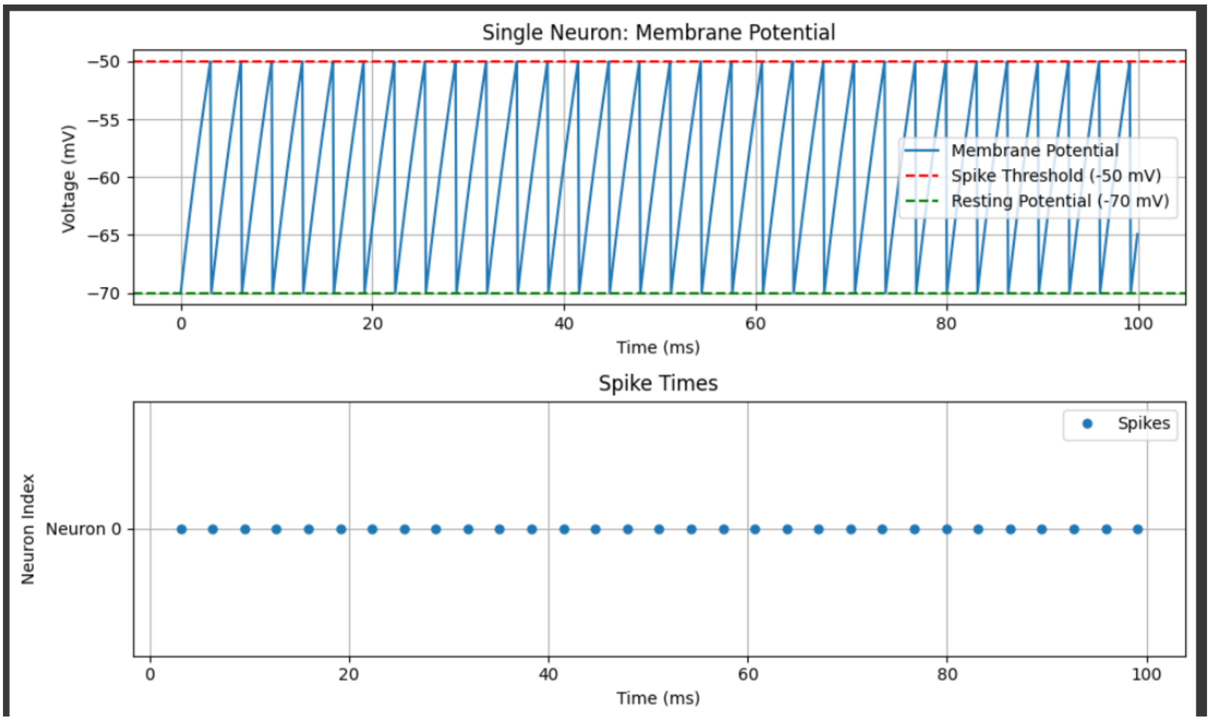
Simulating a Single Neuron Using Leaky Integrate and Fire

In the beginning I created a Single Neuron simulation using Leaky Integrate and Fire model or LIF. Lif is one of the simplest model to simulate a neuron. However the model is not that similar to real life brain activities however is a good starting point to understand the basics about a neuron. The research paper I studied also uses this model for the simulation.

