Modeling Neurons

George Smith

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Abstract

The purpose of this lab was to build circuits that could successfully model the production of action potentials within axons. The circuits built were based on a set of differential equations called the Fitz-Hugh Nagumo model. By changing key resistor values from the values derived from the model, the expected periodic response was achieved and recorded. Furthermore, the input current was varied in order to study the relationship between the period of the response and the magnitude of the input current. The results matched the theoretical prediction.

1 Introduction

Electronics based on biological systems fit into two broad categories: bio-mimicking and bio-inspired. Bio-inspired circuits are based on concepts from nature, but do not seek to replicate biological phenomena exactly. An example of this would be basing a navigation system on the object-avoidance behavior of insects [1]. The goal of this system would not be to replicate the behavior exactly, rather it would take aspects of insect behavior into account in the design. Bio-mimicking electronics, rather than borrowing ideas from nature, seek to replicate natural biological phenomena exactly. They can be very useful research tools if built to a sufficiently robust level. If one is able to replicate a biological phenomenon using an electronic system, it may be possible to perform extensive tests on the electronic system rather than having to use the biological system that it is modeling.

In this lab, the circuits that were constructed and studied were bio-mimicking circuits. These specific circuits were based on the Fitz-Hugh Nagumo model of a neuron. This model is a set of differential equations that models the production of action potentials within a neuron in response to a weak input current.

A neuron has three main elements: the soma, the axons, and the dendrites. The circuit that I focused on in this lab models behavior within the axon. The axon serves as a conduit for intracellular communication. Information is received by the cell at the synaptic terminal at the end of an axon. That information is then relayed through the axon to other parts of the cell. Information within the axon is communicated via electrical pulses known as action potentials. The cell receives an input through the synapse in the form of a current signal. When this current becomes greater than a certain threshold, an action potential is produced which then propagates down the length of the axon. In the time after the production of an action potential, the value of the threshold current becomes much greater than normal. It then decays to its original value [3]. In this way, a constant current input that is above the base threshold current will produce periodic action potentials. Furthermore, the frequency with which it produces action potentials will increase as the magnitude of the input current increases.

The circuits used in this lab are based on designs provided by the Cornell University electrical and computer engineering department [2]. They were modified as needed.

2 The Circuit

bipolarized transistor

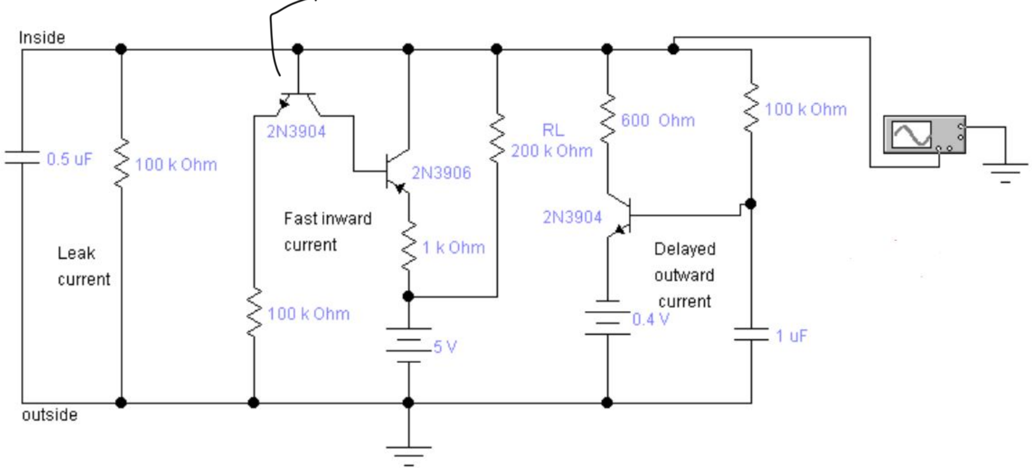


Figure 1: A circuit based on the Fitz-Hugh Nagumo model requiring two voltage sources [2]. When this circuit was implemented, it was found that in order to induce a periodic voltage response, the 100kΩ resistor on the far right of the circuit had to be replaced with a 12kΩ resistor.

