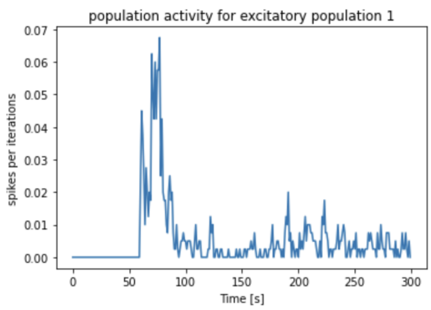
(a) E1



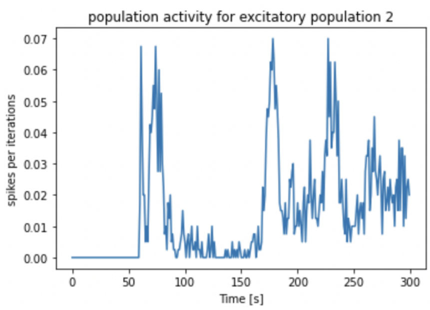
(b) E2

Figure 2: Raster plots

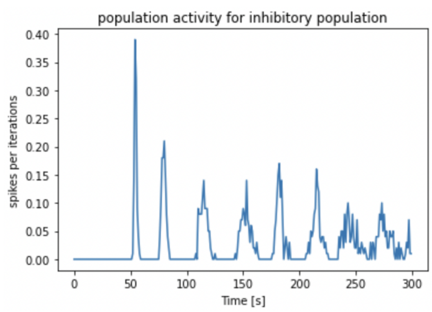
As you see, in the first population the effect of inhibitory neurons is high and the activity of neurons in E1 is suppressed. On the other hand in E2, we first apply current as high as the current in first population until iteration 150. then we slowly increase the value of current. In this case we see the current of inhibitory population grows up and the activity increases. Then inhibitory neurons spike more and they want to lower the activity of both excitatory population but inhibition doesn't happen in the second population because the current is stronger. Now see the population activity plots:



(a) population activity of E1



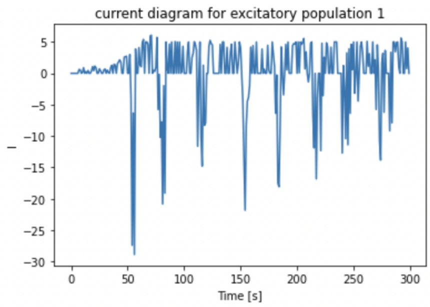
(b) population activity of E2



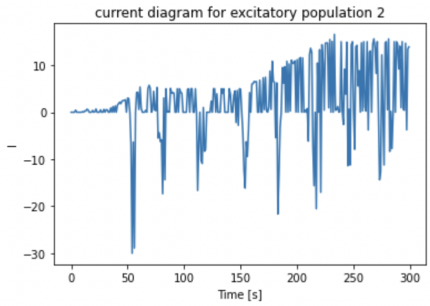
(c) population activity of I

Figure 3: Population activity plots

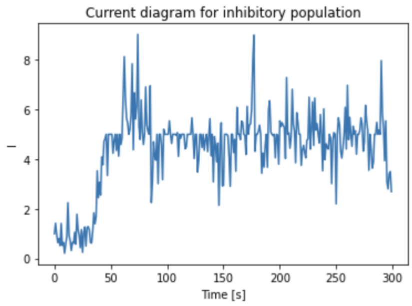
As you see the activity of population E2 increases and the other population's activity is less than population E2, because the current in inhibitory population increases and this make the population E1 to spike less.
At the end check the plots of currents:



