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Modeling of Cortical Network Dynamics

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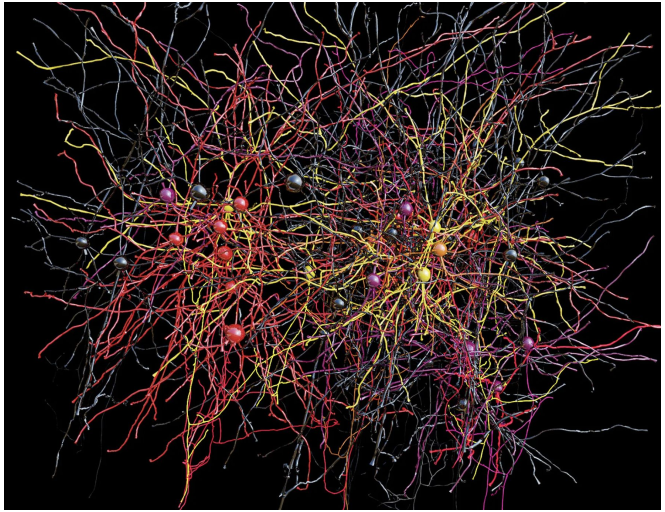
Biological Networks in the Brain

The human brain contains:

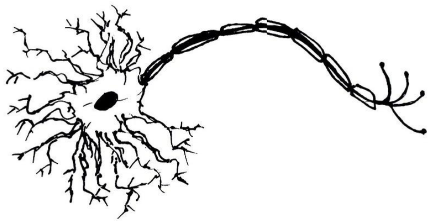
- 10^{10} neurons
- 10^{14} synapses/connections

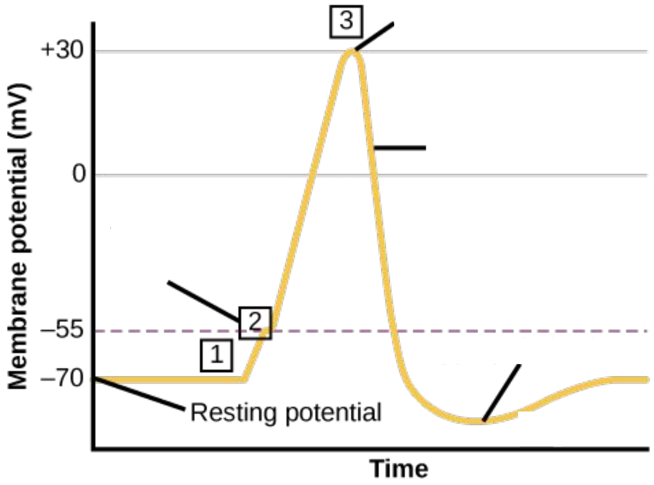
A **neuron** is the most fundamental unit for neurocomputation in the brain.



de Vries, S.E.J., Lecoq, J.A., Buice, M.A. et al.