1 microF capacitor was also replaced with a 10 microF. See my sticky note comment on the page 4.

The first circuit that was studied in this lab is shown in Figure 1, and is based on the Fitz-Hugh Nagumo Model. In order to construct and modify this circuit, it was first necessary to understand how it works. The circuit was modeled using LTSpice software in order to find its response to the two voltage inputs. The results of this simulation are shown in Figure 2

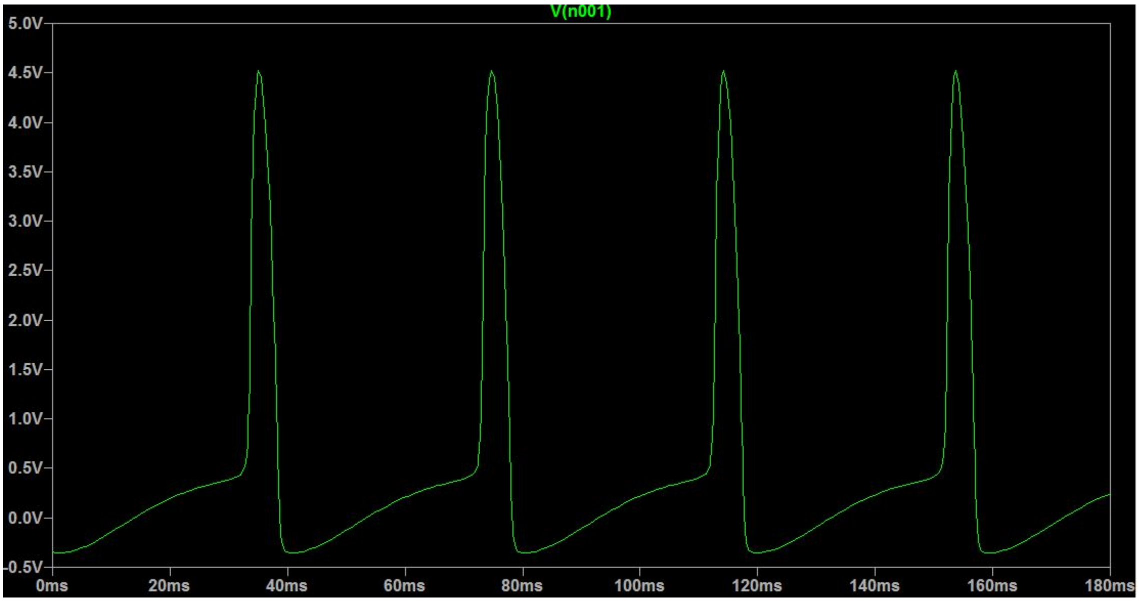


Figure 2: The simulated voltage response of the top node in the circuit featured in Figure 1. The simulation was performed using a software called LTSpice.

As can be observed in Figure 2, the periodic response has three general areas, the long buildup in which the voltage rises to approximately 0.5V, the first half of the spike in which the voltage rises to approximately 4.5V, and the second half of the spike in which the voltage falls from 4.5V to approximately -0.5V. These three parts of the response correspond to different parts of the circuit being studied.

The 5V voltage source provides an input current through the 200kΩ resistor that is labeled RL in the diagram. This input current charges the 0.5μF capacitor. As it does so, the voltage at the top node increases. The charging of this capacitor corresponds to the first part of the response in which the voltage at the top nod gradually increases to approximately 0.5V. When the voltage becomes sufficiently high, current is able to flow from the base of the 2N3904 transistor in the middle section of the circuit to its emitter. This base current draws current from the collector as well. As can be seen in the diagram, drawing current from the collector of the 2N3904 transistor also draws current from the base of the adjacent 2N3906 transistor. Doing this "opens" the 2N3906 transistor, allowing current to flow from the emitter to the collector. This current draws from the 5V source through a 1kΩ resistor, producing a much larger current than was previously being supplied by the 5V source through RL. This large increase in current rapidly increases the voltage at the top node of the circuit, corresponding to the first half of the spike in the response. This large current source then begins to charge the 1μF capacitor in the right-most section of the circuit. Charging this capacitor increases the voltage at the base of the adjacent 2N3904 transistor. Once this voltage is high enough, this third transistor opens, allowing current to flow through a 600Ω resistor to a voltage that is 0.4V lower than ground. This rapid flow of current through the transistor represents the second half of the spike in the periodic response in which the voltage at the top node rapidly decreases down to -0.5V.

