Modelling the Action Potential of A Neuron

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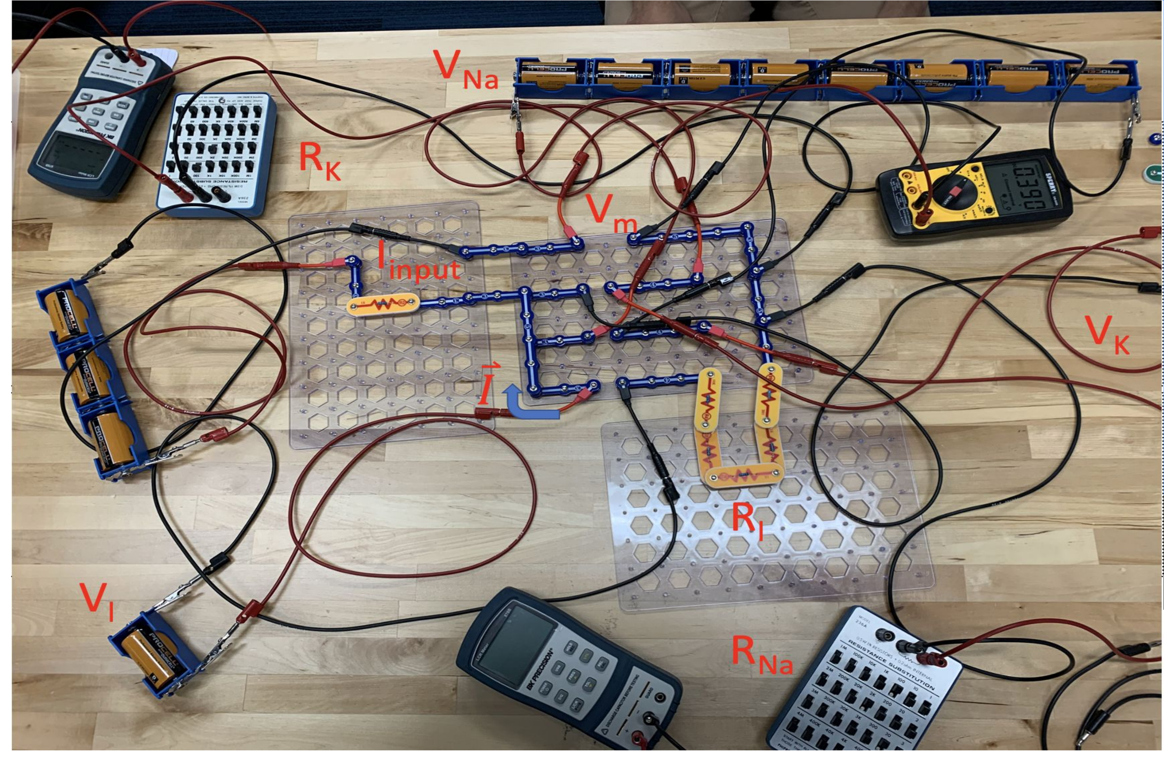


Figure 1. Image of the electrical circuit with Hodgkin-Huxley elements.

Abstract

Neurons form the basis of the nervous system, and rapid changes in voltage induced by chemicals - action potentials, or spikes - are their primary means of interaction. The Hodgkin-Huxley (HH) model describes action potentials as a result of changing conductances of the membrane to potassium (K) and sodium (Na) ions. Here, we replicate the spiking dynamics as described by the HH model for a neuron supplied with an input current, using an electrical circuit employing variable resistors.