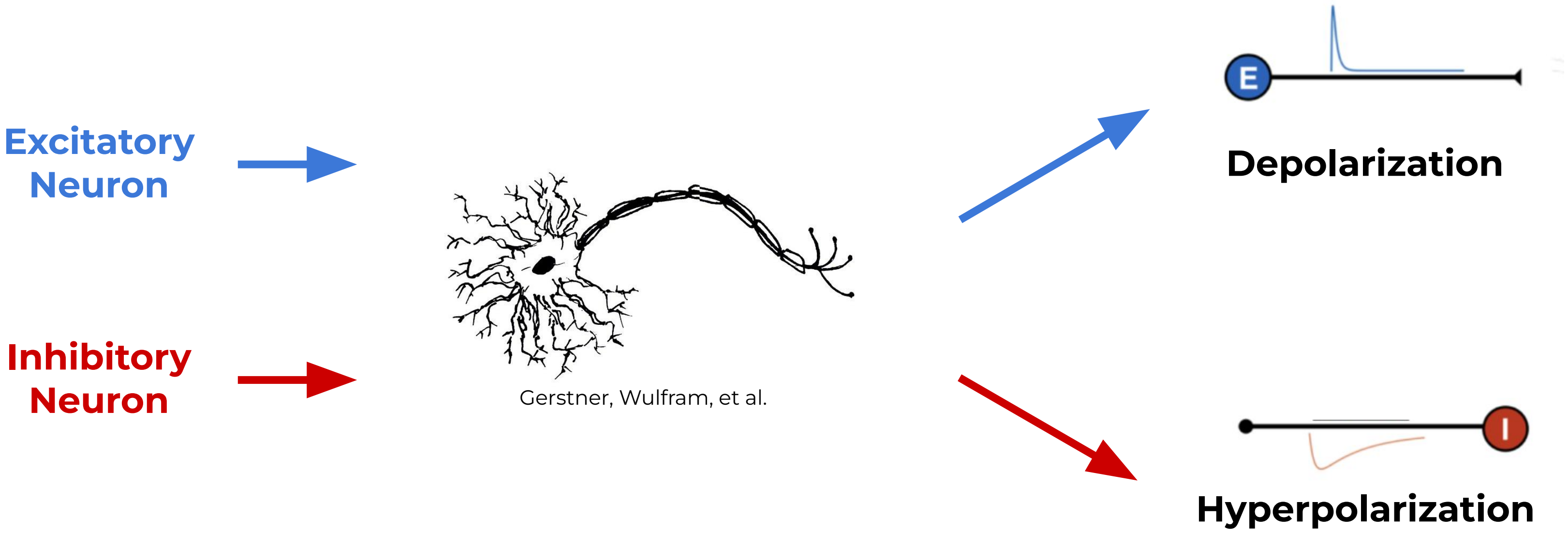
Neuronal Dynamics



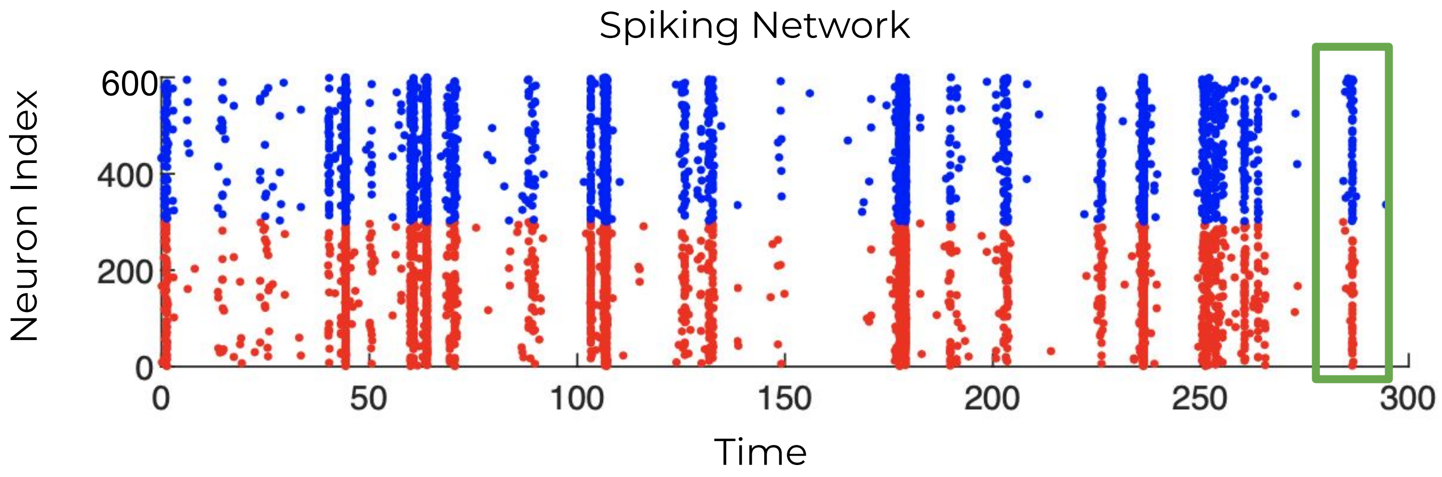


Behaves similar to an electrical capacitor.

