

Implementation of Neuron Models Using MATLAB; an Introduction to Brain-Inspired Artificial Intelligence

Eshita Afrin, Dr. Md. Shahjahan Ali

Abstract— This paper aims at understanding a different route to Artificial Intelligence (AI), i.e. Brain –Inspired AI based on deep learning movement which involves building artificial neural networks, which mimic the behavior of the human brain. Artificial neurons are the building blocks of artificial neural network. To fulfill this goal the paper starts with building a mathematical Model of a single neuron by making analogy between biological and electrical components. Then the analogous electrical circuit is expressed in terms of differential equation and simulated using MATLAB to study various characteristics. Then one of the simplest single neuron model, the Integrate and Fire model is discussed and simulated. Various affords were made to make the model more realistic. Finally, the Hodgkin and Huxley model which very closely approximate a real biological neuron is discussed and simulated using MATLAB. The results shows that step by step the single neurons models closely approximate the behavior of the biological neuron which is the building block of artificial neural network.

Index Terms— Artificial Intelligence, Artificial Neuron, IF model, HH model, Differential equation, MATLAB.

I. INTRODUCTION

The science and engineering of making intelligent machines, that mimics the way humans think, feel, move and make decisions is called Artificial Intelligence (AI)[1]. In the early days, AI engineers believed that, they would have to build and combine thousands of individual computing algorithm. One algorithm, would mimic language, another would mimic speech and so on. But there's a theory that human intelligence stems from a single algorithm which arises from experiments suggesting that the portion of the brain which process sound from ears can also handle sight for eyes, which is possible only when brain is in the earliest stage of development. In this way brain can be thought of at its core a general-purpose machine that can be tuned to specific tasks. These leads a new field of AI research known as Deep Learning, which involves building neural networks, that mimic the behavior of the human brain. Artificial neurons are the building blocks of artificial neural network. This movement seeks to meld AI with neuroscience. [2] The scientific study of the nervous system is known as Neuroscience., Neuroscience was thought of as a branch of

Eshita Afrin, Dept. of Applied Physics, Electronics & Communication Engineering, Islamic University, Kushtia-7003, Bangladesh.

Md. Dr. Shahjahan Ali, Professor, Dept. of Applied Physics, Electronics & Communication Engineering, Islamic University, Kushtia-7003, Bangladesh.

biology, traditionally. Currently however, it is an interdisciplinary science that collaborates with other fields such as, computer science, engineering, linguistics, mathematics, medicine, chemistry, philosophy, physics, and psychology. Inclusion of different approaches used to study the molecular, cellular, developmental, structural, functional, evolutionary, computational, and medical aspects of the nervous system has broadened the scope of neuroscience.[3]

II. NEURON

The basic building blocks of the nervous system are Neurons. These specialized cells are known as the information processing units of the brain, as they receives processes and transmits information. There are three main structures in a typical neuron-

- The cell body –it directs all activities of the neuron,
- Dendrites –it extend out from the cell body and receive messages from other neurons, and
- Axon -a long single fiber ,it transmits messages from the cell body to the dendrites of other neurons or to other body tissues.

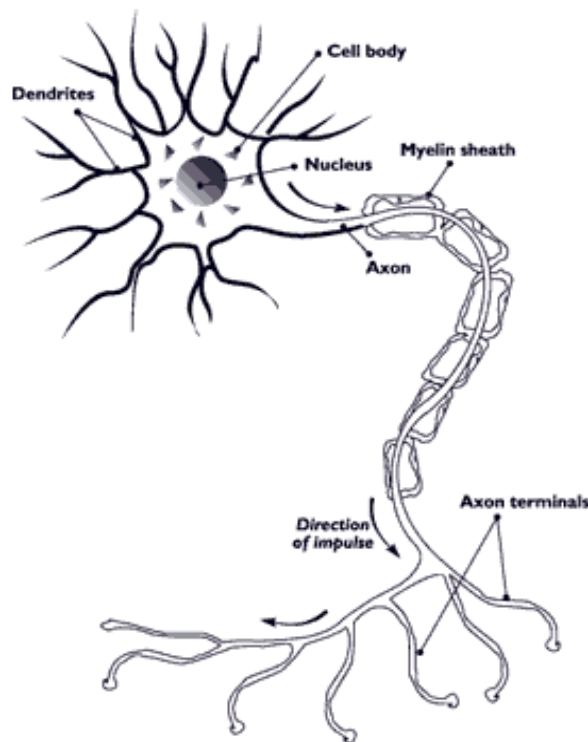


Fig.1 Structure of a typical neuron .

