Mission Synaptech: Save Dr. Z's Mind

INTRODUCTION

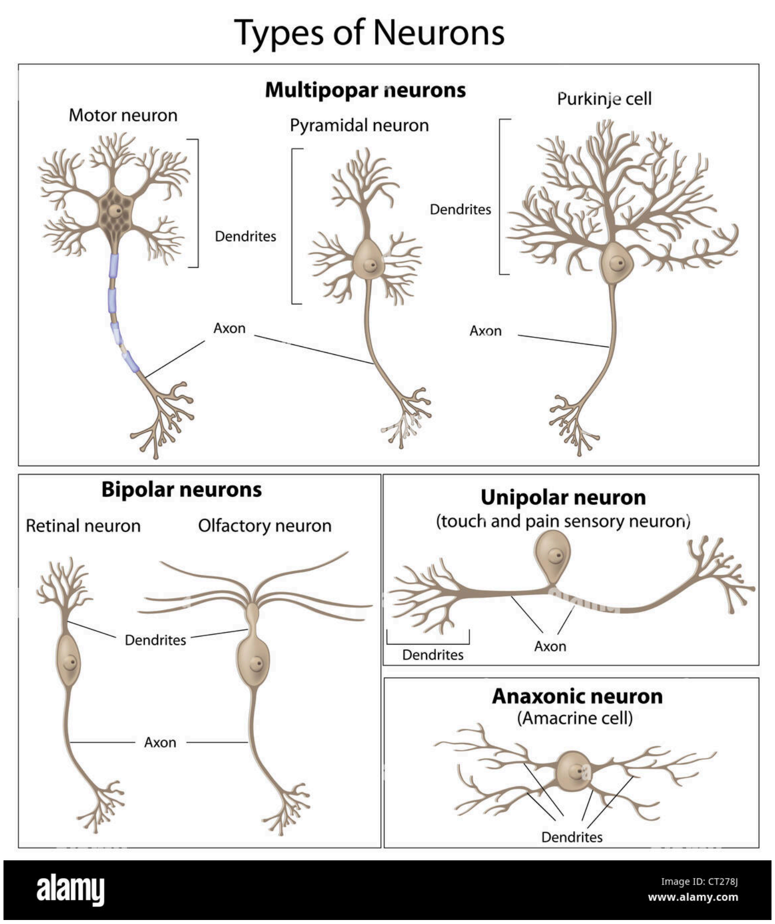
The outer layer of our brain is made up of multiple layers, together constituting the cortex which contain various neurons exhibiting varying functions ~ but all of them do one thing in common - fire!

Here I attempt to model that cortex or lets say, the cortical microcircuit of Dr. Z who has been infected by this neural parasite Corticon - hijacking his circuits and causing mayhem. And then ultimately try to save him :)

The cortical microcircuit has 6 layers, and with differing neural connections and density - really complex to model mathematically. So here, I just create a single layer with randomised synapses using the Izhikevich neuron model - it resembles the layer 4 / layer 2-3 the most when we compare it with the layered model.

NEURON AND ITS TYPES

A neuron is the most fundamental unit of a microcircuit (at least for a computer). Below is a diagram showing different varieties of neurons found in the body



Of these, the pyramidal neurons are found mainly in the cortical circuit. Now even these can be of 2 types - Excitatory and Inhibitory

Or also called **Excitatory Pyramidal neurons** and **Inhibitory Interneurons** and are generally found in a 80:20 ratio in the cortex. Excitatory neurons in the cortex promote and transmit information, while inhibitory neurons regulate and refine that information

In my model, I use 560 neurons total and they are modelled by the Izhikevich neuron model, it is described as follows by the 2 differential equations and controlled by parameters a,b,c,d and variables v (membrane potential) and u (recovery variable)

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

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

With a spike reset condition: if $v \geq 30$, then $v \leftarrow c$ and $u \leftarrow u + d$.

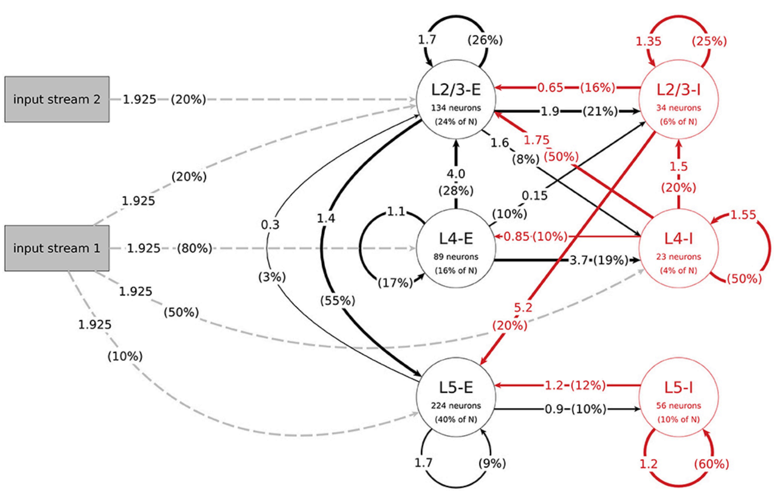
- (v): Membrane potential (dimensionless, spiking at 30)
- (u): Recovery variable (dimensionless)
- (a), (b), (c), (d): Parameters controlling neuronal dynamics