How do neurons communicate?



Multiple Firing Events (MFEs)



A class of significant firing patterns of neurons exhibiting transient synchrony produced by the recurrent interactions between neurons.

Issues with Modeling Cortical Networks

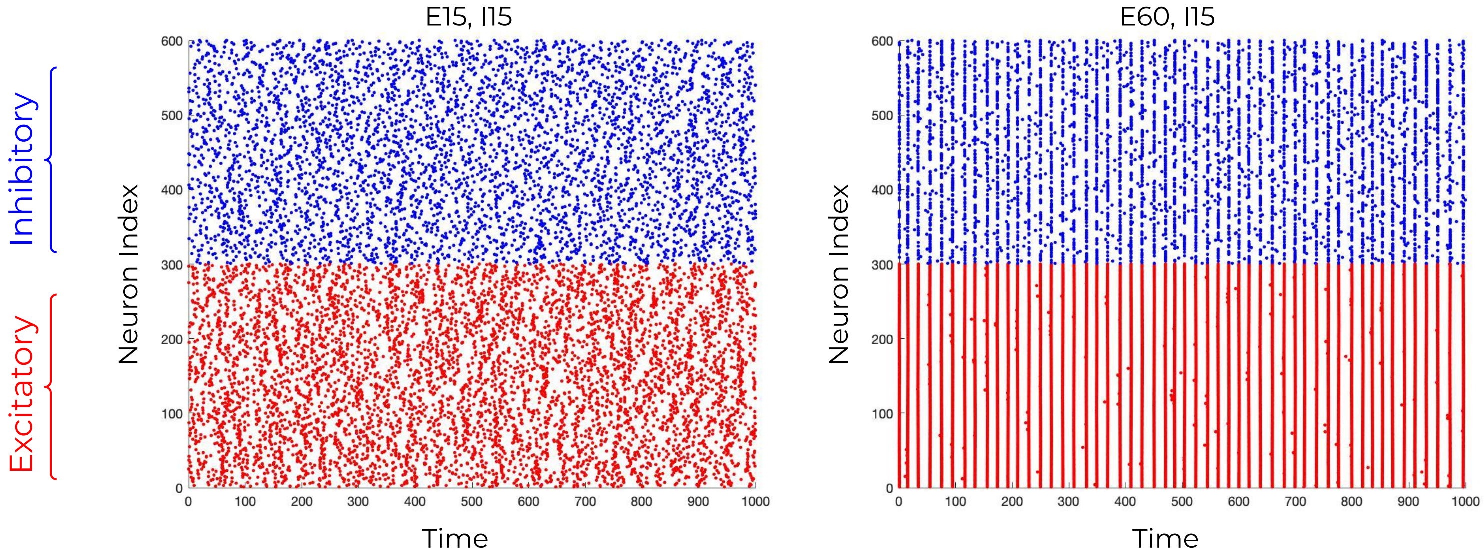
Coupled spiking networks have proven to be successful in modeling the brain and serve as a central aspect of computational neuroscience.

However, large spiking networks are hard to analyze and computationally expensive to simulate due to:

1. High-Dimensionality
2. Nonlinearity

Research Question: Can we successfully utilize machine learning to explore multiple firing events (MFEs)?