III. NEURAL SIGNALING

An electrochemical signal known as action potential (AP) is through which the neurons communicate.[4]The difference in concentration of ions between the inside and outside of the membrane.is the cause of AP. The Na^+ and K^+ are the dominating ions . Without any externally applied stimulus the equilibrium membrane potential is -70mV which is known as the resting membrane potential.The membrane is composed of lipid bilayer which is impermeable to any charged particle and protein pore only through which ions can pass. This pores are called ion channels which are guarded by special molecules called gatekeepers which open and close depending on certain conditions.

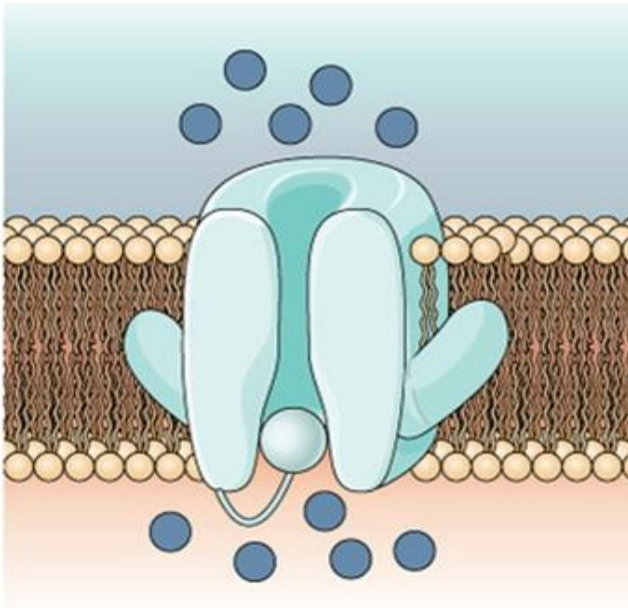


Fig. 2 Small section of the biological neuron membrane.

There are different ion channels for different types of ions. A stimulus from a sensory cell or another neuron depolarizes the target neuron to its threshold potential (-55mV), and Na^+ channels in the axon hillock open, starting an action potential. Once the sodium channels open, the neuron completely depolarizes to a membrane potential of about $+40\text{mV}$. The action potential travels down the neuron as Na^+ channels open. As soon as depolarization is complete, the cell "resets" its membrane voltage back to the resting potential. The Na^+ channels close, beginning the neuron's refractory period. At the same time, voltage-gated K^+ channels open, allowing K^+ to leave the cell. As K^+ ions leave the cell, the membrane potential once again becomes negative. The diffusion of K^+ out of the cell hyperpolarizes the cell, making the membrane potential more negative than the cell's normal resting potential. At this point, the sodium channels return to their resting state, ready to open again if the membrane potential again exceeds the threshold potential. Eventually, the extra K^+ ions diffuse out of the cell through the potassium leakage channels, bringing the cell from its hyperpolarized state back to its resting membrane potential.[5] This sequence of events occurs in a local area of the membrane,but these changes get passed on to the next area of membrane, then to the next area, and so on to the entire length of the axon. Thus, the action potential gets transmitted down the nerve cell.[6]