(a) current of E1



(b) current of E2



(c) current of I

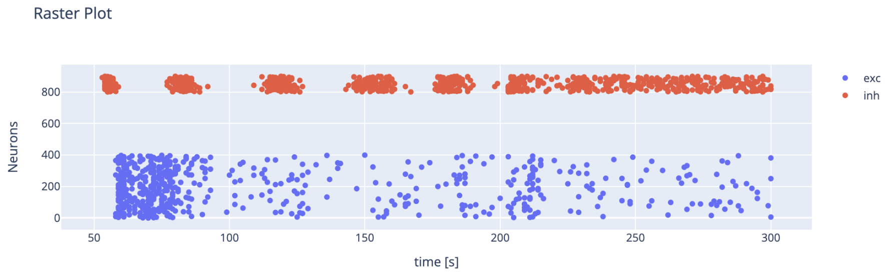
Figure 4: Input current plots

2.2

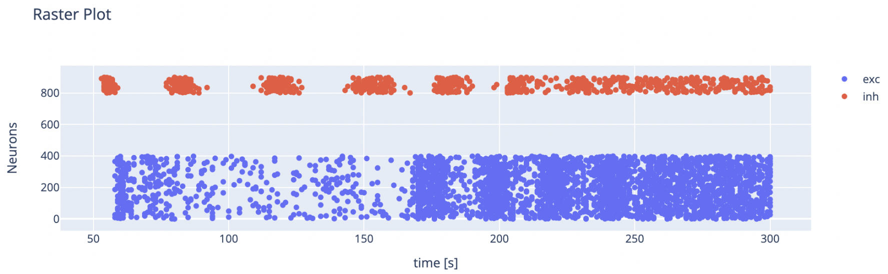
Now we set the parameters of population E2 in a way that they spike fast. So the parameters of E1 and inhibitory population remain the same, but the parameters of E2 become:

- $a : 0.1$
- $b : 0.2$
- $c : -65$
- $d : 8$

Let's see the raster plots:



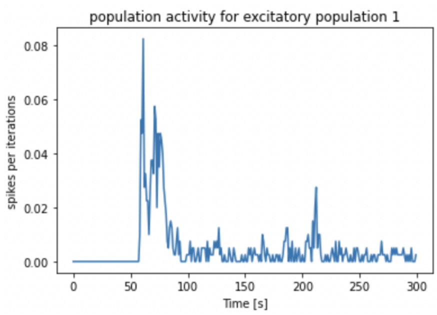
(a) E1



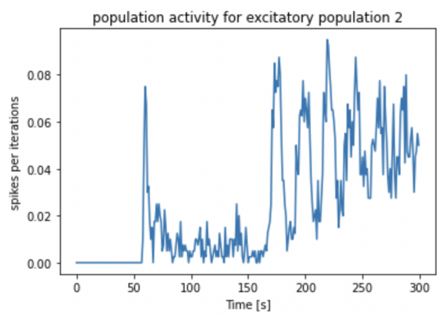
(b) E2

Figure 5: Raster plots

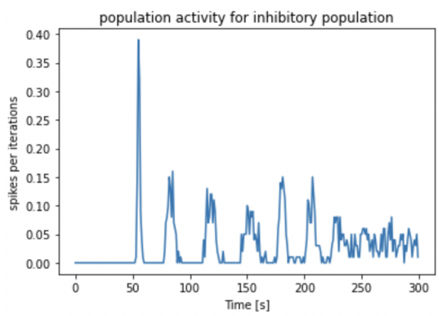
In this case the population E2 spike fast, so the number of spikes increases. So the current in inhibitory population rises more and they spike more compared to previous experiment. In this situation the effect of inhibition in population E1 increases and they spike less. In this case the spikes decrease by the value of 60. Check the plots of population activity:



(a) population activity of E1



(b) population activity of E2

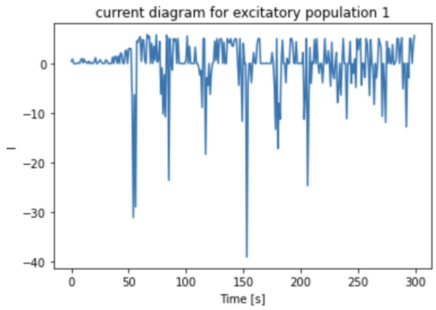


(c) population activity of I

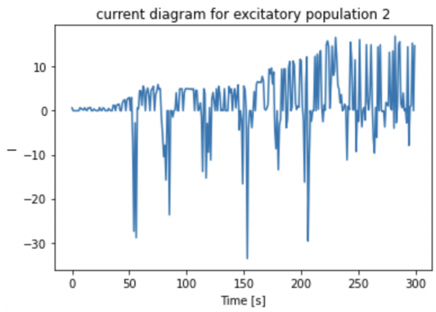
Figure 6: Population activity plots

As you see the inhibition effects more compared to the previous test and the population E1 spike less. But the activity of E2 increases, because they spike fast.

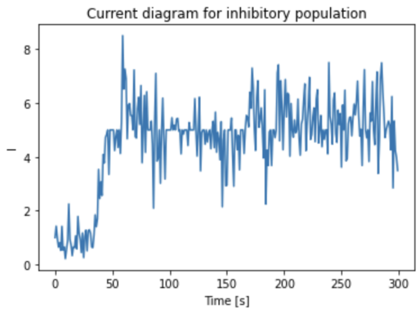
The point is when we go forward through the iteration in inhibitory population, we see that the activity decreases. That's because the inhibition effects more on the excitatory populations and the spikes of them decreases and so the activity falls a little in the inhibitory population.
Now check the current plots:



(a) current of E1



(b) current of E2



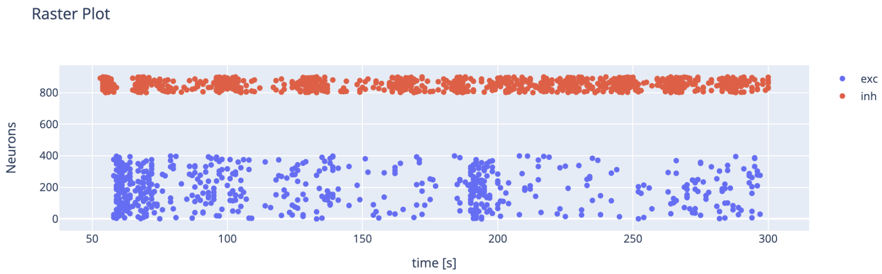
(c) current of I

Figure 7: Input current plots

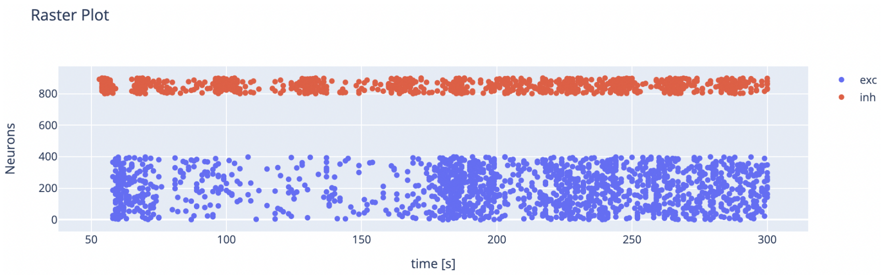
If you compare figure 7 part(a) with figure 4 part(a), you see that the number of falls in population E1 in this experiment is more than the number of falls in the previous experiment, that's because the inhibitory population inhibits more.

2.3

In this test, we increase the value of density from population E2 to inhibitory population. The parameter of density indicates the probability of connections. When the amount of density increases, the chance of connectivity of any two neurons will rise. So now we increased the probability of connections from E2 to the inhibitory population.
In this case the number of spikes from E2 to inhibitory population increases, therefore the current in the inhibitory population rises and the number of spikes in that population becomes more compared to the first experiment. Because of this the inhibition impacts more in both E1 and E2. The number of spikes decreases in both of them but the plots of population activity remains the same. It means the activity of E2 will increase through the iteration but the activity of E1 will decrease.
Now check the raster plots:



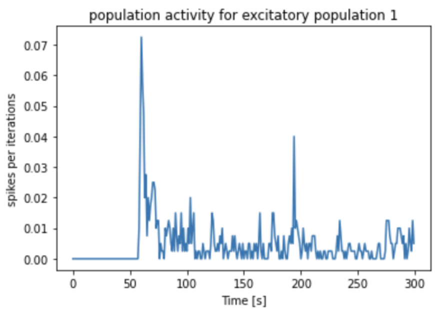
(a) E1



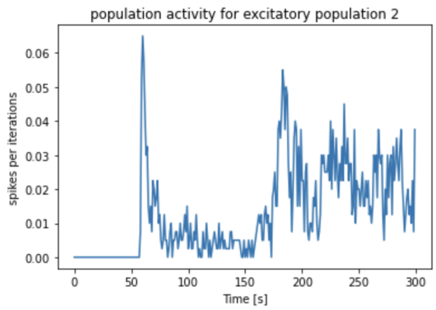
(b) E2

Figure 8: Raster plots

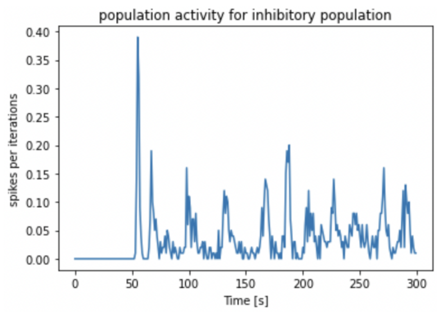
See the population activity plots:



