

# **Neuron and Nerve Electrical Stimulation Environment Guide**

This guide accompanies the *Neuron and Nerve Electrical Stimulation Environment*, a MATLAB-based interactive tool designed to support learning and exploration of neuron and nerve response to electrical stimulation. The app provides three simulations based on well-established neuroscience principles. This document explains the underlying theory, guides the user through each simulation, and highlights learning objectives.

## **Acronyms:**

AP – Action Potential

CAP – Compound Action Potential

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# 1. Introduction

The Neuron and Nerve Electrical Stimulation Environment is an interactive MATLAB app that helps users explore how action potentials (APs) travel through unmyelinated neurons and nerves. Designed as an educational tool, the app provides a hands-on way to visualise and experiment with the electrical behaviour of neurons. Users can adjust neuron parameters and input stimulus to immediately see how these affect signal propagation and nerve responses.

Whether you're learning about nerve signals or teaching others, this app gives you the tools to:

- Understand how individual neurons generate APs.
- See how APs propagate along an axon.
- Explore how bundles of neurons combine to produce compound action potentials (CAPs).

The app includes three core simulations based on well-established neuroscience principles: APs, CAPs, Hodgkin-Huxley model and Cable Theory.

## 2. Getting Started

This section will guide you through setting up and launching the Neuron and Nerve Electrical Stimulation Environment in MATLAB. The app has been designed to be clear and easy to use, even for those with limited experience in MATLAB.

### 2.1 Software Requirements

To run the app, you will need the following:

- MATLAB R2016b or newer (The app was developed and tested in MATLAB R2023b)
- MATLAB App Designer (Included by default in most MATLAB installations)

OR

- MATLAB Online (<https://uk.mathworks.com/products/matlab-online.html>)

No additional toolboxes are required beyond the standard MATLAB installation.

### 2.2 Running the App

1. Unzip 'Neuron\_and\_Nerve\_Electrical\_Stimulation\_Environment.zip'.
2. Open MATLAB and navigate to the unzipped folder.
3. Right-click the '.mlapp' file and select "Run."

Navigate the app using the tabs located at the top of the window to explore the different simulations described below.

### 3. Simulation Information and Guidance

#### 3.1 Simulation 1: Action Potentials – Single Compartment Hodgkin-Huxley Neuron Model

This simulation uses the Hodgkin-Huxley model, which describes a neuron's electrical characteristics as an electrical circuit (shown in Figure 1). The lipid bilayer is represented as membrane capacitance ( $C_m$ ), and ion channels are represented by voltage-dependent conductances ( $G$ ) for sodium ( $\text{Na}^+$ ) and potassium ( $\text{K}^+$ ). These conductances, controlled by gating variables ( $m$  for  $\text{Na}^+$  activation,  $h$  for  $\text{Na}^+$  inactivation, and  $n$  for  $\text{K}^+$  activation), depend on both voltage and time. Leak channels are modeled as linear conductances ( $G_L$ ), and electrochemical gradients driving ion flow are represented by voltage sources ( $E$ ). The membrane potential ( $V_m$ ) fluctuates due to external stimuli, generating an AP. For further details on the Hodgkin-Huxley model, please refer to section 4.3.

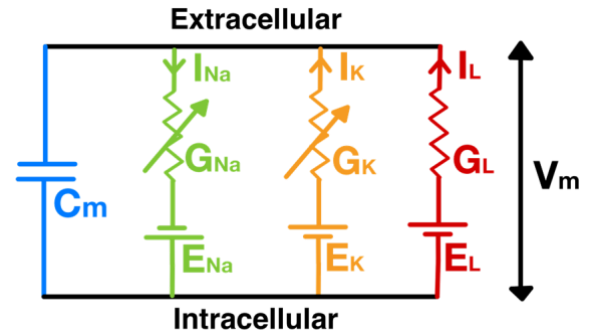


Figure 1 - Hodgkin - Huxley Model Circuit

##### Learning Objectives:

- Understand the form of an AP.
- Explore how ion reversal potentials and conductances influence APs.
- Investigate the role of external electrical stimuli on AP triggering.

##### Things to Try:

- Increase the Amplitude of the 2<sup>nd</sup> stimulus to see the AP firing frequency increase.
- Change the conductances to observe their impact on AP characteristics.
- Decrease potassium reversal potential to increase the hyperpolarization.
- Watch the gating variables ( $n$ ,  $m$ ,  $h$ ) to understand their role in AP generation.