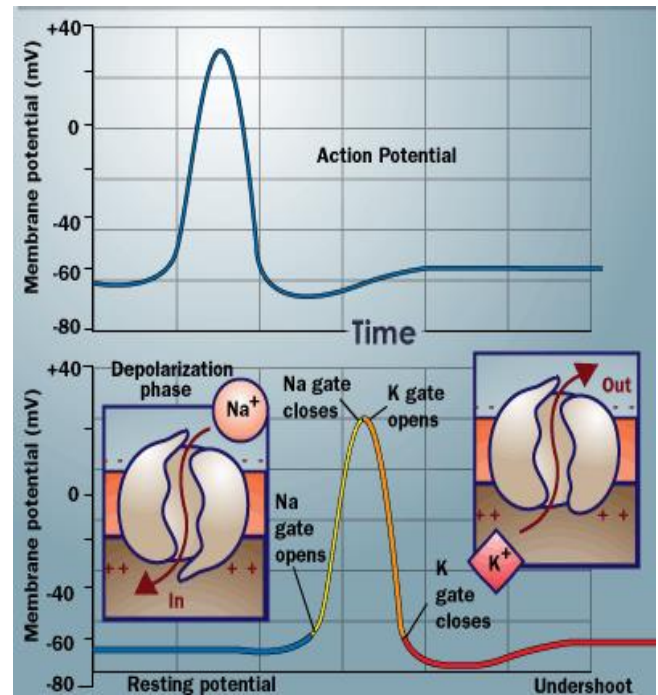


Fig. 3 An action potential with its different states caused by the sodium and potassium channels' kinetics.

Both excitatory and inhibitory inputs from multiple neurons can be received in a single neuron and added together at the axon hillock. The neuron will fire, If the EPSPs are strong enough to overcome the IPSPs and reach the threshold of excitation.[5]

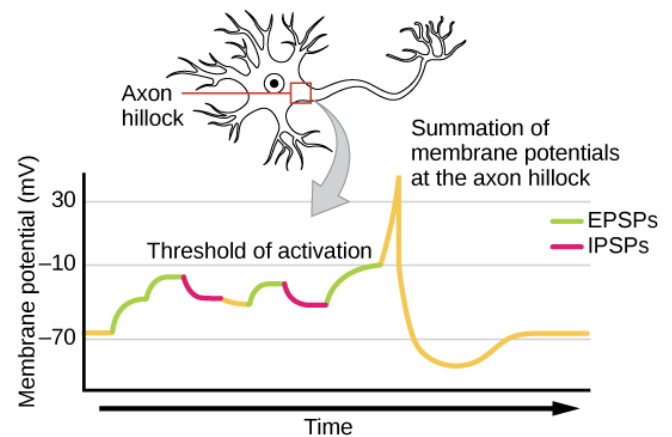


Fig. 4 Signal summation at the axon hillock.

Like FM radio, information is encoded by the frequency of action potentials. A low frequency train of a few action potentials will be initiated by a small stimulus. The frequency of action potentials increases as the intensity of the stimulus increases.[6]

IV. ELECTRICAL ANALOGY OF THE BIOLOGICAL NEURON

We can make an electrical analogy of the biological neuronal membrane by representing the lipid bilayer which are impermeable to charged particles as the capacitor(C), the protein pores which allows passage of charge through them as the resistors (R,reciprocal of conductors) and the synaptic

input as the current injection (I_{in}). Now if we insert an electrode through the membrane and then inject current into the inside of the cell, this current will pass out of the cell through the resistor or the capacitor (through the pores or via the capacitance). Once the current reaches the outside of the cell it will disperse to the rest of the body and the surrounding world. In the diagram this is represented by the ground symbol. Now according to the Kirchoff's law this can be mathematically expressed as:

$$I_{in} = I_C + I_R \quad (1)$$

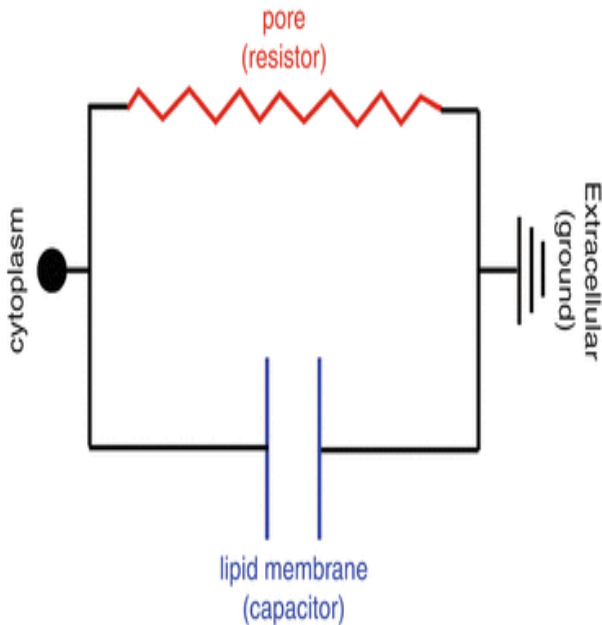


Fig. 5 RC circuit analogy of the biological neuron membrane. I_{in} is a known number, I_C and I_R can be re-expressed using the current-voltage equations for capacitance and resistance. Therefore:

$$I_{in} = C.\Delta V/\Delta t + g.V \quad (2)$$

Setting Δt to an infinitesimal value, this equation is called a differential equation, which can be solved using a numerical integration, getting very close to the analytical solution by making Δt very small. By using finite numbers and finite time steps, a discrete approximation to the differential equation can be created. By setting $\Delta t = 1 \mu s = 0.001 \text{ ms} = 1 \cdot 10^{-6} \text{ s}$. ΔV can be expanded out as a difference: $V^+ - V$. Substituting for ΔV leaves us with:

$$I_{in} = C.(V^+ - V)/\Delta t + g.V$$

$$I_{in} = V^+ (C/\Delta t) + V (C/\Delta t) + g.V$$

$$V^+ = (1 - \Delta t .g/C) V + \Delta t(I_{in}/C) \quad (3)$$

This is an update equation. The voltage (V^+) is updated at each time step based on the previous voltage V . At the same time, time, t , is updated by simply adding Δt : $t^+ = t + \Delta t$. The new voltage then becomes the V and the new time the t for the next update step.

By setting $g = 1 \text{ ms/cm}^2$ and $C = 1 \mu\text{F/cm}^2$ Using the chosen values, $g/C = 1/\text{ms}$. Similarly, we will set the injected current to $1 \mu\text{A/cm}^2$ so that $I_{in}/C = 1 \text{ mV/ms}$. We'll set $\Delta t = 0.001 \text{ ms}$. With these convenient choices, the update equation is:

$$V^+ = (1 - 0.001) V + 0.001 \quad (4)$$

At every step, V^+ will be updated according to this rule and t^+ will be updated by Δt . So the update for the full simulation requires equations for updating both t and V :

$$t = t + 0.001 \quad (5)$$

$$V = 0.999.V + 0.001 \quad (6)$$

Now we can construct MATLAB code for this model and simulate (to) observe various characteristics

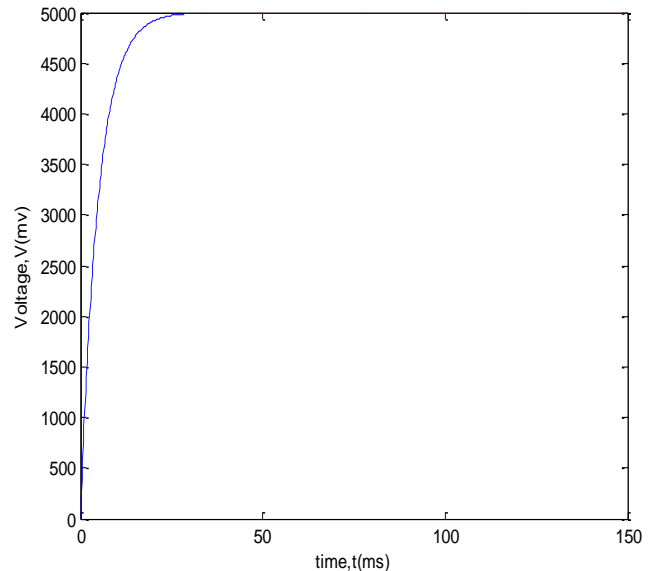


Fig. 6 Plot of membrane potential vs. time for constant current input. $I = 10 \text{ nA}$, $C = 0.1 \text{ nF}$, $R = 100 \text{ M-ohms}$, Time constant, $RC = 10 \text{ ms}$.