(a) population activity of E1



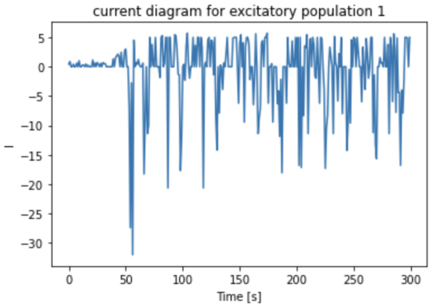
(b) population activity of E2



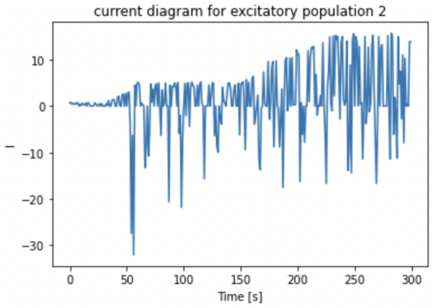
(c) population activity of I

Figure 9: Population activity plots

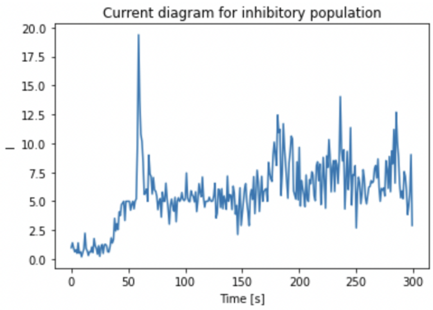
As you see, the behaviour of E1 and E2 is like figure 3, the point is activity of the inhibitory population is more compared to the first test so the number of spikes in both E1 and E2 decreases. That's because we have more spikes from E2 to I, and this make the inhibitory neurons to spike more and inhibits more than before.
Check the current plots:



(a) current of E1



(b) current of E2



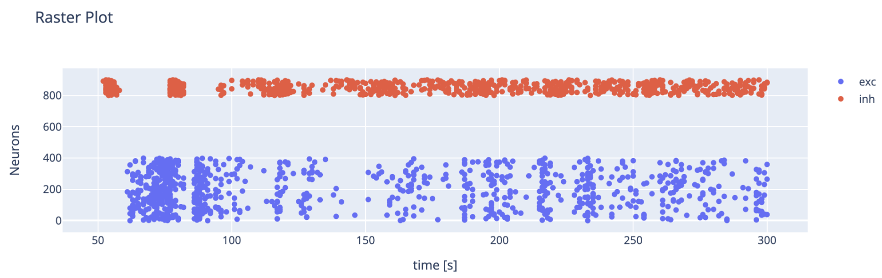
(c) current of I

Figure 10: Input current plots

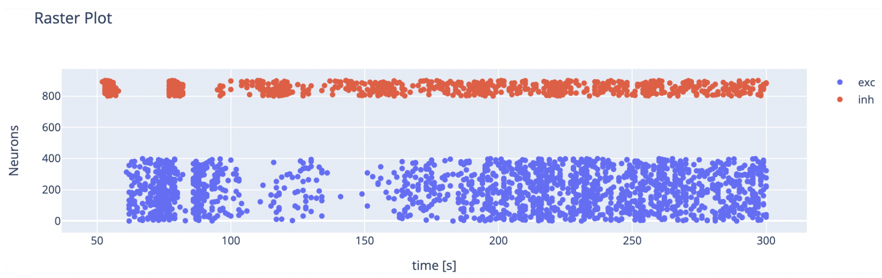
In the figure above part(c), we see the current of inhibitory population increases more compared to the last tests. We explained why this happens. Also you can see the current of excitatory plots, they decrease more compared to the first experiment.(see figure 4)

2.4

In this test, we increase the density of inhibitory population to both E1 and E2. first let's see the plots, then we analyze the behaviours:

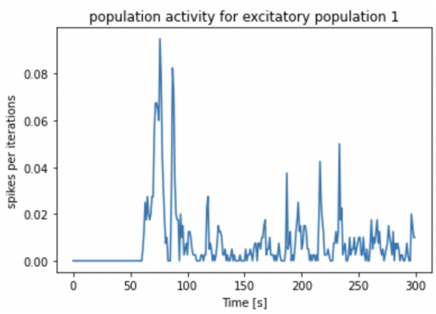


(a) E1

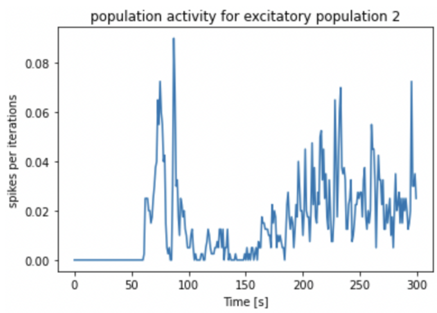


(b) E2

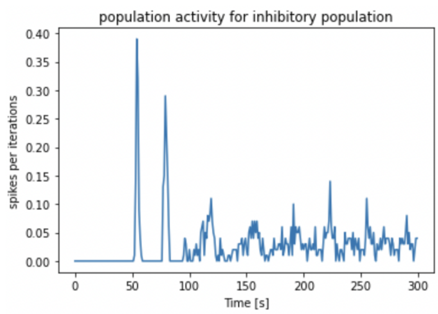
Figure 11: Raster plots



(a) population activity of E1

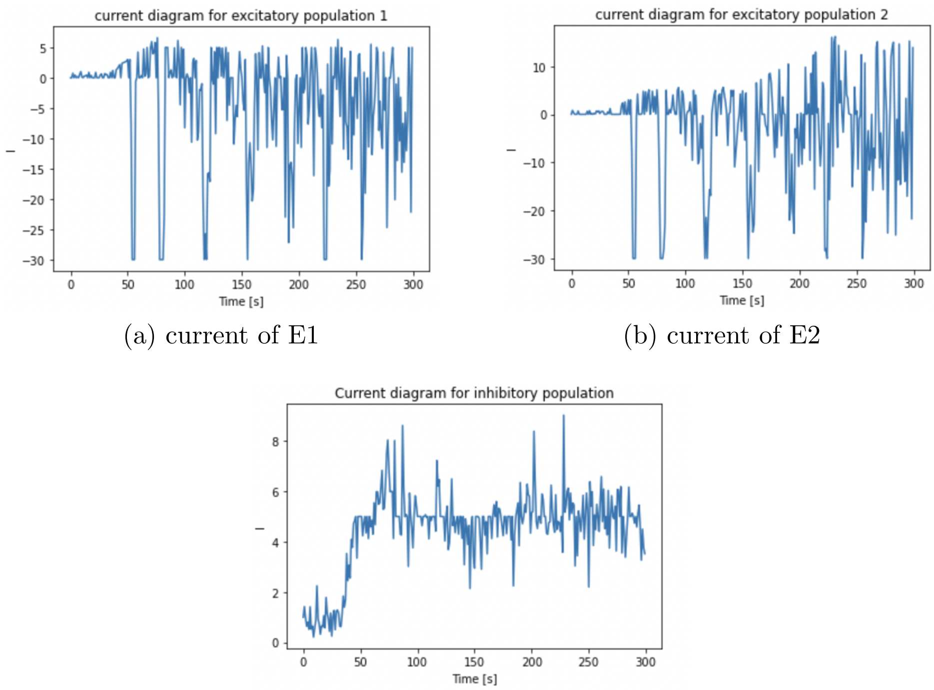


(b) population activity of E2



(c) population activity of I

Figure 12: Population activity plots



(a) current of E1

(b) current of E2

(c) current of I

Figure 13: Input current plots

If you see the figure 11, you see that the spikes of both populations E1 and E2 increases. Now when density goes up, the neurons of inhibitory population will inhibit more and the currents of E1 ad E2 decreases. Then the activity of excitatory population will decrease and this cause the excitatory population to spike less to to the inhibitory population. In the following the spikes in excitatory populations increase, that's because the effect of inhibition is lower than before, so E1 and E2 spikes more. That's you see in the figure 12, the activity of E1 and E2 increases compared to the first experiment(figure 3). In figure 13 part(a) and part(b), you see the effect of inhibition on E1 and E2, then it makes the excitatory population to spike less to the inhibitory population, so the inhibitory neurons spike less and finally both E1 and E2 spike more compared to figure 4.

2.5

Now we change the connection. Here is the diagram:

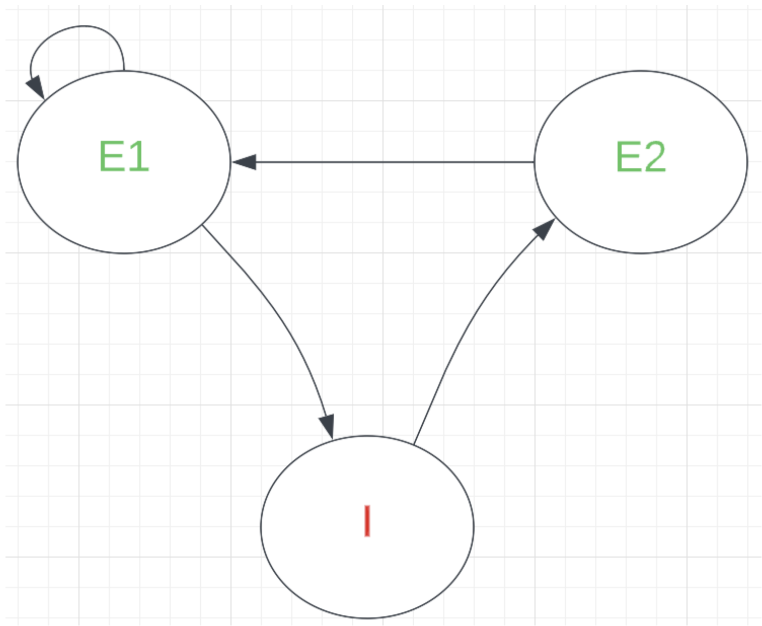
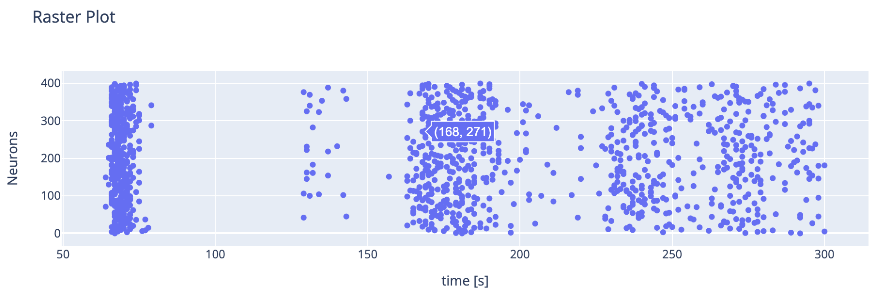
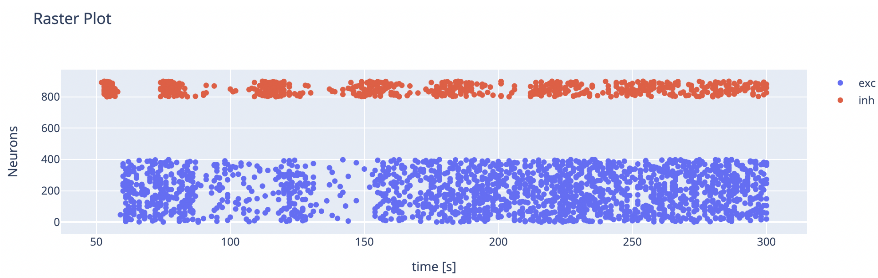


Figure 14: diagram of connections

First let's see all the plots then analyze:

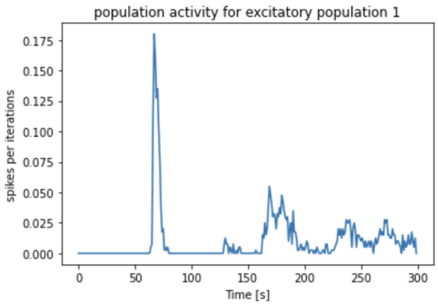


(a) E1

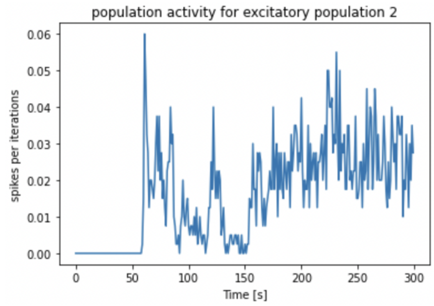


(b) E2

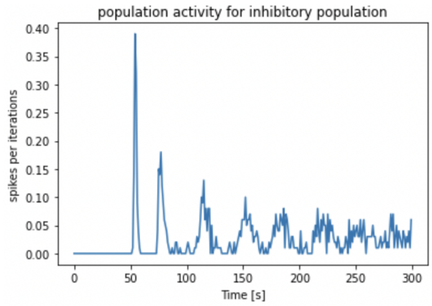
Figure 15: Raster plots



(a) population activity of E1

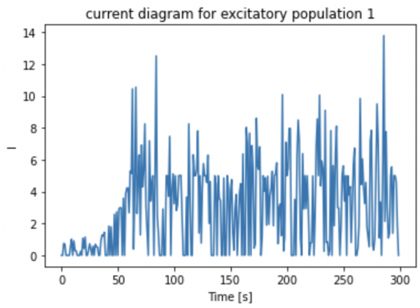


(b) population activity of E2

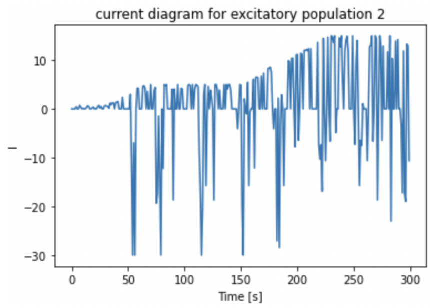


(c) population activity of I

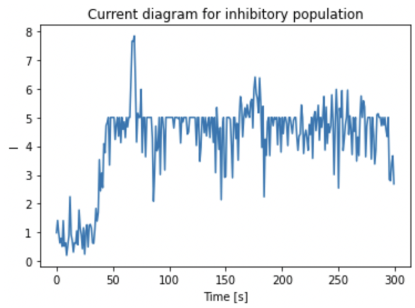
Figure 16: Population activity plots



(a) current of E1



(b) current of E2



(c) current of I

Figure 17: Input current plots

Like last experiments, the current of E2 is greater than E1. Here the only connection from inhibitory population is from I to E2. So the inhibitory neurons spike and they inhibit the neurons of E2. Now when neurons of E2 spike, they effect on E1 and the neurons of E1 spike more. We also have connection from E1 to E1. So the current increases more on E1 and they spike more than before.