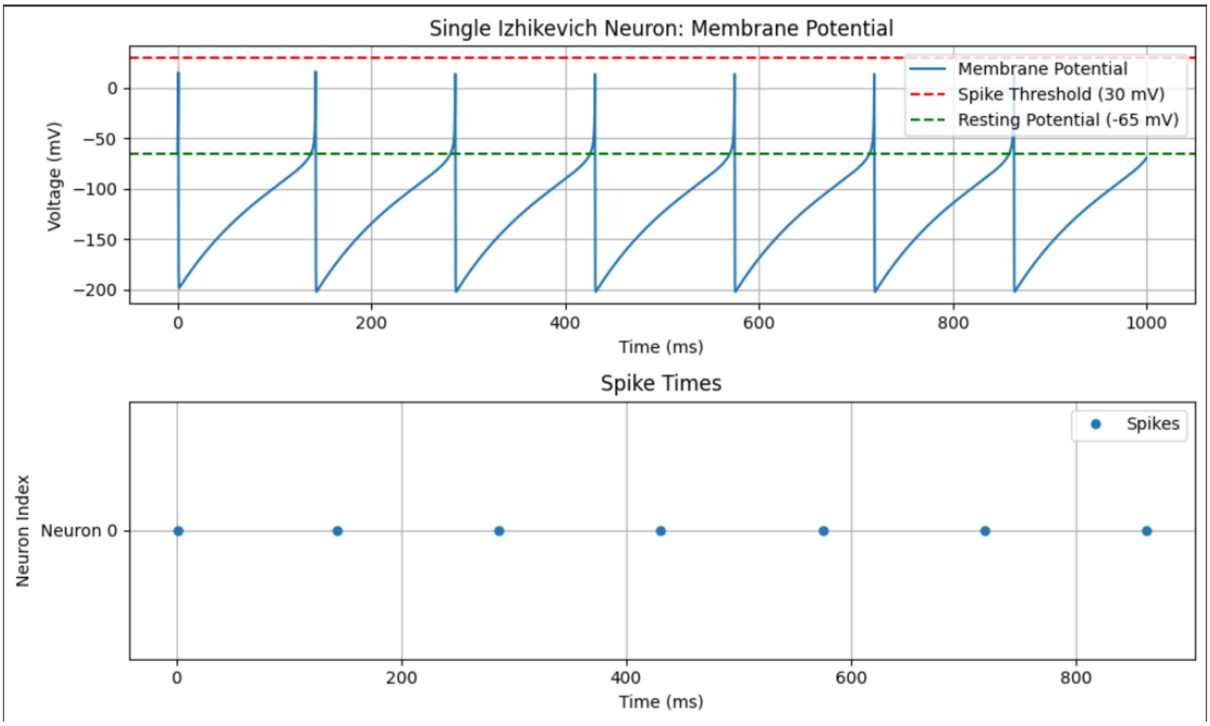
- **Neuron Model**: The LIF neuron is governed by the equation dv/dt = (-v + R*I) / tau, where v is the membrane potential, R is resistance, I is input current, and tau is the time constant. The neuron spikes when v > -50 mV and resets to -70 mV.
- **Parameters**: Resting potential = -70 mV, tau = 10 ms, R = 50 Mohm, constant input I = 0.1 nA. Initial v = -70 mV.
- **Simulation**: Runs for 100 ms with a single neuron, using the exact integration method.
- **Inputs**: A constant 0.1 nA current drives the neuron, causing v to rise toward the threshold.
- **Outputs**:
    - A membrane potential plot shows v over time.
    - A spike raster plot shows spike times as dots for the neuron.



Simulating a Single Neuron Using Izhikevich Model

Further I also simulated a neuron using the Izhikevich Model which is a significant improvement on the previous LIF model as it is better able to replicat biological complexities of a neuron while still being computationaly cost efficient. The model is being used for my Network simulations and hence is an improvement of my cited research paper.

- **Neuron Model**: The Izhikevich neuron is defined by dv/dt = (0.04/mV*v**2 + 5*v + 140*mV - u + I)/ms for membrane potential v and du/dt = a*(b*v - u) for recovery variable u. The neuron spikes when v >= 30 mV, resetting v = c and incrementing u += d.
- **Parameters**: Resting potential = -65 mV, initial u = -13 mV, I = 50 mV, a = 0.02/ms (regular spiking), b = 0.2, c = -65 mV, d = 0.8 V.
- **Simulation**: Runs for 1000 ms with a single neuron, using the RK4 integration method.
- **Inputs**: A constant 50 mV current drives the neuron, with u regulating spiking.
- **Outputs**:
    - A membrane potential plot shows v over time, with lines for the threshold (30 mV) and resting potential (-65 mV).
    - A spike raster plot shows spike times as dots.
    - The neuron produces regular spiking, with u modulating the firing pattern, visualized in the plots.