Now if we change the value of R and C and run simulations we observe that the membrane potential reaches a stable value slowly as we increase only R and quickly as we reduce the value of C only. When we change these together the membrane potential reaches a stable value quicker than the initial condition. We can also calculate the value of time constant t_{memb} that is the time needed for the membrane potential to reach 63% of its final value which is given by $t_{memb} = g/C = RC$. Time constant is a measure of the "stickiness" of the update equation dependent on how close the coefficient for voltage is to 1. A bigger C/g (bigger RC) will make the coefficient closer to 1 causing the voltage to rise slower.[7]

Now as we have made an electrical analogy of the neuron membrane we can implement various mathematical neuron model using MATLAB. A number of single neuron models are available since the early twentieth century.

V. THE INTEGRATE AND FIRE MODEL (IF)

One of the earliest single neuron model proposed by Louis Lapicque in 1907, is the Integrate and Fire model. This is one of the most popular single neuron models that still widely used today due to its simplicity. In the equivalent circuit membrane capacitance C and membrane resistance R . V is the membrane potential, V_{rest} is the resting membrane potential, and I is the injected current.

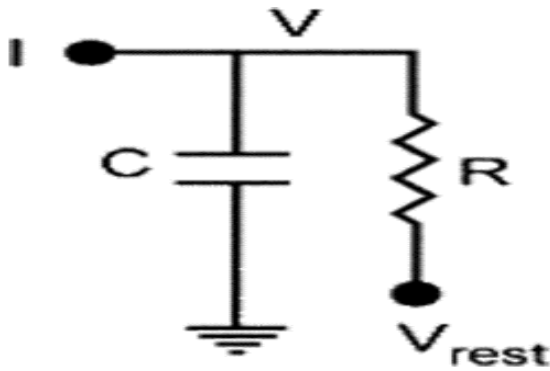


Fig.7 The equivalent circuit of IF model.

This can be mathematically expressed as-
 if $V(t) \geq V_{th}$ and $\frac{dV}{dt}(t) > 0 \rightarrow \hat{t} = t$ (7)

Where \hat{t} is called the firing time of the neuron and V_{th} is the threshold voltage.[4]

This model implies that the neuron fires only when the membrane potential $V(t)$ reaches a certain value called the threshold potential V_{th} . Now we can simulate the model using MATLAB and obtain the following results by varying input current from vary small to large values.

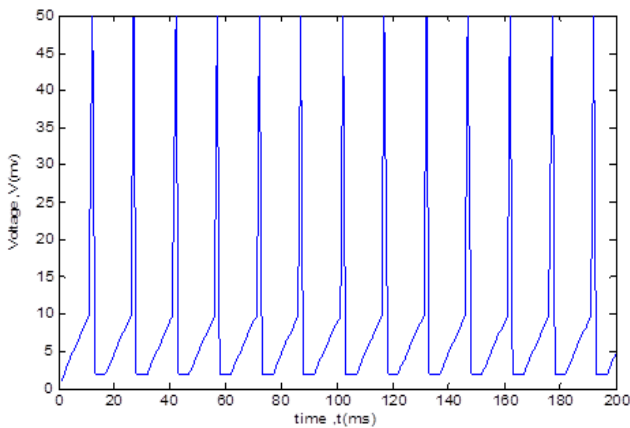


Fig.8 An integrate-and-fire model neuron driven by input current $I=1nA$ and the threshold voltage $V_{th}=10mv$, i.e; the neuron only fires when the membrane potential exceeds 10mv.