The current of E2 is high enough that the inhibition doesn't effect that much on the population. So the current of E2 just decreases and the current of E1 just increases. That's why we have the current plots in figure 17. The current of inhibitory population increases using E1. On the other hand we have less current in E1 so the inhibition doesn't effect that much on E2 and the activity of E2 rises.(figure 16).

2.6

Now if we delete the connection of E2 to E1, the spikes in the E1 will decrease. So they spike less compared to the previous experiment, therefore the current of inhibitory population increases less than before and they spike less. Finally when inhibitory neurons spike less, the effect of inhibition will become lower compared to the previous test. So we have more spikes in E2. See the diagram of connections:

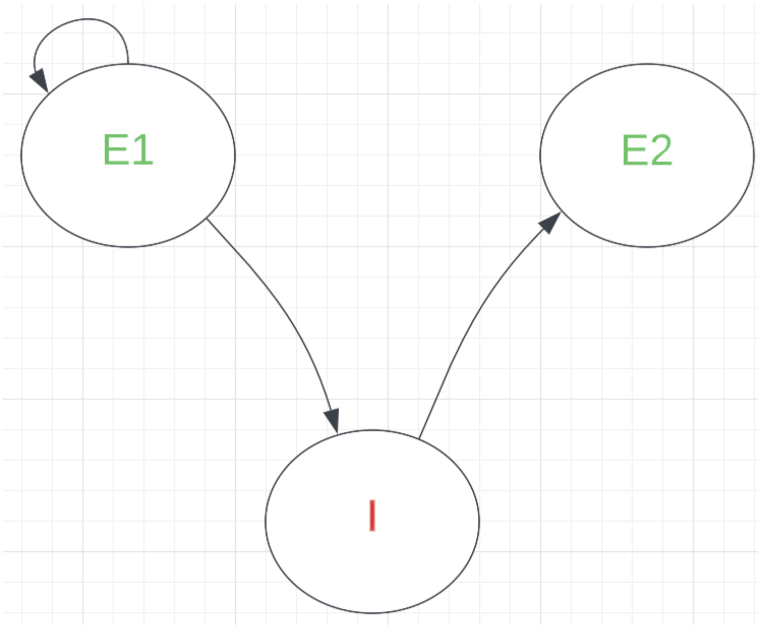
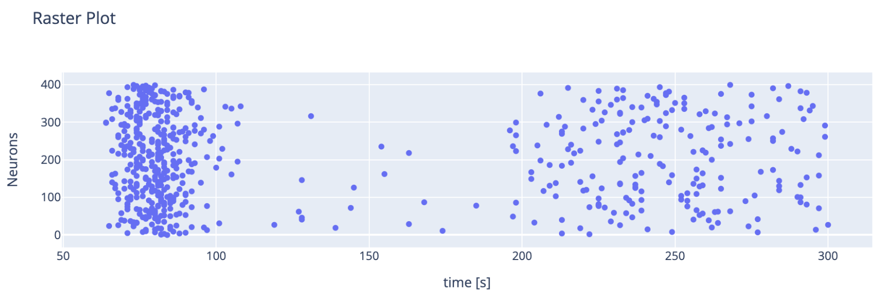
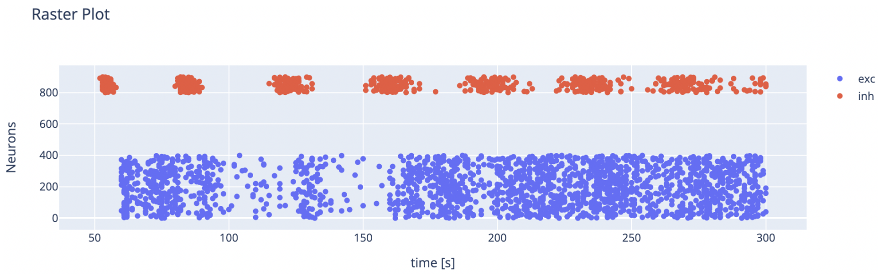