a: recovery speed
b: sensitivity to membrane potential (link between v-u, increase causes high firing)
c: reset potential after spike
d: recovery reset (changes u by that amount after spike)

Other mathematical models include Leaky - Integrate and Fire (LIF) - very basic and Hodgkin-Huxley model - which is more complex. I Use the Izhikevich neuron model as it resembles the biological neuron with decent accuracy all while being computationally light. According to the research paper, the actual efficacy of the cortex is derived from its laminar structure and not the neuron model - i.e. a simpler neuron model should also provide similar results.

CONNECTIVITY

The neurons are randomly connected to each other with a 50% connection probability and the input is connected with a probability of 70%. STDP allows the network to adapt, strengthening connections between co-active excitatory neurons, which can lead to synchronized activity and increased frequency some time after the simulation starts, but eventually stabilising due to capping of maximum weight.
A real cortex has a laminar structure with 6 layers of neurons with differing connections. The image below shows these connections as used in the research paper:



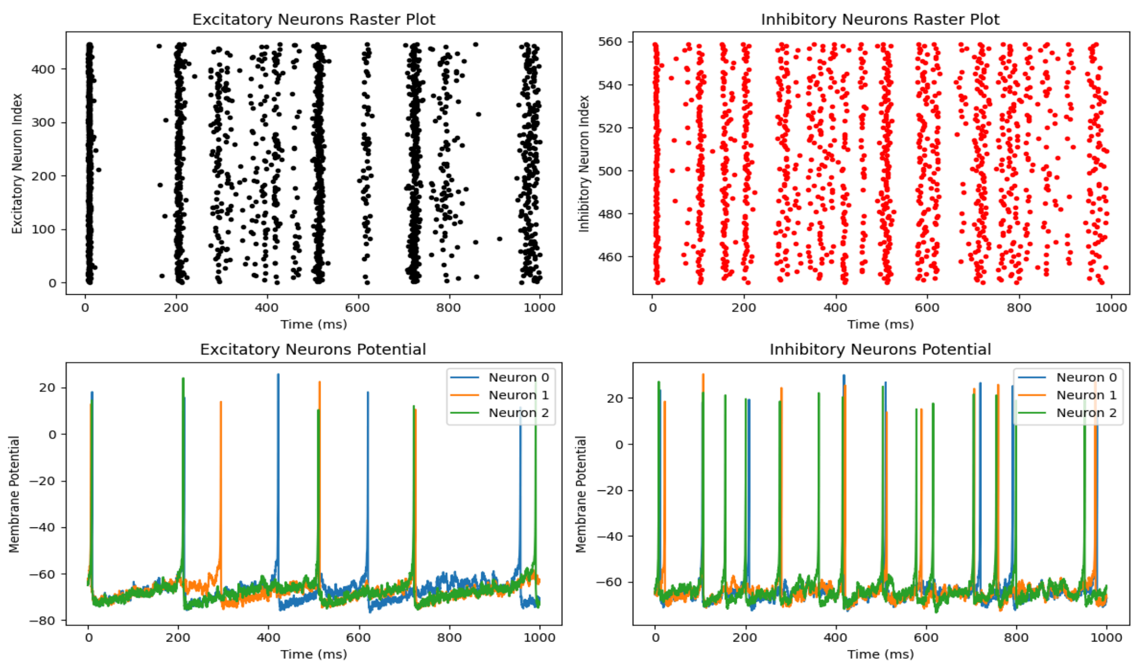
The research paper highlights that it is this very specific layered structure which provides the brain the processing power and efficiency that it has and no other connection type tested in the paper came close to it. Thus, it is natural that my circuit can only be used as a baseline to observe how firing of neurons works keeping efficiency aside. To keep things as realistic as possible, I have used the average firing frequency of layer 4 to be the state of normalcy in my circuit as it is the closest to my random modelling with inputs - which are 100 Poisson neurons (fire at random times with a fixed avg. frequency) at 100Hz.