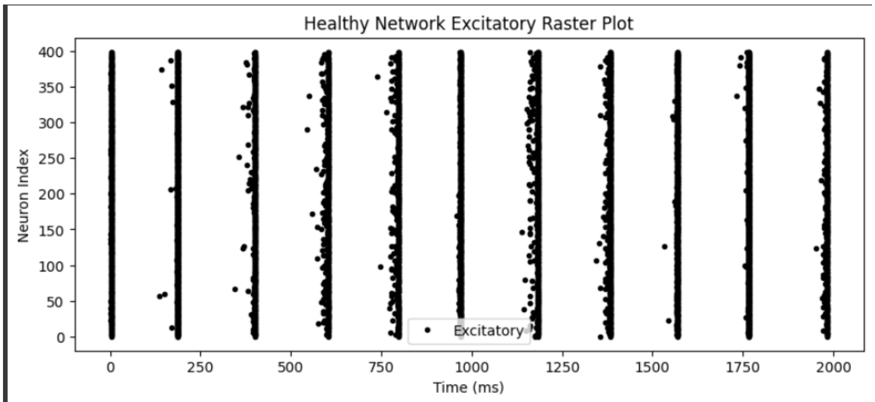


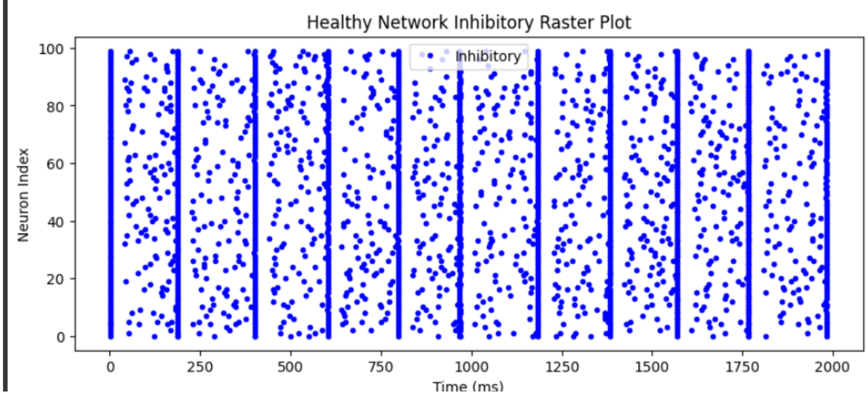
Healthy Brain Network Simulation

Now I have simulated a neural network which displays the functioning of a Healthy brain. As stated earlier I have used Izhikevich model here to improve biological similarities additionally STDP has also been applied between EE and EI synapses. Based on general trends throughout the project normal state has been assumed to be 5-10 Hz for excitatory neurons and 10-15 for inhibitory neurons. After a significant amount of parameter and weight tuning the model was made to produce synchronous spikes at proper frequency.

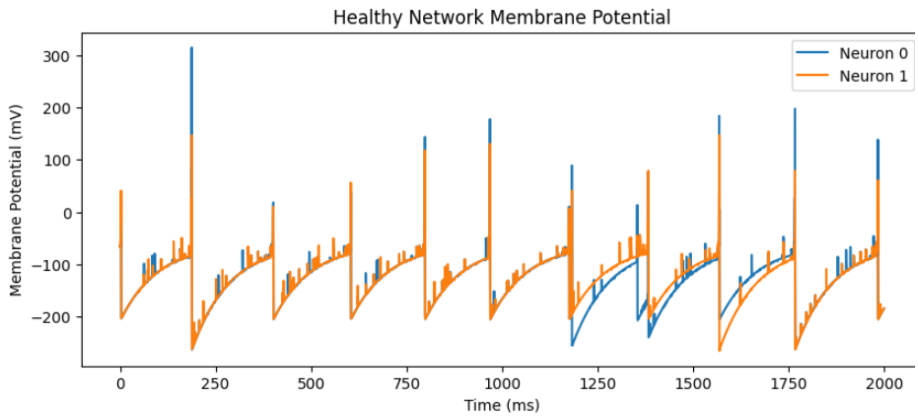
- **Neuron Model**: Uses Izhikevich neurons (400 excitatory, 100 inhibitory) with quadratic membrane potential dynamics and a recovery variable. Excitatory neurons have parameters for regular spiking (a=0.02/ms, b=0.2, c=-65mV, d=0.8V), while inhibitory neurons are fast-spiking (a=0.1/ms, b=0.2, c=-65mV, d=0.2V). Initial membrane potentials are set to -65 mV.
- **Network Structure**: Total of 500 neurons with 80% excitatory and 20% inhibitory. Connections are probabilistic (20% for most synapses, 15% for inhibitory-to-inhibitory), mimicking sparse cortical connectivity.
- **Synaptic Mechanisms**: Excitatory-to-excitatory and excitatory-to-inhibitory synapses use spike-timing-dependent plasticity (STDP) with pre- and postsynaptic traces (taupre=taupost=20ms, Apre=0.01, Apost=-0.015). Inhibitory synapses are static with fixed negative weights. Synaptic weights are initialized to small values (e.g., 0.0062 for excitatory, 0.0015 V for inhibitory-to-excitatory).
- **Inputs**: Poisson inputs drive the network: 20 Hz for excitatory neurons (aiming for 5-10 Hz firing), 10 Hz for inhibitory neurons (aiming for 10-15 Hz firing), and a 40 Hz common input to 50% of excitatory neurons for synchrony. Input weights are set to evoke appropriate firing (e.g., 0.04 V for excitatory inputs).
- **Simulation**: Runs for 2000 ms with a 0.1 ms time step using the RK4 integration method.
- **Outputs**: Spike monitors record excitatory and inhibitory spikes. State monitors track membrane potentials for two excitatory neurons. Plots include:
    - Excitatory and inhibitory raster plots showing spike times.
    - Membrane potential traces for two excitatory neurons.
    - Firing rate histograms (50 ms bins) for excitatory and inhibitory groups.
    - Average firing rates are calculated as spikes per second per neuron: excitatory rate of 7.94 Hz (within target 5-10 Hz) and inhibitory rate of 11.87 Hz (within target 10-15 Hz).