In practice, implementing the circuit as it is presented in Figure 1, does not produce the periodic response predicted by the simulation. Rather, it produced a constant voltage at the top node. It was found that choosing a smaller value for the right-most 100kΩ resistor that is in series with the 1μF capacitor causes the circuit to produce the predicted periodic response. It is hypothesized that the reason that the circuit was not working in its original configuration was that the 100kΩ resistor was overly constricting the current entering the base of the transistor, which in turn, was limiting the collector current. This could potentially lead to a situation in which the top node reaches an equilibrium voltage. Switching the 100kΩ resistor that controls the base current for a much smaller resistor greatly increased the current entering the base of the transistor, which greatly increased the allowed collector current, allowing current to flow out of the top node much more quickly, which corresponded to the predicted rapid drop in voltage.

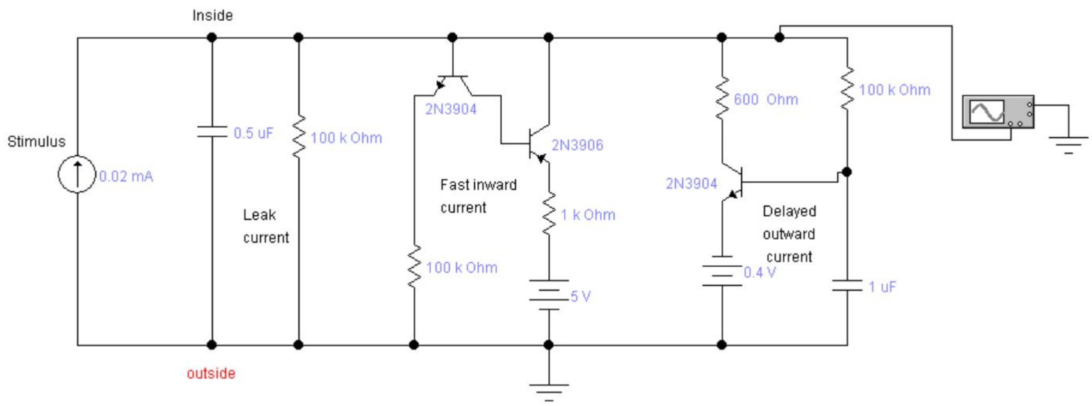
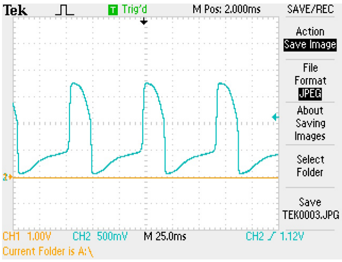


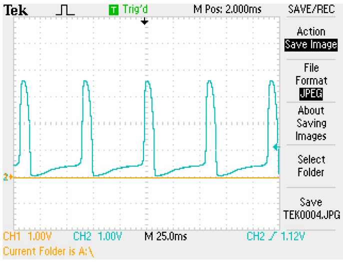
Figure 3: A variant of the circuit shown in Figure 1 [2]. As with the previous circuit, in order to induce a periodic response, it was necessary to exchange the 100kΩ resistor on the far right of the circuit with a 12kΩ resistor. Furthermore, in order to implement the current source, a voltage source was used in series with an 8.2kΩ resistor. This resistor value was chosen in order to provide a range of values for the input current that would allow for a full exploration of the dependence of the response period on the magnitude of the input current.

A variant of the first circuit, shown in Figure 3, was also constructed. This circuit has the same basic properties, except rather than supplying the input current from the 5V voltage source, a separate current source is provided. Despite these changes, the response is expected to be very similar to that of the first circuit in both shape and frequency. Due to a lack of pure current sources available in the lab, a voltage source in series with an 8.2kΩ resistor was used. This method has the drawback that it is not a perfect current source. Varying the applied voltage does indeed vary the applied current, but it also varies the voltage at the top node of the circuit in unexpected ways.