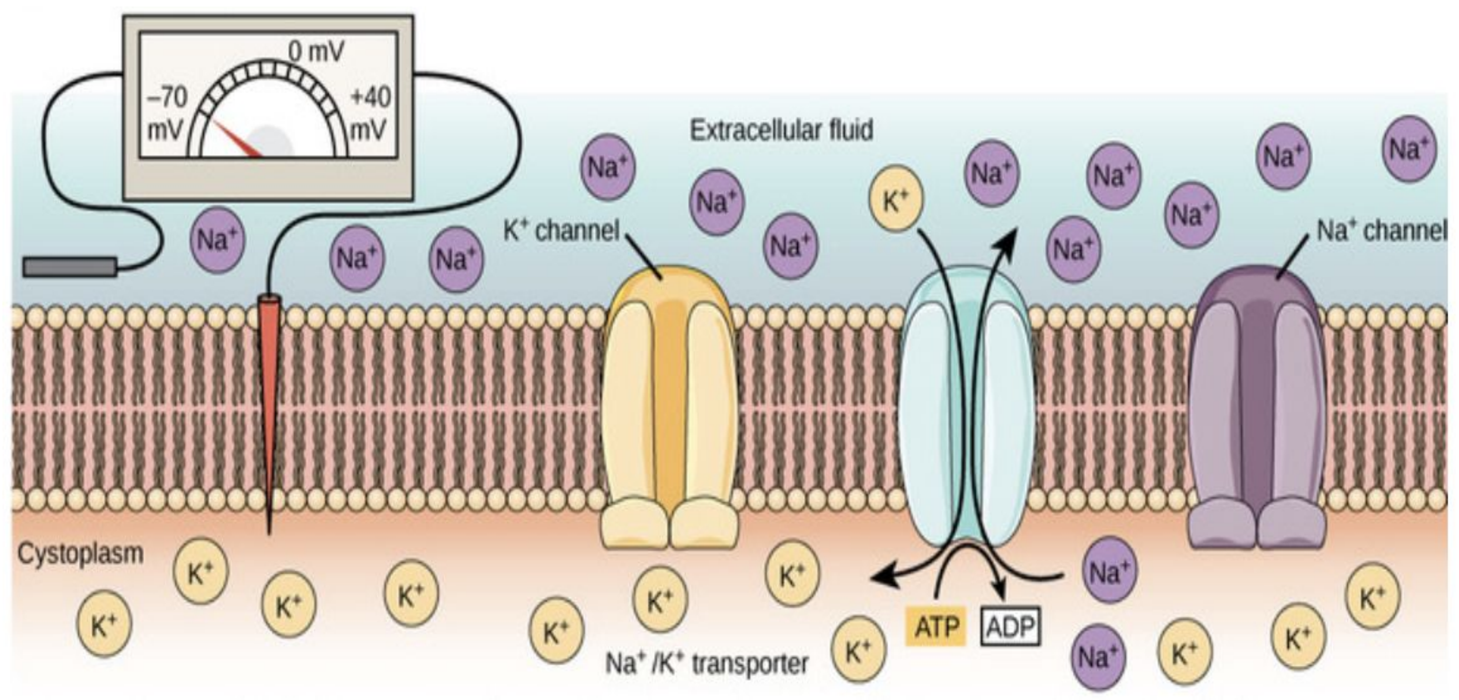


Figure 2. Model of the membrane with ion channels for K+ and Na+.

Purpose

Our experiment's purpose was to replicate the spiking dynamics of biological neuron as described by the HH model with an electrical circuit employing variable resistors to model the variable channel conductance.

Experimental Design

We employed Python to simulate the spiking dynamics of a HH-governed neuron. As the HH model provides the time-varying conductance of the ion channels, we calculated the corresponding time-varying resistance. We then set up our circuit (Figure 1), scaling the voltage and current values appropriately, and employed variable resistors to replicate the time-dependent channel resistance at discrete points in time, measuring the voltage drop. We measured resistance with an LCR meter, and voltage with a DMM.