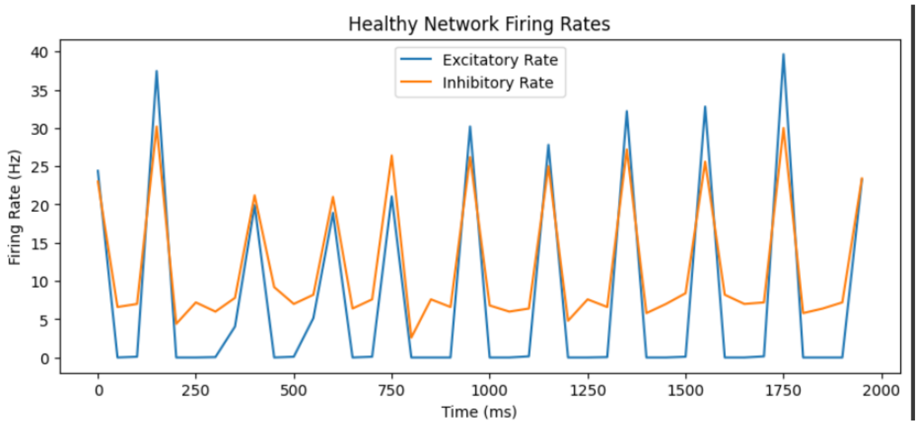
The simulation models a balanced cortical network with STDP-driven plasticity, producing realistic firing patterns and network dynamics for a healthy brain state, with observed firing rates aligning with the target ranges.





Time (ms)



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Healthy Network - Average excitatory rate: 7.94 Hz
Healthy Network - Average inhibitory rate: 11.87 Hz
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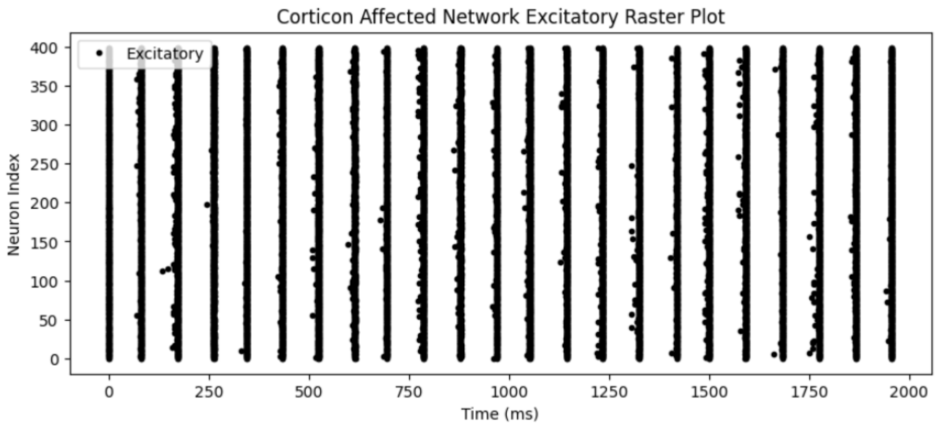
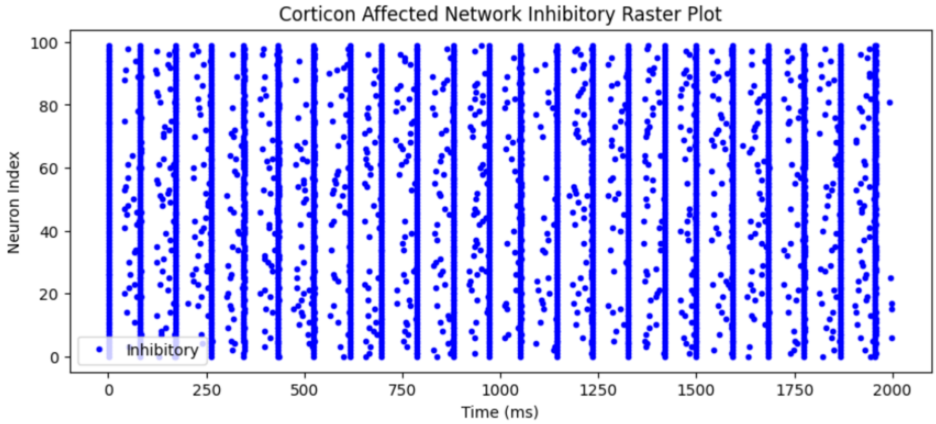
Simulating Corticon Attack