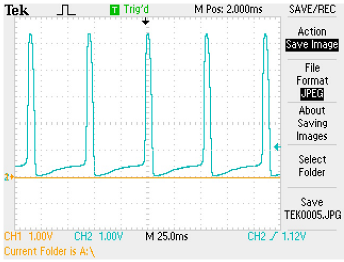
The results of varying the input voltages for both circuits are presented in Figures 4 and 5.



(a) 2000mV

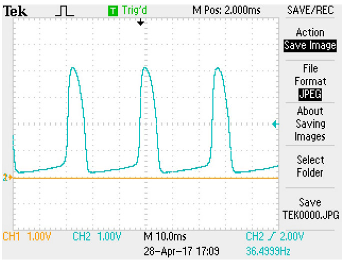


(b) 4000mV

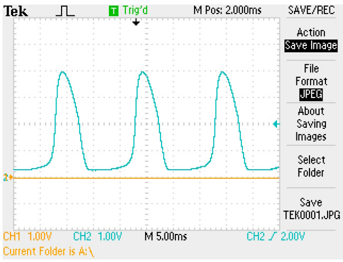


(c) 6000mV

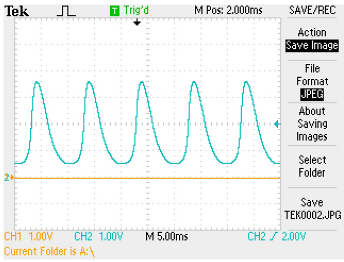
Figure 4: Response of the circuit in Figure 1 to various input voltage magnitudes. In this case the input voltage that was being varied was the one that is labeled 5V in the original diagram



(a) 500mV



(b) 1600mV



(c) 4000mV

Figure 5: Response of the circuit in Figure 3 to various input voltage magnitudes. In this case, the voltage being varied was the one placed in series with an 8.2kΩ resistor to create a current source.

To vary the input voltage of the first circuit, the magnitude of the larger of the two voltage sources was varied. Using this method meant also varying the magnitude of the large input current responsible for the voltage spike, so the results represent a deviation from the original circuit design. Another key difference exists between the implementation of the two circuits. The first circuit only has two inputs. To implement this, a two-output function generator was used to produce two constant voltage outputs. The second circuit required three voltage sources. To implement this, a function generator was used to provide the current source, while a purely DC power supply was used to provide the other two voltage sources. Due to a phenomenon that is not fully understood, the use of the DC power supply caused the circuit response to change significantly. There were still defined spikes, but the period before the spike was shaped differently as can be seen in Figure 5. Rather than rising quickly then beginning to level off right before the spike as predicted by the simulation, the buildup to the spikes produced by the second circuit grew gradually until the spike without any sign of beginning to level off. It is unclear why this phenomenon occurs, although when the first circuit was implemented using voltage sources supplied by the DC power supply, it exhibited similar behavior. Therefore, it can be concluded that this effect is likely due to the use of the DC power supply.

2.1 Frequency of Response

The circuit presented in Figure 3 was implemented using a voltage source in series with an 8.2kΩ resistor. In order to vary the input current, the magnitude of the voltage source was varied. As was discussed in the introduction, in an axon, with a constant applied current source, the frequency of action potentials increases with the magnitude of the applied current. In order to find the relationship between the two factors, the input voltage was varied from 360mV to 6V, and the period of the response was recorded. The results of this are found in Figure 6