Theoretical Derivation

The change in voltage across the membrane is defined by the following equation,

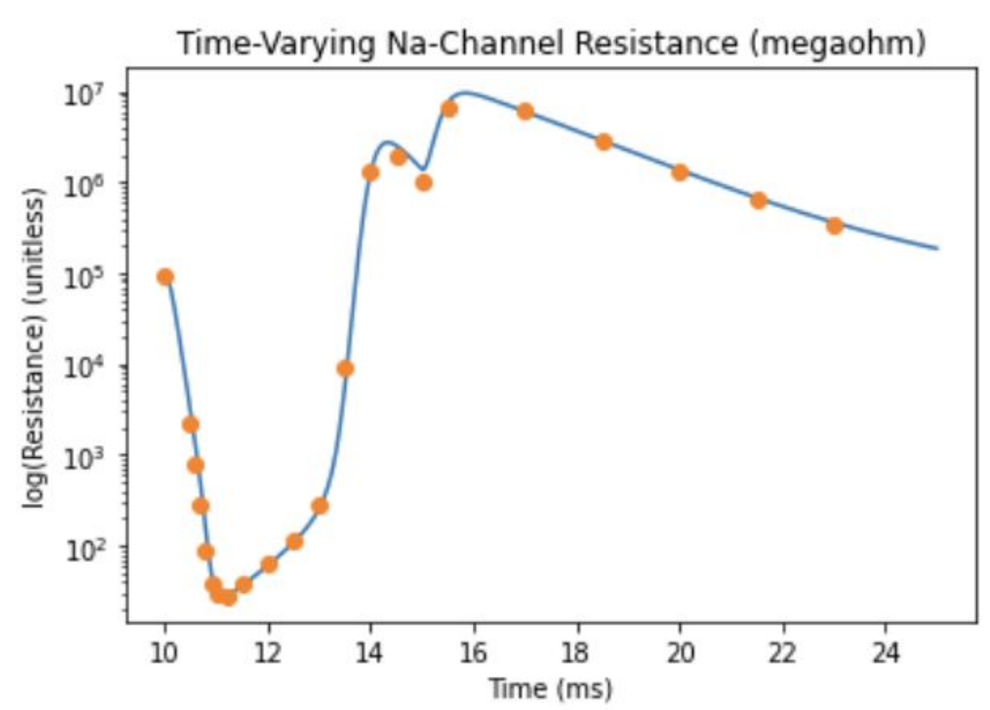
$$C\frac{dV}{dt} = I - g_{k,max}n^4(V - V_k) - g_{Na,max}m^3h(V - V_{Na}) - g_L(V - V_L) \quad \text{(i)}$$

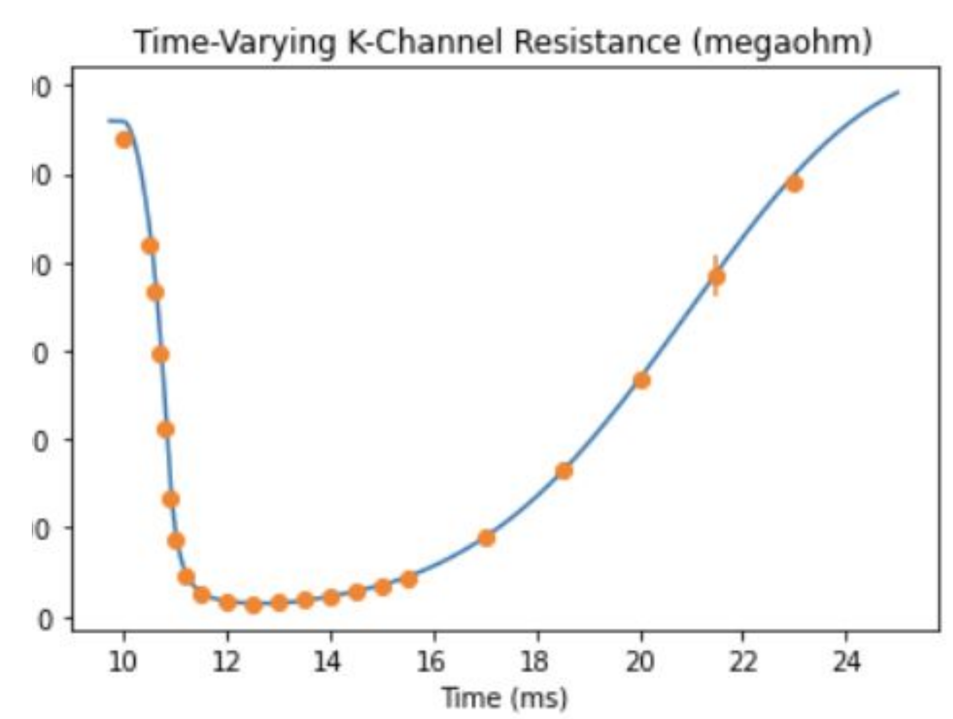
where x = *n, m* and *h* are gating variables controlling the opening of ion channels. They are governed by differential equation of the form (ii),