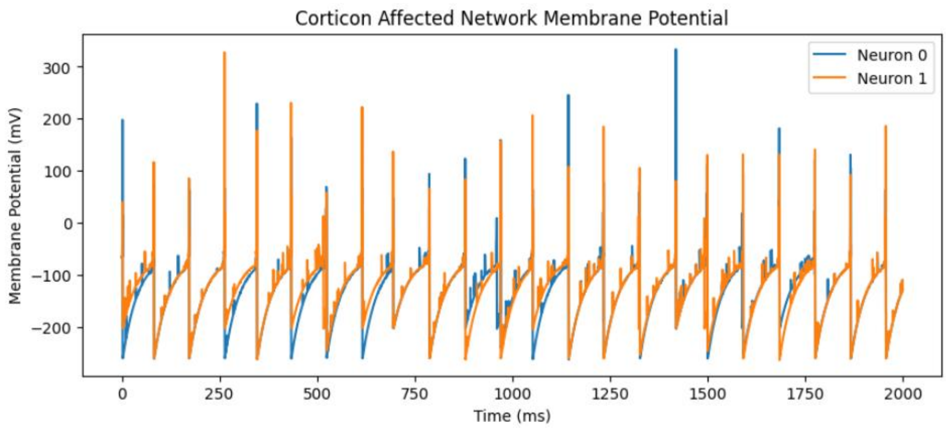
Now it was time for our Corticon to Attack our healthy brain. A modified version of the code simulates a "corticon attack," representing a pathological state of cortical hyperexcitability, such as seizure-like activity. The tweak in the parameters is what is caused by the corticon who is trying to hinder the brains functioning.

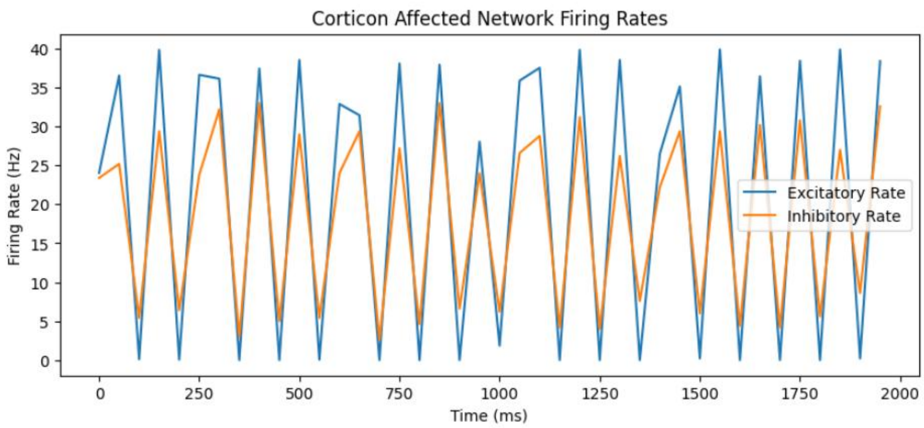
- **Code Change**: The Izhikevich parameter a for excitatory neurons (a_e) is increased from 0.02/ms (healthy) to 0.05/ms (corticon). This parameter governs the recovery time scale of the recovery variable u, which provides negative feedback to the membrane potential. All other parameters, network structure, synapses, inputs, and monitoring remain identical.
- **Mechanistic Impact**: A higher a_e (0.05/ms) speeds up the recovery of excitatory neurons after spiking, reducing their refractory period and increasing their excitability. This allows excitatory neurons to fire more frequently in response to the same Poisson inputs (20 Hz for excitatory, 40 Hz for common input), leading to a cascade of excitatory activity. STDP in excitatory-to-excitatory synapses further amplifies this by strengthening connections during high-frequency firing.
- **Simulation of Corticon Attack**: The increased excitability mimics a corticon attack, characterized by excessive and synchronized neuronal firing, resembling epilepsy or seizure-like states. The excitatory-inhibitory balance is disrupted, as inhibitory neurons (unchanged a_i=0.1/ms) cannot fully counteract the heightened excitatory drive, despite increased firing. This results in a hyperactive network state.
- **Observed Firing Rates**: The corticon-affected network shows significantly elevated firing rates compared to the healthy network:
  - **Healthy**: Excitatory rate = 7.94 Hz (target 5-10 Hz), inhibitory rate = 11.87 Hz (target 10-15 Hz).
  - **Corticon Affected**: Excitatory rate = 20.67 Hz, inhibitory rate = 18.45 Hz.
  - The excitatory rate (20.67 Hz) far exceeds the healthy target, indicating hyperexcitability. The inhibitory rate (18.45 Hz) also rises, driven by excitatory-to-inhibitory synapses, but fails to restore balance, consistent with pathological cortical dynamics.
- **Outputs**: The simulation generates raster plots, membrane potential traces, and firing rate histograms showing denser spiking and higher rate peaks, reflecting seizure-like activity.