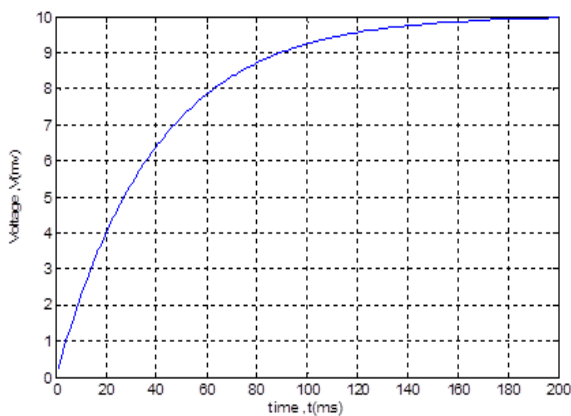


Fig. 9 When $I=2.51nA$ the membrane potential $V=10mv$ which is just equal to the threshold ,thus the neuron does not fire.

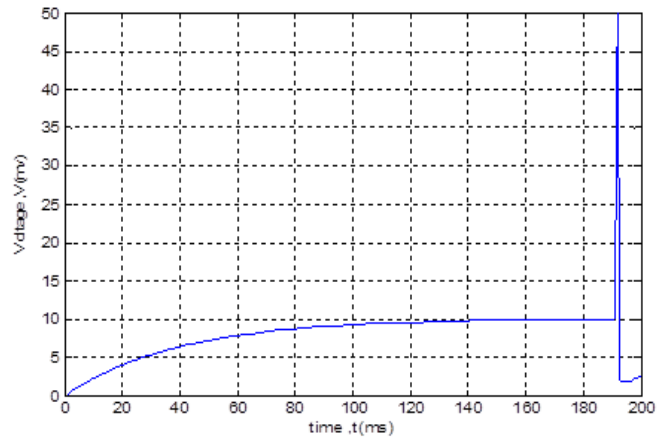


Fig.10 When $I=2.52nA$, the membrane potential is slightly more positive than the threshold and the neuron fires..The action potential reaches the peak amplitude which is 50mv in this case and then hyperpolarizes to 3mv. The firing frequency is 5.10Hz.

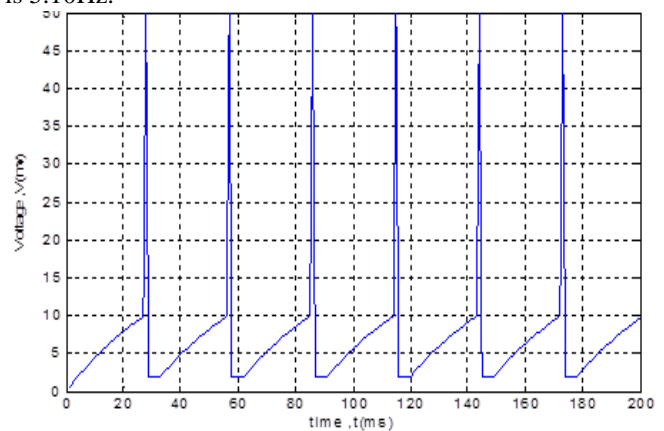


Fig. 11 When the input current I is further increased ,i.e, $I=5nA$ firing frequency further increased which is 31.25Hz now. The firing frequency keep increasing with input current and finally become fixed at 220Hz. When input current $I=10.1nA$. After that inspite of increasing the input current firing frequency does not increase. This is the maximum firing frequency of the neuron.

From the above simulations we observe that when the input current is increased from very low value the membrane potential starts increasing but the neuron does not fire until the membrane potential exceeds the threshold potential. As we further increase the input current the firing frequency increases until the maximum frequency is achieved. When the maximum firing frequency is reached the frequency does not increase in spite of increasing the input current. But the firing frequency can be further increased if we increase the absolute refractory period i.e, is the interval during which a second action potential absolutely cannot be initiated, no matter how large a stimulus is applied.[8] Biological spike trains look noisy. Noise interferes with frequency estimation. Thus it is necessary to smooth out the noise by signal averaging. This spiking irregularity may actually be some kind of uninterrupted signal that is being used by neurons in their calculations. This speculation is the province of an entirely different class of models (e.g., synchronization models). Following simulation shows integrate and fire model with noise.