Figure 18: diagram of connections

Now see the plots:

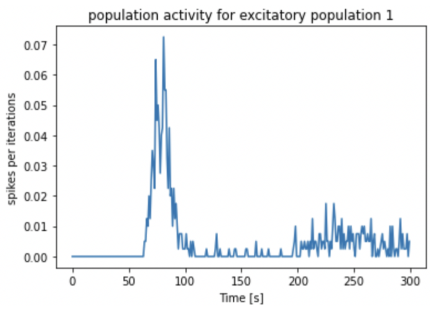


(a) E1

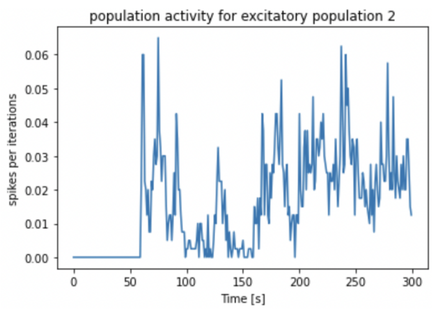


(b) E2

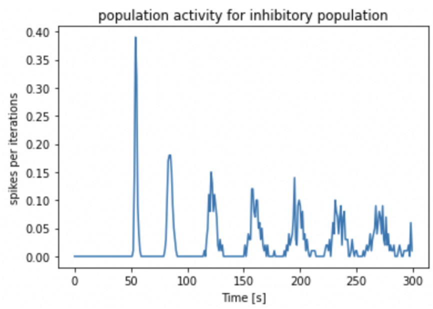
Figure 19: Raster plots



(a) population activity of E1

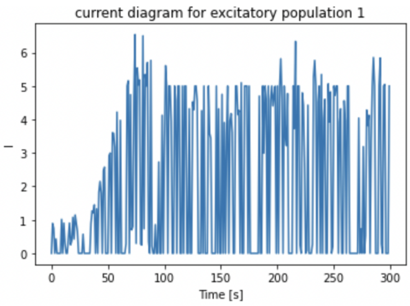


(b) population activity of E2

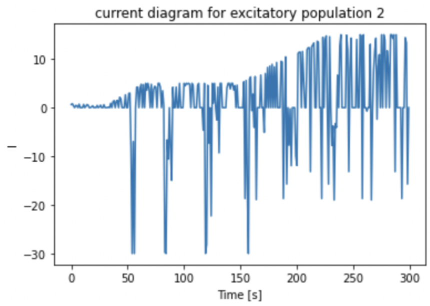


(c) population activity of I

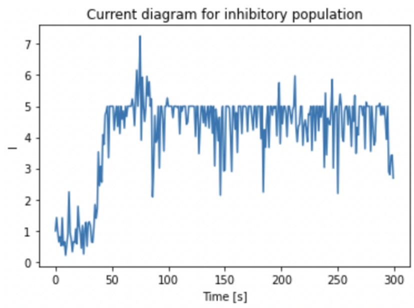
Figure 20: Population activity plots



(a) current of E1



(b) current of E2



(c) current of I

Figure 21: Input current plots

As we said before, the activity of E1 decreases(see figure 19 part(a) and figure 20 part(a)). In figure 21 part(a) we have less rises compared to figure 17.

3 References

[1] Izhikevich, E.M., 2003. Simple model of spiking neurons. IEEE Transactions on neural networks, 14(6), pp.1569-1572.

[2] Decision Making https://maktabkhooneh.org/course/%D8%A2%D9%85%D9%88%D8%B2%D8%B4-%D8%B1%D8%A7%DB%8C%DA%AF%D8%A7%D9%86-%D8%B9%D9%84%D9%88%D9%85-%D8%A7%D8%B9%D8%B5%D8%A7%D8%A8-%D9%85%D8%AD%D8%A7%D8%B3%D8%A8%D8%A7%D8%AA%DB%8C-mk744/%D9%81%D8%B5%D9%84-%D8%A7%D9%88%D9%84-%D8%B9%D9%84%D9%88%D9%85-%D8%A7%D8%B9%D8%B5%D8%A7%D8%A8-%D9%85%D8%AD%D8%A7%D8%B3%D8%A8%D8%A7%D8%AA%DB%8C-ch2077/%D9%88%DB%8C%D8%AF%DB%8C%D9%88-%D9%81%D8%B1%D8%A2%DB%8C%D9%86%D8%AF%D9%87%D8%A7%DB%8C-%D8%AA%D8%B5%D9%85%DB%8C%D9%85-%DA%AF%DB%8C%D8%B1%DB%8C-%D9%85%D8%BA%D8%B2/.