This modification effectively simulates a corticon attack by inducing runaway excitation, disrupting network balance, and producing firing rates indicative of a pathological state.







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Corticon Affected Network - Average excitatory rate: 20.67 Hz
Corticon Affected Network - Average inhibitory rate: 18.45 Hz
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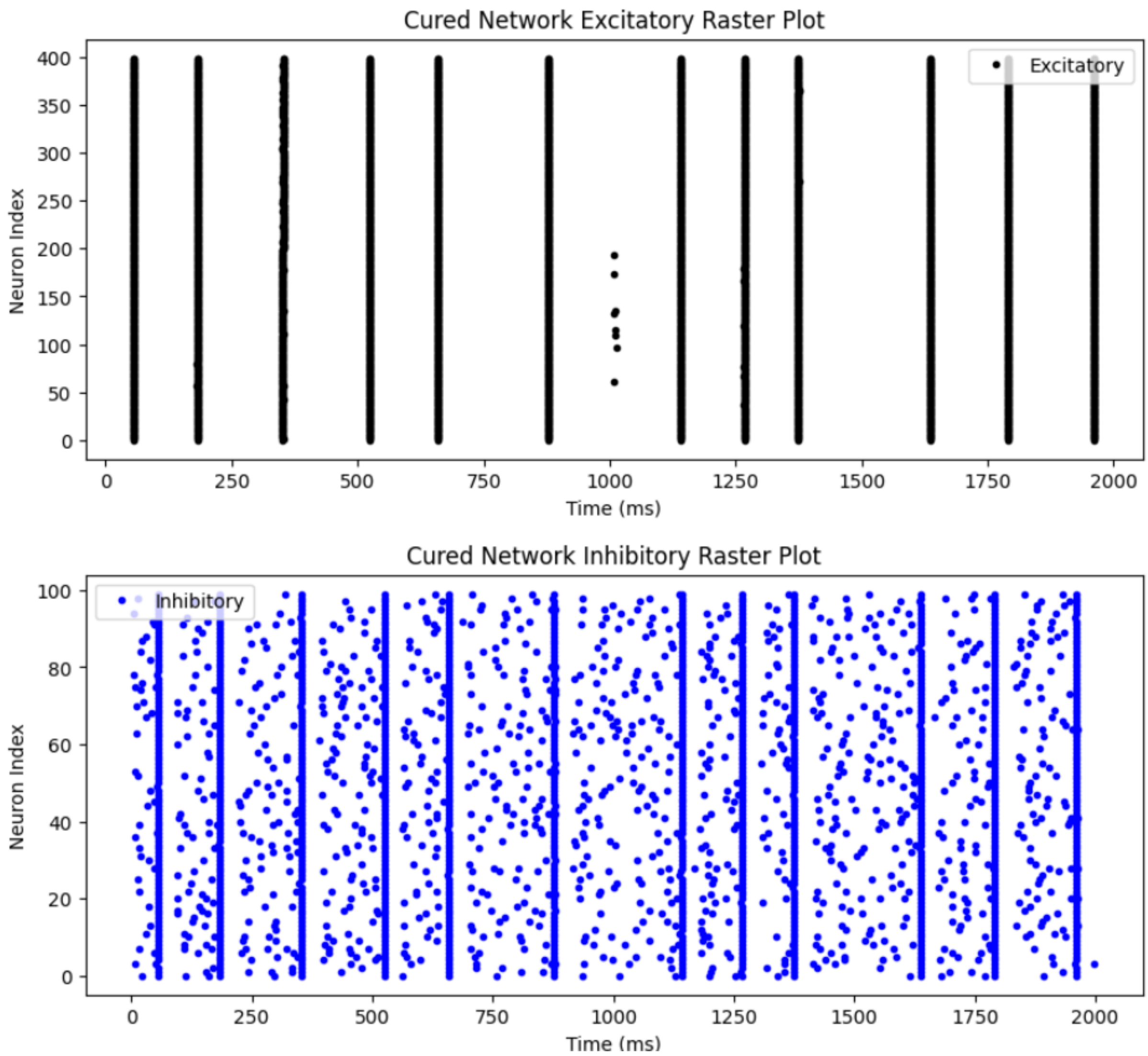
Saving Dr Z's Mind

Now it was time to Save Dr Z's Mind from this corticon. A further modified version of the code, simulates the restoration of normal cortical function following the corticon attack, effectively "saving Dr Z's mind." The core driver of these were the understanding of the various elements of the network like the synapses , their connection and effect on the simulation.