The approximate average firing frequency data for layer 4 is as follows:
Excitatory: 3-6 Hz
Inhibitory: 9-12 Hz
(Taken from the web and reference from Potjans and Diesmann model)

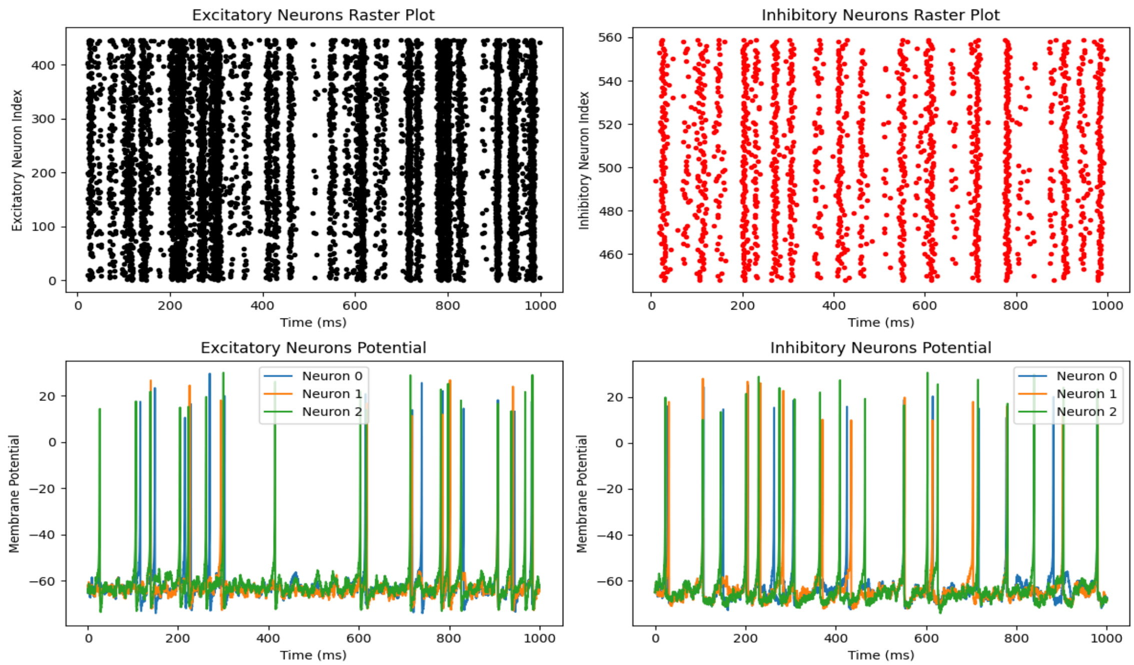
COMPUTATIONAL FUNCTIONS AND OBSERVATIONS

The network dynamics were analysed using the firing frequency, raster plots and membrane potential plots/neuronal responses of 3 random neurons.

For normal cortex:
Average firing rate of excitatory: 4.54 Hz
Average firing rate of inhibitory: 12.28 Hz



For Corticon infected cortex:
Average firing rate of excitatory: 17.52 Hz
Average firing rate of inhibitory: 14.80 Hz
Corticon has caused an increase in the recovery speed of excitatory neurons i.e. ‘a’ of excitatory neuron group, causing quick recovery after firing and causing seizures



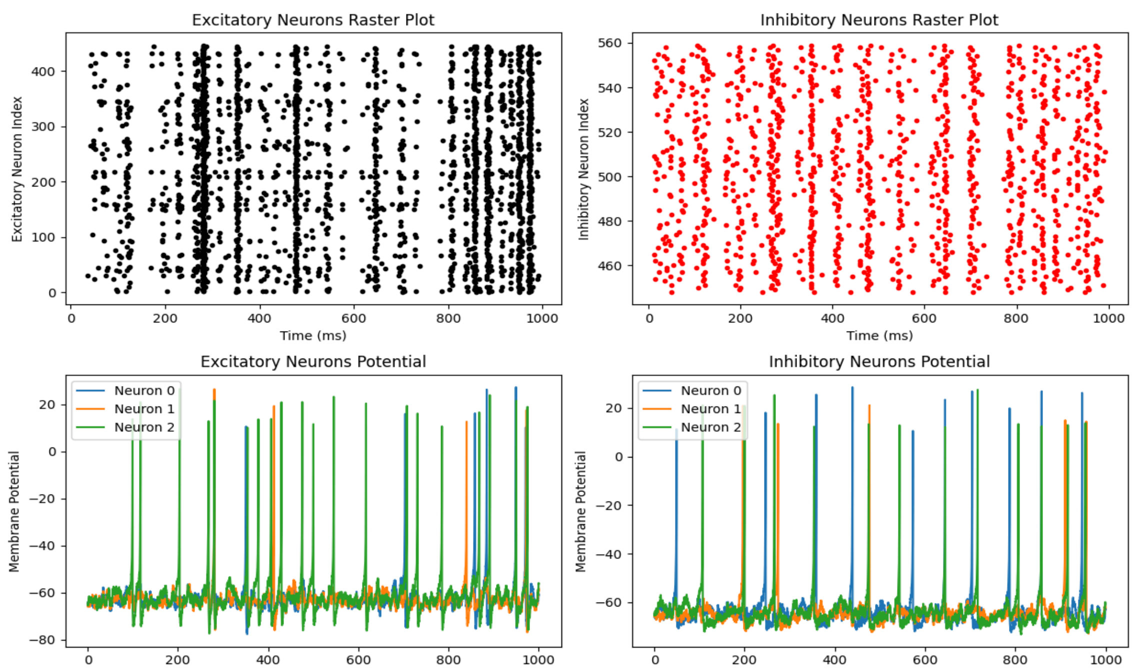
Attempt to recovery:

Average firing rate of excitatory: 5.07 Hz

Average firing rate of inhibitory: 10.91 Hz

Using Anticonvulsants and Anti-Seizure(GABAergic) drugs which directly impact the synaptic connections of the neurons ~ modifying STDP connections

The E-E and E-I weights were reduced while the I-E and I-I weights were increased negatively



Although not ideal, this would at least calm down the firing, preventing seizures and further neural breakdown. In the meantime neuro experts can try to find a permanent cure to corticon :)

Computational Roles:

1. **Pattern Formation via STDP:**
   STDP in excitatory synapses enables the network to form synchronized assemblies, where neurons that fire together strengthen their connections. This mimics cortical mechanisms for learning and memory, such as the formation of cell assemblies that encode information.

2. **Excitatory-Inhibitory Balance:**

   The network maintains a balance between excitation and inhibition, a hallmark of cortical function. The inhibitory weights ensure that excitatory bursts are regulated, preventing runaway activity that could mimic seizures. This balance is crucial for stable computation, such as maintaining a resting state or processing inputs without overload.

3. **Response to External Input:**

   The Poisson input (100 Hz) drives network activity, simulating sensory or thalamic input to the cortex. The network's response—sparse excitatory firing with inhibitory regulation—mimics how cortical circuits process external stimuli, filtering and integrating information.

COMPARING WITH RESEARCH PAPER

Neuron Model: The paper uses Hodgkin-Huxley model which uses 4 differential equations and has a more accurate modelling of Na, K, Ca ion channels, while my model uses Izhikevich model which has 2 differential equations with a recovery variable instead mimicking the combined effects of these ion channels - less realistic but less heavy computationally.

Connectivity and structure: The paper uses the multilayer approach - L4 (Input), L2/3 (processing) and L5/6 (processing and output) with a set of synapses closely mimicking a real animal cortex, while my model is made of single layer random synaptic connections with arbitrarily fixed probabilities. As mentioned before in my report, this layered structure is the key differentiating factor when it comes to computational performance.

The paper hypothesizes that even on choosing a simpler neuron model, but keeping the layered structure would yield similar performance - in fact even better as a simpler structure would be computationally less taxing. This hypothesis is further verified in the paper as well. This is the basis of my decision of using the Izhikevich model as it would be resource saving and won't really impact the overall performance

Weights of synapses, parameters: The paper uses real life scaled values for their circuit while I use arbitrarily chose values to mimic actual firing rate frequencies of the cortex (layer-4) which means that there is high probability that the firing patterns may not be exactly as found in nature even though the net averaged frequency is the same. Though, both models use 560 neurons with STDP - Spike Time Dependent Plasticity.

The parameter values and implementation for STDP in my model are chosen with the help of standard examples of Brian2 official documentation - although over there it was used on the LIF neuron model.

Scope of improvement: Changing the structure of circuit to incorporate multiple layers should give more realistic firing and membrane potential curves as this random arrangement may show unexpected behaviour if the connection patterns, timing of input firing and weights are aligned in a specific fashion. So, in total adopting the layered circuit and real life weights would give a biologically accurate modelling of Dr. Z's cortex.

CONCLUSION

The purpose of modelling the cortex, a corticon attack and then using Anticonvulsants and Anti-Seizure(GABAergic) drugs to try to recover from the attack by changing synaptic parameters - while corticon was still active, is achieved through this implementation when looking at average firing frequency as the key parameter which was brought to about 5 Hz from 17 Hz preventing seizures and subsequent neural shutdown of Dr. Z !

BCS - Saving Dr. Smith.ipynb

REFERENCES

1. Frontiers | Characteristic columnar connectivity caters to cortical computation: Replication, simulation, and evaluation of a microcircuit model ~ Research Paper

2. Introduction to Brian part 1: Neurons — Brian 2 0.0.post128 documentation