$$\frac{dx}{dt} = \frac{x_\infty(V) - x}{\tau_x(V)} \quad \text{(ii)} \qquad Resistance, R(x, V(t)) = \frac{1}{Conductance, g} = \frac{1}{g_x \cdot \prod x^i} \quad \text{(iii)}$$

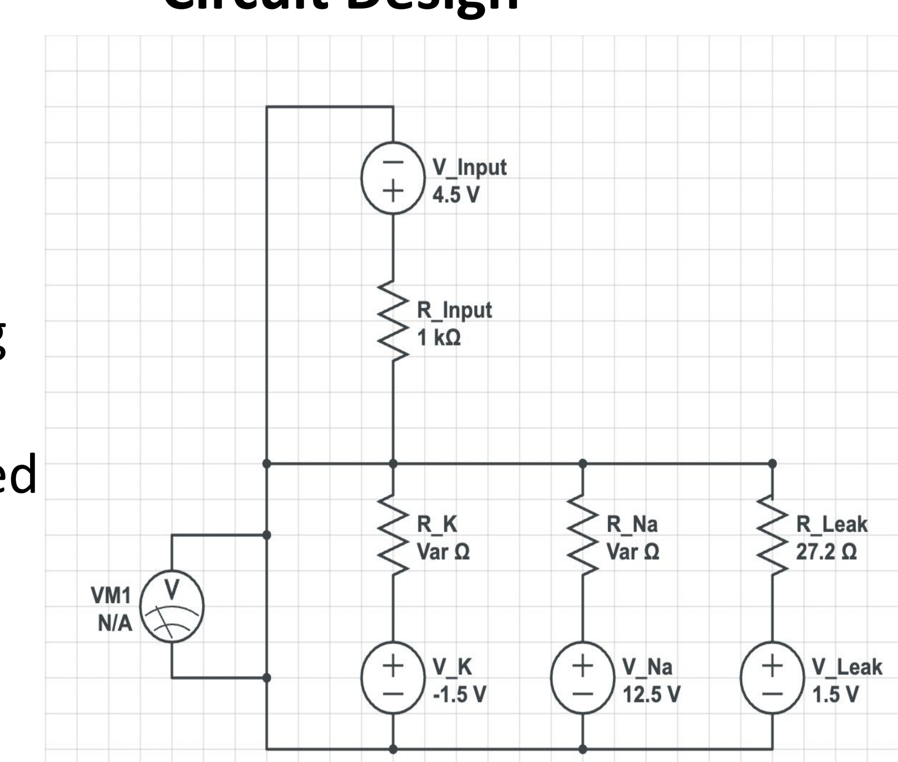
We chose the maximal conductances and reversal potentials V_K = −12mV and g_K= 36 mS/cm^2, V_{Na}= 120mV and g_{Na} = 120 mS/cm^2, V_L = 10 mV and and g_L = 0.3 mS/cm^2 for K, Na and the membrane leak respectively. Our simulation works by numerically integrating the differential equations above to determine *V, n, m* and *h* at all times. We determined the resistance at each time by the relation using Python as shown in (iii).