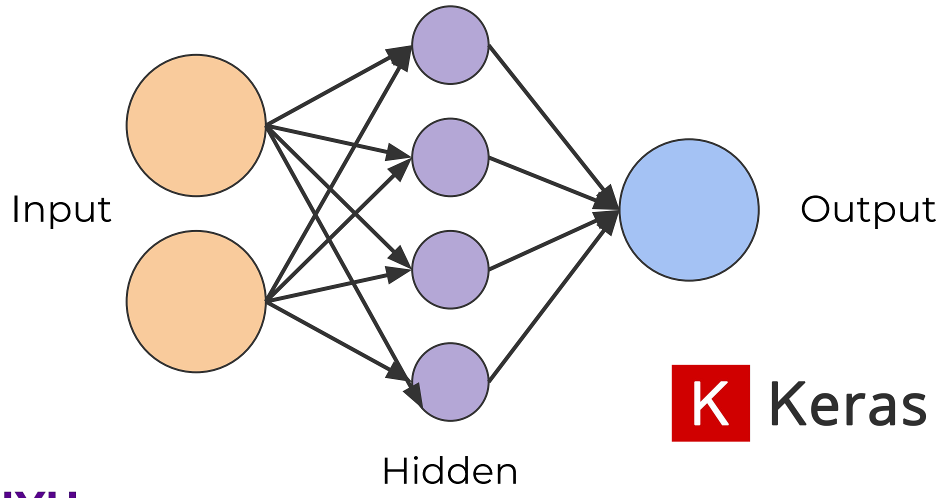
Simulating Spiking Data



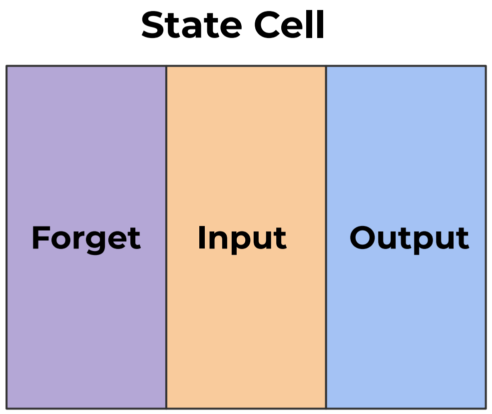
Through varying degrees of connections, we can notice synchronicity between spiking patterns.

Modeling Spiking Networks with LSTMs

Multiple Firing Events (MFEs) are a temporal dynamic. Therefore, since we are dealing with time series data, we will utilize Long-Short Term Memory Networks (LSTMs), which are adept at extracting intrinsic dimensionality of the dynamics of the system.



Keras



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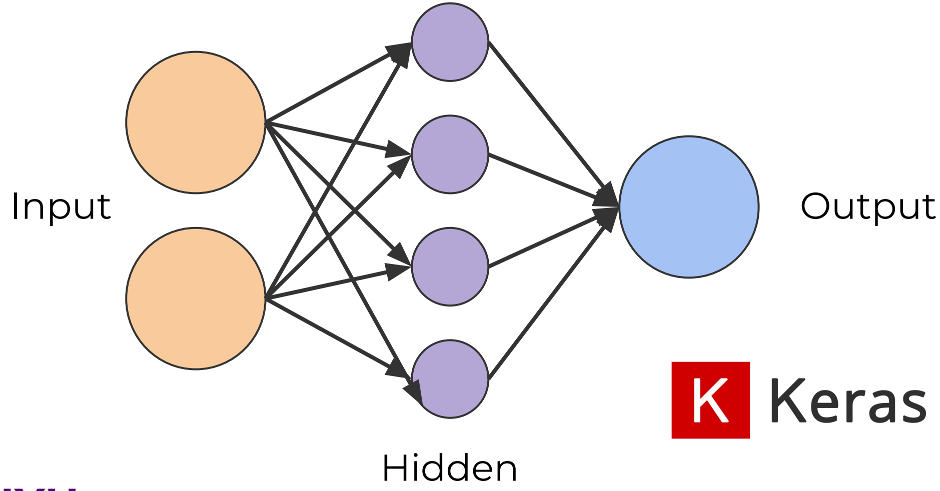

Keras

Our goal is to minimize the
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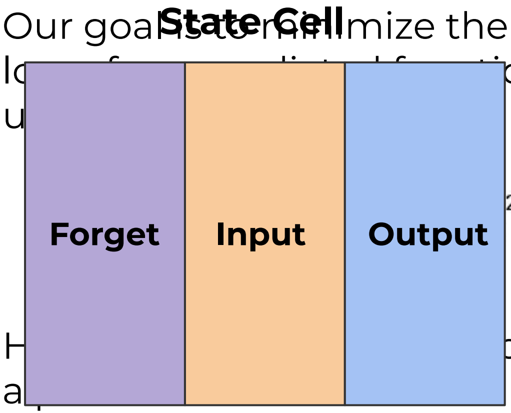
a
"vanishing gradient."