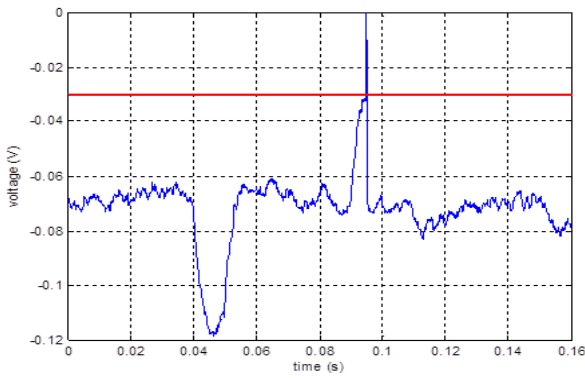


Fig. 12 Integrate and fire model with noise.

Artificial current injections from electrodes are square. But real biological signals are curvy. The alpha function is popular model for a PSP. The alpha function is parameterized as

$$I_{in} = I_{max} \frac{t}{\tau_{\alpha}} e^{-(t-\tau_{\alpha})/\tau_{\alpha}} \quad (8)$$

This is a complicated equation that produces a simple curve as shown in Figure-13. It rises quickly for τ_{α} time and then falls slowly over about $5 \tau_{\alpha}$ (a little slower than exponentially).[7] Thus we made an effort to make the above model more realistic by using alpha function as input current. Figure-14 shows the input and output spikes in an integrate and fire model using alpha function.

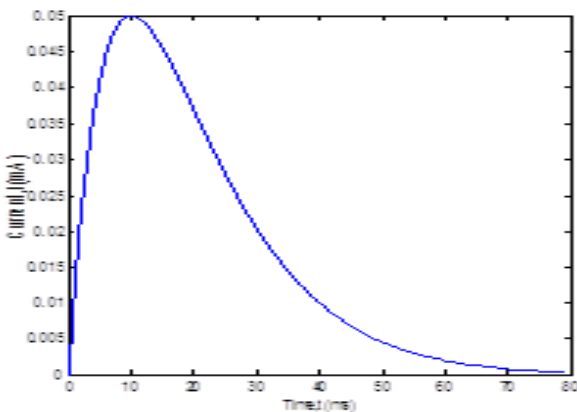


Fig. 13 Alpha Function.

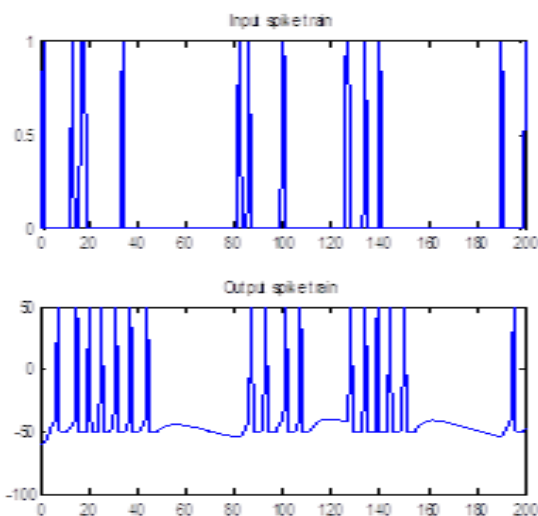


Fig. 14 Input and output spikes in an Integrate and fire model using alpha function.