#### 3.2 Simulation 2: Propagated Action Potentials – Multi-Compartment Cable Model

Simulation 2 uses cable theory, which models an axon as a series of connected compartments (as in Figure 2). Each compartment has its own membrane capacitance and ion conductances, and they are linked by axial resistances. When an AP is generated in one compartment, it travels along the axon to adjacent compartments. This model demonstrates the spatial and temporal propagation of APs. For more details on the multi-compartment cable model, refer to section 4.4.

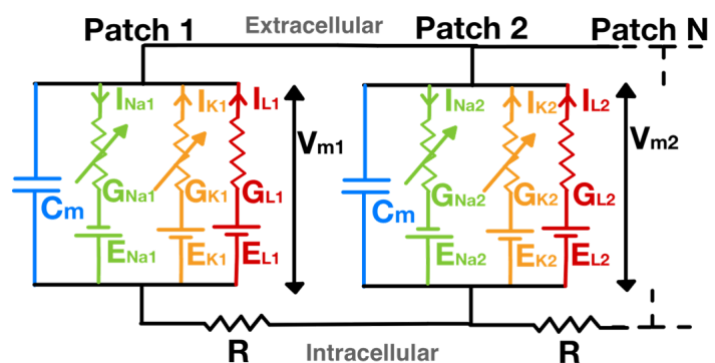


Figure 2 - Hodgkin - Huxley Model Circuit Extended with Cable Theory

### Learning Objectives:

- Understand how APs propagate using cable theory.
- Explore how axon radius, membrane capacitance, axial resistivity affect AP propagation.
- Investigate how the axon's properties and stimulation location influence the AP response.

### Things to Try:

Choose where the stimulus and recording electrodes are placed along the axon, like shown in Figure 3:

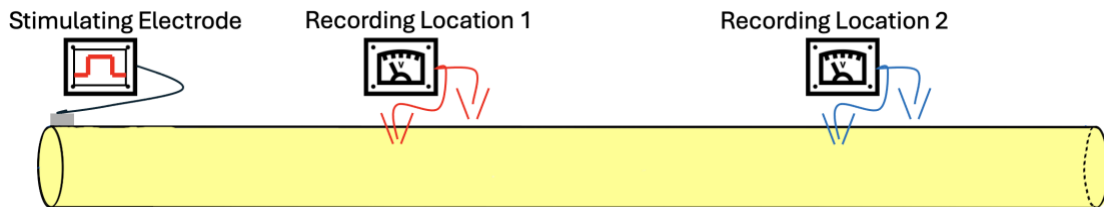


Figure 3 - Stimulation and Recording Locations along an Axon Diagram

- Increase the axon radius to see how it affects AP conduction velocity.
- Use the tabs at the bottom to view the full response across the axon in several formats.
- For example, move the stimulus location to the centre of the axon and select "Full Analysis: 2D" tab to see a symmetric response.

## 3.3 Simulation 3: Compound Action Potentials – Nerve Model (Multiple Unmyelinated Neurons)

Simulation 3 models a nerve as multiple unmyelinated neurons. These are split into three different 'types' each with different properties that determine their conduction velocities. The CAP is formed by the summed APs of the individual neurons. Electrical stimulation activates the neurons, and their APs combine to form the CAP, which can be recorded by electrodes (like shown in Figure 4). The model captures how the variability in conduction velocities between unmyelinated neurons influences the overall nerve response.

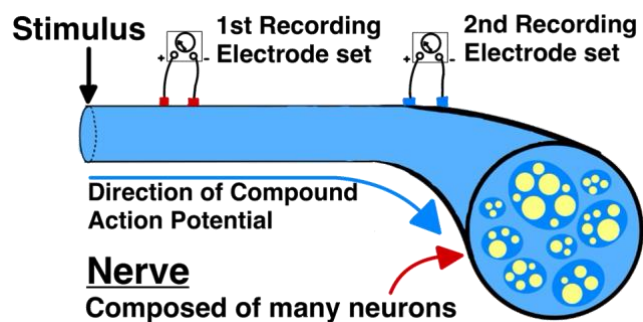


Figure 4 - Simulation 3 Nerve Diagram

### Learning Objectives:

- Understand how individual unmyelinated neurons combine to form a CAP.
- Learn how neuron properties (radius, capacitance, resistivity) affect conduction velocity and CAP characteristics.