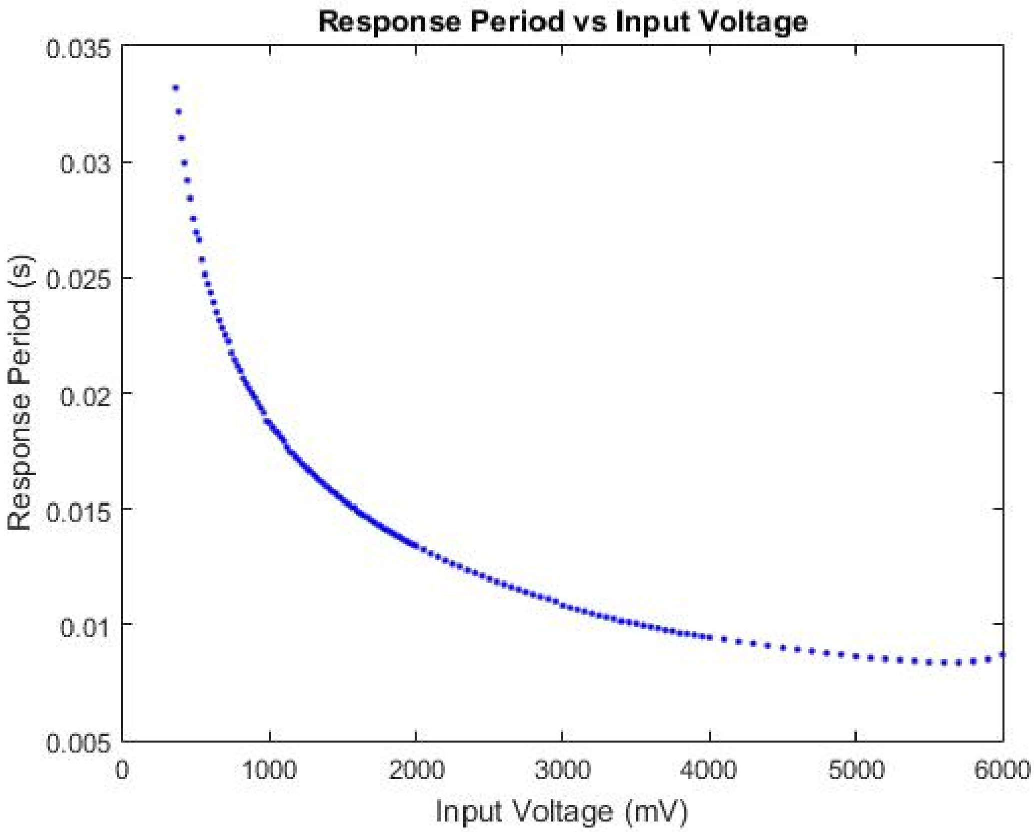


Figure 6: The relationship between the response period of the circuit featured in figure 3 and the applied input voltage. Varying the input voltage served as a way of varying the input stimulus current.

As expected, the period of the response decreases as the magnitude of the applied voltage increases. An attempt was made to fit a mathematical model based on an exponential decay function to the data, however, no meaningful correlation was found. `I guess it is the result of using non ideal current source.`

3 Future Work/Improvements

Much of my time doing this lab was spent working with the circuit in Figure 1, and trying to achieve the predicted periodic response. If I had found the solution earlier, I would have had much more time to work with the circuit and explore the extent to which it successfully models its corresponding biological system.

An obvious future improvement to this lab is to devise a way to measure the actual input current to the circuit in Figure 3 rather than just measuring the input voltage. This could provide a more nuanced understanding of the relationship described by Figure 6.

There are also many more models of neurons other than the Fitz-Hugh Nagumo model [2], and many of these models can be implemented with electronic circuits. Furthermore, with the proper time and resources, it is possible to build a network of the circuits built in this lab in order to model more complex neural phenomena. However, debugging the circuits presented in this report was a difficult task, and doing so with more complicated circuits may prove to be very difficult and time consuming.

References

[1] Luo, Junwen. Digital neural circuits: from ions to networks. Thesis. Newcastle University, 2015. N.p.: n.p., n.d. Print.

[2] "Analog and Digital Hardware Neural Models." Model Neurons. Cornell Electrical and Computer Engineering, n.d. Web. 03 May 2017. <https://people.ece.cornell.edu/land/PROJECTS/NeuralModels/>.

[3] Levitan, Irwin B., and Leonard K. Kaczmarek. The neuron: cell and molecular biology. New York: Oxford U Press, 1997. Print.