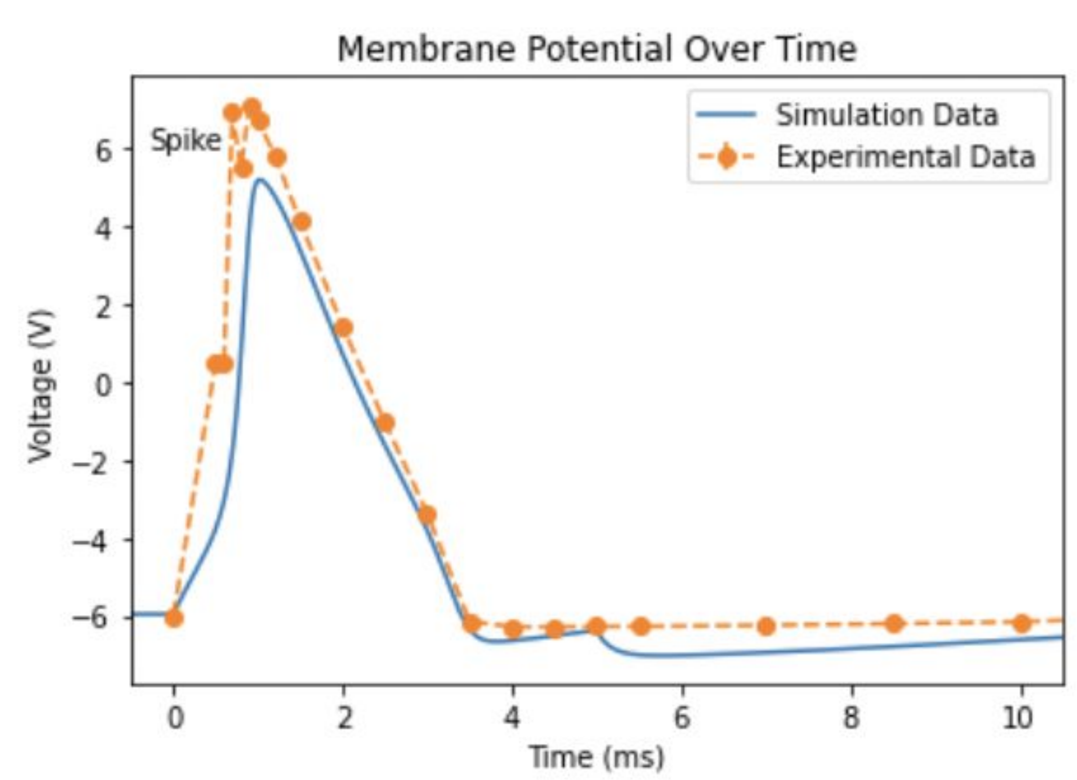
Data Collection And Results





Circuit Design





Uncertainties

Sources of random uncertainty include:

1) Some switches on the resistor didn't work and could have lead to over or under-estimations.
2) Resistance uncertainties could have been propagated to get uncertainty values for time using the model equations.

Sources of systematic uncertainty include:

1) Connections between batteries were poor enough that we had to compress them together to get a proper voltage reading. The degree of compression is something that we did not account for. We also only compressed the Na source, because it had the most batteries connected. So input current may have also been lower than expected, which could have resulted in a systematic.

2) Our simulation values for the ion potentials did not precisely correspond with our experimental values.

Conclusions

- Our circuit mimicked the HH model in its design. Additionally, it precisely captured the spiking *pattern* predicted by it. The sodium and potassium resistances used were highly precise to the theoretically suggested values (see left), confirming the basis for using them. However, this precision is limited by the number of data points we took, especially considering the rapid changes in resistance as demonstrated by our simulation.
- We observed systematic errors with higher-than-expected voltage values near the peak. Our simulation suggests a reason for this to be a higher $V_{Na.}$ This diminishes the accuracy of our set-up in light of the simulation data.
- Possible directions of research could investigate the replication of additional neuron models, such as the integrate-and-fire model, with electronic circuits. Additionally, varying resistance could be made automated to allow for a more precise replication of the model.