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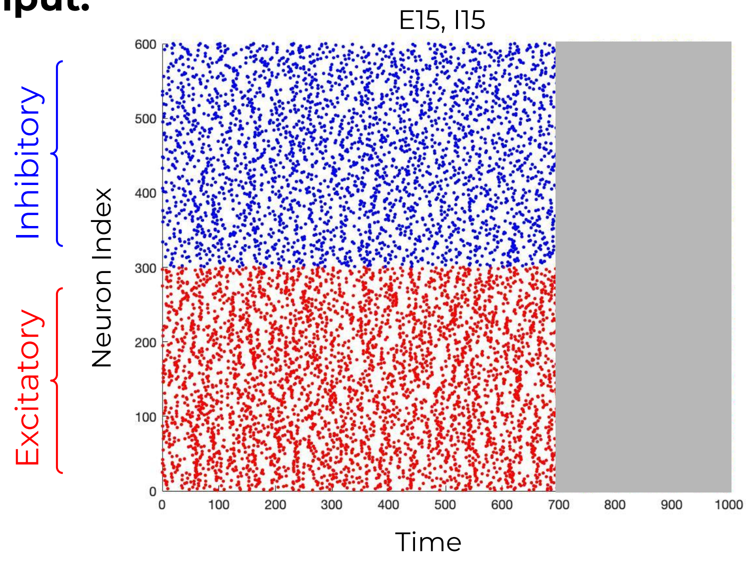
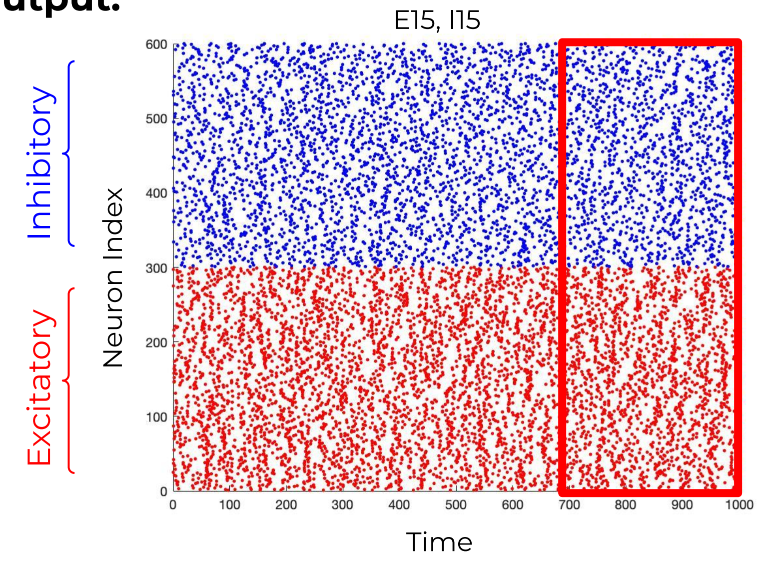
Model Parameters

Input:



Output:



Predictions for Time-Series

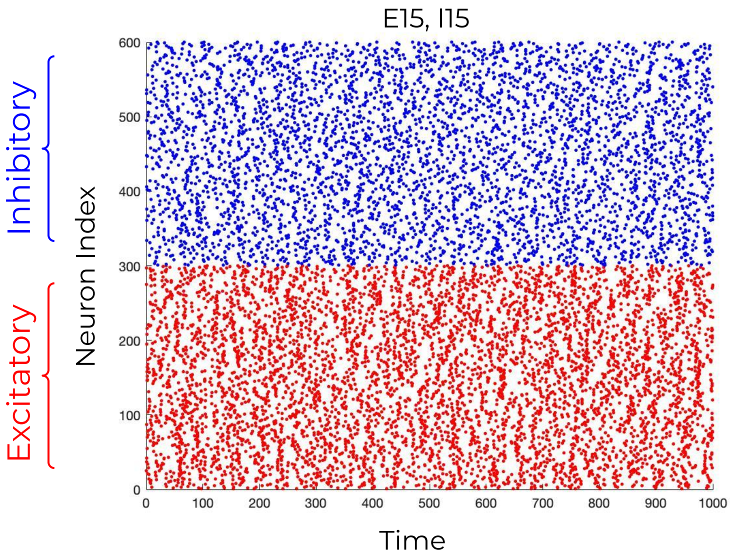
Accuracy over a hundred predictions: **54.7%**

Issues:

- Data is 600-dimensional over 1000 time steps
- Sample Data:

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Revised Model Parameters



Sum of Excitatory Spikes over Time

Sum of Inhibitory Spikes over Time

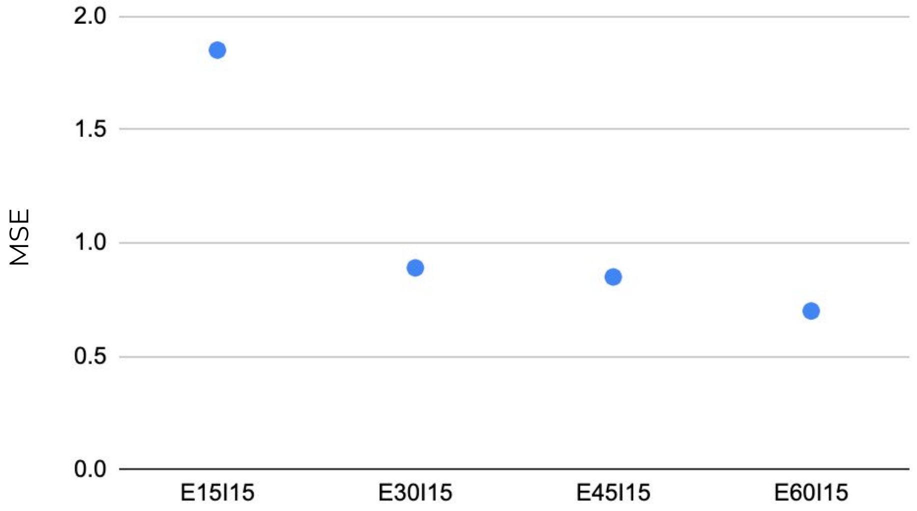
Since our objective is to study MFEs, we can reduce the dimensionality of the model while still being able to observe the synchronicity of the outputs.

Predictions for Time-Series

Error Metric: MSE

$$J(\theta) = \frac{1}{m}\sum_{i=1}^{m}\left(h_\theta\left(x^{(i)}\right) - y^{(i)}\right)^2$$

Average MSE over a hundred predictions: **2.11**



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Conclusions

- Shows promise in determining the intrinsic dynamics of a neural system based off of its excitatory and inhibitory connections
- However, accuracy can be further improved

Future Work

- Factor in external signals inputted into our simulation model
- Create classification machine learning models with input as time series and output as ratio of excitatory and inhibitory connections

References

1. de Vries, S.E.J., Lecoq, J.A., Buice, M.A. et al. A large-scale standardized physiological survey reveals functional organization of the mouse visual cortex. Nat Neurosci 23, 138–151 (2020). https://doi.org/10.1038/s41593-019-0550-9
2. Gerstner, Wulfram, et al. "O Foundations of Neuronal Dynamics." *Neuronal Dynamics from Single Neurons to Networks and Models of Cognition*, Cambridge University Press, Cambridge, 2016.
3. Xiao ZC, Lin KK. Multilevel monte carlo for cortical circuit models. J Comput Neurosci. 2022 Feb;50(1):9-15. doi: 10.1007/s10827-021-00807-3. Epub 2022 Jan 9. PMID: 35000059.

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