### Things to Try:

- Adjust neuron parameters, such as the number of neurons, radius, membrane capacitance, and axial resistivity, to explore how changes in conduction velocity affect the CAP amplitude, shape, and timing.
- Switch between monophasic and biphasic recording types.
- Move the recording locations to see how over the distance of the axon, the CAP peaks diverge due to the difference in conduction velocities.

## 4. Additional Background Theory

### 4.1 Unmyelinated Neuron Physiology

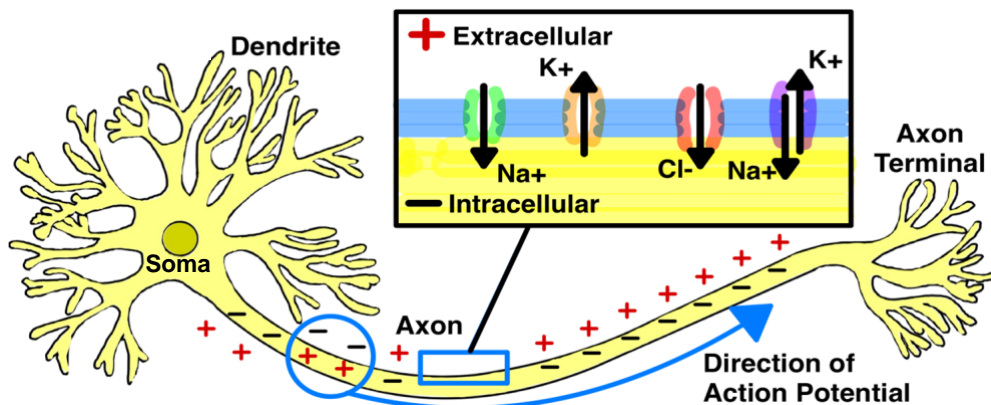


Figure 5 - Neuron Diagram

A typical unmyelinated neuron (Figure 5) consists of the soma, dendrites, axon, and axon terminals. Dendrites receive input from neighbouring neurons via chemical synapses, causing changes in membrane potential. At rest, this potential is negative due to the uneven distribution of  $\text{Na}^+$ ,  $\text{K}^+$  and  $\text{Cl}^-$  ions across the membrane. External stimuli or synaptic input can shift the membrane potential, and if it reaches a threshold, voltage-gated ion channels open. This triggers a rapid influx of  $\text{Na}^+$  ions, depolarizing the membrane and generating an AP. The AP then travels along the axon. In myelinated neurons, it jumps between nodes of Ranvier, allowing faster transmission than the continuous conduction in unmyelinated fibres.

### 4.2 Action Potential

Figure 6 shows the typical membrane voltage response of an AP in a neuron.

1. **Stimulus:** triggers ion channel activity and a change in membrane potential.
2. **Depolarisation:**  $\text{Na}^+$  channels open, allowing  $\text{Na}^+$  to enter and making the membrane more positive.
3. **Repolarisation:**  $\text{Na}^+$  channels close;  $\text{K}^+$  channels open, and  $\text{K}^+$  exits the cell, restoring negativity.
4. **Hyperpolarisation:**  $\text{K}^+$  channels stay open briefly, making the membrane more negative than resting.
5. **Resting state:** Membrane potential returns to baseline, maintained by ion channels and pumps.