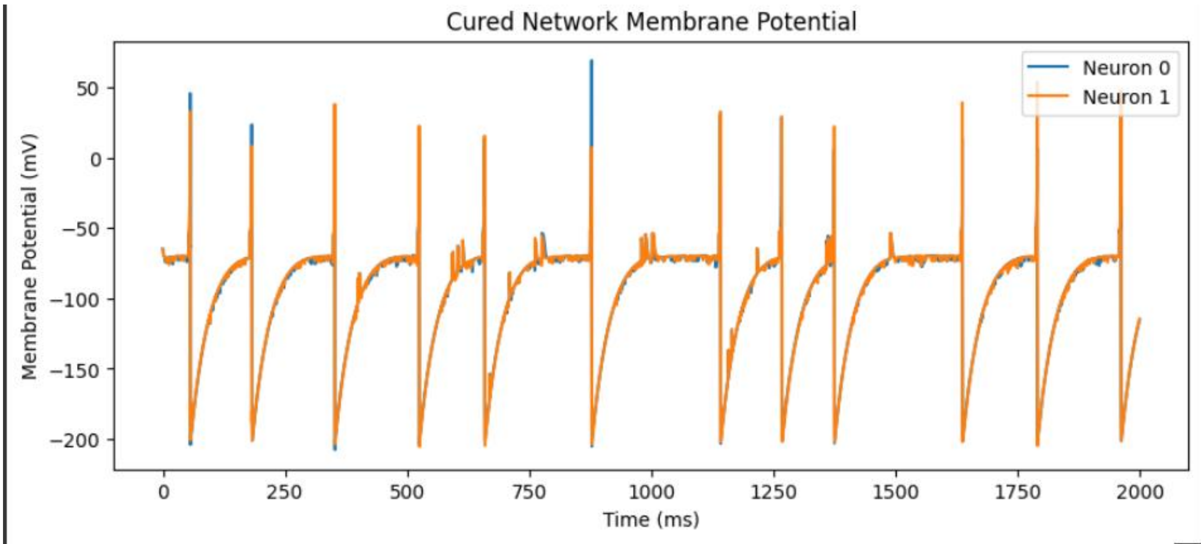
- **Code Changes**:
  - **Excitatory Neuron Parameter**: The Izhikevich parameter a_e remains at 0.05/ms (same as corticon, higher than healthy 0.02/ms), indicating no change in excitatory neuron recovery time. This was maintained to make it challenging if I just retweeked it , it wouldn't be fun.
  - **Poisson Input Rates**:
    - Excitatory input rate reduced from 20 Hz (corticon) to 3 Hz (cured), targeting 5-10 Hz firing.
    - Common input rate (for 50% of excitatory neurons) reduced from 40 Hz (corticon) to 20 Hz (cured).
    - Inhibitory input rate unchanged at 10 Hz as those rates were also out of the range
  - **Synaptic Weights**:
    - Excitatory input synapses (input_syn_E) weight reduced from 0.04 V (corticon) to 0.001 V (cured).
    - Common input synapses (common_syn_E) weight slightly reduced from 0.02 V (corticon) to 0.0179 V (cured).
    - Excitatory-to-excitatory synapses (see) weight reduced from 0.0062 (corticon) to 0.002 (cured).
    - Inhibitory-to-excitatory synapses (sie) weight increased from 0.0015 V (corticon) to 0.003 V (cured).
    - Excitatory-to-inhibitory (sei) and inhibitory-to-inhibitory (sii) weights unchanged at 0.002 and 0.0004 V, respectively.
- **Restoration of Normalcy**:
  - **Reduced Excitatory Drive**: Lowering the excitatory Poisson input rate (20 Hz to 3 Hz) and common input rate (40 Hz to 20 Hz), along with significantly reducing excitatory input weight (0.04 V to 0.001 V) and slightly reducing common input weight (0.0179 V), decreases the external drive to excitatory neurons. This counteracts the hyperexcitability caused by the high a_e (0.05/ms), reducing excessive spiking.
  - **Weakened Excitatory Synapses**: The reduced excitatory-to-excitatory synaptic weight (0.0062 to 0.002) limits recurrent excitation, preventing the amplification of activity seen in the corticon attack (20.67 Hz excitatory rate).