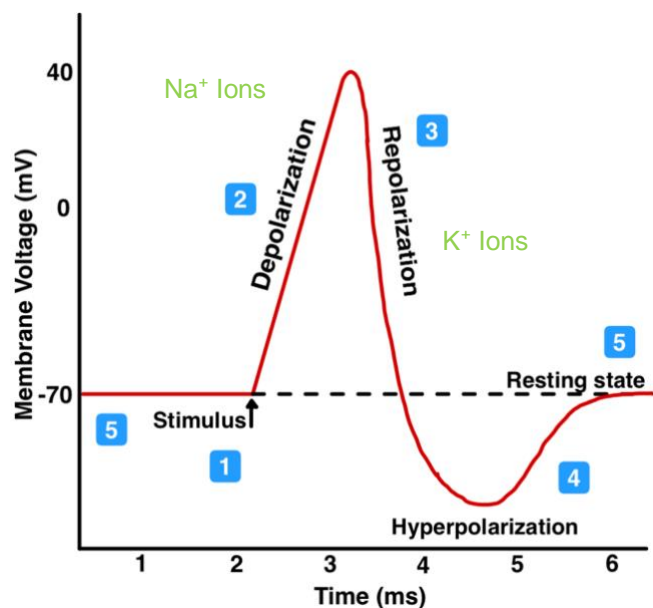


Figure 6 – Action Potential Response

### 4.3 Hodgkin-Huxley Model

The Hodgkin-Huxley model is a mathematical framework that describes how APs are initiated and propagated in neurons. Developed from voltage-clamp experiments on squid axons, it models the neuron membrane as an electrical circuit (as in Figure 1) with capacitive and conductive properties. The model captures the flow of sodium ( $\text{Na}^+$ ), potassium ( $\text{K}^+$ ), and leak currents through ion channels, each controlled by voltage-dependent gating variables [1].

The membrane potential is governed by the following equation:

$$C_m \frac{dV_m}{dt} = I_{\text{stim}} - I_{\text{Na}} - I_{\text{K}} - I_{\text{L}}$$

- $C_m$  is the membrane capacitance,
- $I_{\text{stim}}$  is the external stimulus current density,
- $I_{\text{Na}}$ ,  $I_{\text{K}}$ ,  $I_{\text{L}}$  are the sodium, potassium, and leak currents densities.

Each ionic current density is defined by:

$$I_{\text{Na}} = \bar{g}_{\text{Na}} m^3 h (V_m - E_{\text{Na}}) \quad I_{\text{K}} = \bar{g}_{\text{K}} n^4 (V_m - E_{\text{K}}) \quad I_{\text{L}} = \bar{g}_{\text{L}} (V_m - E_{\text{L}})$$

- $\bar{g}$  terms are maximum conductances,
- $E$  terms are reversal (Nernst) potentials,
- $m, h, n$  are gating variables that control channel opening probabilities.

The gating variables follow these equations:

$$\frac{dm}{dt} = \alpha_m(1 - m) - \beta_m m \quad \frac{dh}{dt} = \alpha_h(1 - h) - \beta_h h \quad \frac{dn}{dt} = \alpha_n(1 - n) - \beta_n n$$

The rate constants  $\alpha$  and  $\beta$  are voltage-dependent functions that determine how quickly the gates respond to changes in  $V_m$ .

Together, these equations reproduce the key dynamics of AP generation, including threshold behaviour, depolarisation, repolarisation, and refractory periods.

### 4.4 Cable Theory

To describe how the AP propagates along the length of an axon, we extend the model by incorporating current flow between neighbouring segments of the axon. As shown in Figure 2, the axon is modelled as a series of 'patches', where current flows through the axial resistance, and ionic currents flow across the membrane. This results in the following equation:

$$C_m \frac{dV_m}{dt} = I_{\text{ax}} + I_{\text{stim}} - I_{\text{Na}} - I_{\text{K}} - I_{\text{L}}$$

Where:

$$I_{\text{ax}} = \frac{a}{2R} \frac{d^2V}{dx^2}$$

Here ' $a$ ' is axon radius and ' $R$ ' is the axon resistivity.

## 5. Credits and Acknowledgments

Developer: Oliver Foley  
Email: [ojf30@bath.ac.uk](mailto:ojf30@bath.ac.uk)

Supervisor: Leen Jabban

### Important Note - Parts of the code are adapted from:

File Name: NumHH.m  
Paper Title: Optimised Architectures and Implementations for Efficient Neuromorphic Hardware Design [2]  
Author: Jonathan G-H-Cater  
Date: 08/04/2016

File Name: stEcab.m  
Book Title: Mathematics for Neuroscientists [3]  
Author: Gabbiani & Cox  
Date: 2017

(References also cited where used in the code)

## 6. References

- [1] A. L. Hodgkin and A. F. Huxley, "A quantitative description of membrane current and its application to conduction and excitation in nerve," *J Physiol*, vol. 117, no. 4, p. 500, Aug. 1952, doi: 10.1113/JPHYSIOL.1952.SP004764.
- [2] Graham-Harper-Cater and Jonathan, "Optimised Architectures and Implementations for Efficient Neuromorphic Hardware Design".
- [3] F. Gabbiani and S. J. Cox, *Mathematics for Neuroscientists: Second Edition*, 2nd Edition. Elsevier Inc., 2017. Accessed: Mar. 27, 2025. [Online]. Available: <http://www.sciencedirect.com:5070/book/9780128018958/mathematics-for-neuroscientists>