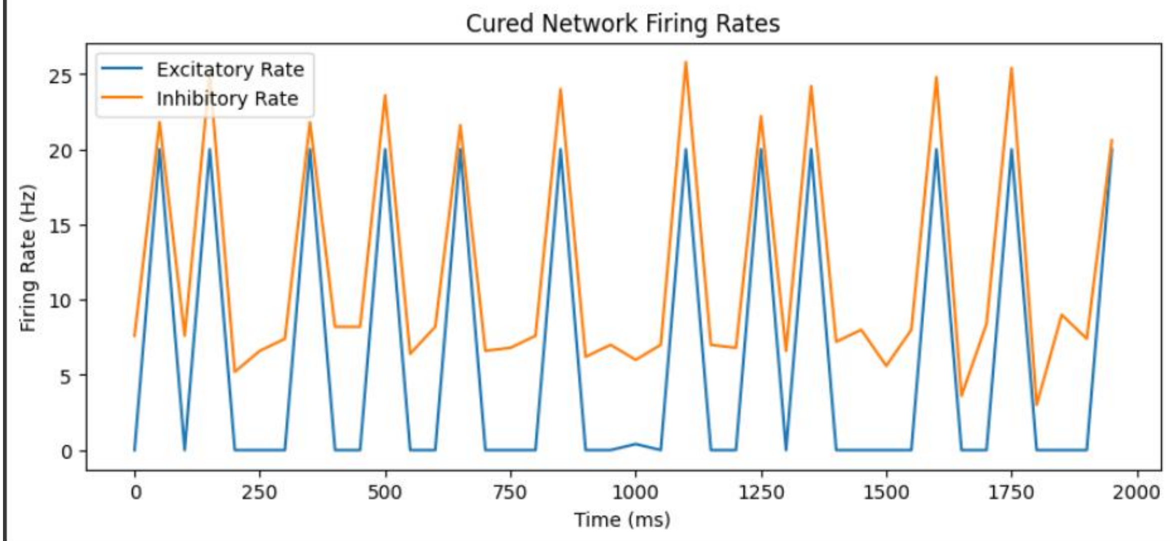
  - **Strengthened Inhibitory Control**: Increasing the inhibitory-to-excitatory synaptic weight (0.0015 V to 0.003 V) enhances inhibition, enabling inhibitory neurons to better suppress excitatory activity and restore the excitatory-inhibitory balance.
  - **Mechanistic Impact**: Despite the retained high a_e, the reduced excitatory inputs and weights, combined with stronger inhibition, prevent runaway excitation. STDP in excitatory synapses continues to adapt weights, but the lower drive limits excessive synaptic strengthening. Inhibitory neurons maintain stable firing (11.85 Hz, close to healthy 11.87 Hz) due to unchanged inputs and parameters, supporting network stability.
  - **Therapeutic Analogy**: These changes mimic interventions like antiepileptic drugs, which reduce excitatory activity or enhance inhibition to control seizures, restoring normal cortical dynamics.
- **Observed Firing Rates**:
  - **Healthy**: Excitatory = 7.94 Hz (target 5-10 Hz), inhibitory = 11.87 Hz (target 10-15 Hz).
  - **Corticon Affected**: Excitatory = 20.67 Hz, inhibitory = 18.45 Hz.
  - **Cured**: Excitatory = 6.01 Hz, inhibitory = 11.85 Hz.
  - The cured excitatory rate (6.01 Hz) falls within the target 5-10 Hz, and the inhibitory rate (11.85 Hz) is within 10-15 Hz, closely matching the healthy network's rates. This confirms the restoration of balanced, normal firing patterns.
- **Outputs**: The simulation generates raster plots, membrane potential traces, and firing rate histograms labeled "Cured Network," showing sparser excitatory spiking and stable inhibitory activity compared to the corticon attack, resembling the healthy network's behavior.

The cured network effectively simulates the recovery from a corticon attack by reducing excitatory drive and strengthening inhibition, restoring firing rates and network dynamics to a healthy state, thus **saving Dr Z's mind.**



Cured Network Excitatory Raster Plot
Excitatory
Neuron Index
Time (ms)
Cured Network Inhibitory Raster Plot
Inhibitory
Neuron Index
Time (ms)



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Cured Network - Average excitatory rate: 6.01 Hz
Cured Network - Average inhibitory rate: 11.85 Hz
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