VI. THE HODGKIN AND HUXLEY MODEL (HH)

A neuron is not as simple as described by the Integrate and fire model. A more realistic model was proposed by Hodgkin and Huxley in 1952. Considering the equivalent electrical circuit shown in Figure-15, the electrical properties of a segment of nerve membrane can be modeled using: capacitors to model the charge storage capacity of the cell membrane, resistors: to model the various types of ion channels embedded in membrane, and batteries: to represent the electrochemical potentials established by differing intra and extracellular ion concentrations.[4] Unlike the previous IF mode HH model consider the resting membrane potential to be -70mv and also takes into account of opening and closing of various ion channels which make it more realistic than the IF model. Hodgkin and Huxley also had an implicit view of the functionality of switches controlling the ion channels. They called these switches particles. Both the sodium and the potassium channel were described as having four particles. In the case of the potassium channel, each of the four particles behaves identically. Each of these potassium particles is called n. Mathematically, the presence of four particles per channel is denoted by a multiplication: $n \cdot n \cdot n \cdot n = n^4$. In the case of the sodium channel there are 3 m particles and one h particle, giving $m^3 \cdot h$ [7].

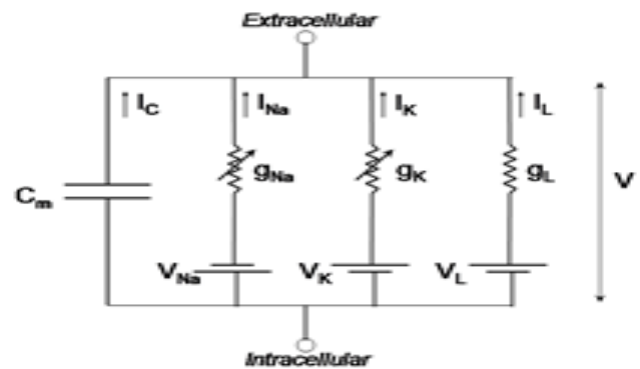


Fig. 15 Equivalent circuit of HH model.

The general form of the mother equation of the Hodgkin-Huxley model can be written as:

$$C_m \frac{dV_m}{dt} = I_{stim} - g \overline{Na} \cdot m^3 \cdot h (V_m - E_{Na}) - g \overline{K} \cdot n^4 (V_m - E_K) - g_L (V_m - E_L) \quad (9)$$

where C_m is the membrane capacitance, V_m is the intracellular potential (membrane potential), I_{stim} is an externally applied current., $g \overline{Na}$ is the maximum sodium conductance, E_{Na} is the sodium reversal potential calculated using Nerst-Einstien relationship, g_L is the maximum leakage conductance per unit area and E_L is the reversal leakage potential m,n and h are the three gating variables.[4]

Now if we simulate the model using MATLAB we get the following results. By applying a significantly large current stimulus at one point in the membrane with a magnitude of a few milliamps and duration of several milliseconds, an action potential arises. It depolarizes to a maximum value then the action potential repolarizes i.e reverts back to the negative direction. It keeps repolarizing and hyperpolarizes below the membrane's resting potential. (-60mv in this simulation). Finally depolarizes to the resting membrane potential. These sequence of events are shown in the simulations below at several instant of time from the initiation of the action potential..

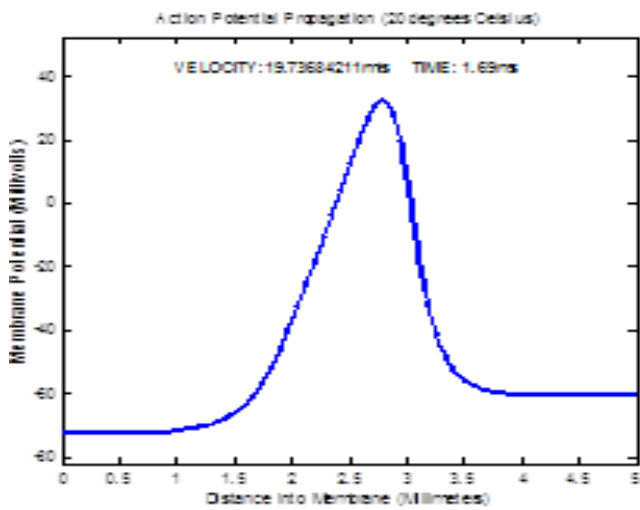


Fig. 16 Propagation of the Action potential 1.69ms after the application of the stimulus.

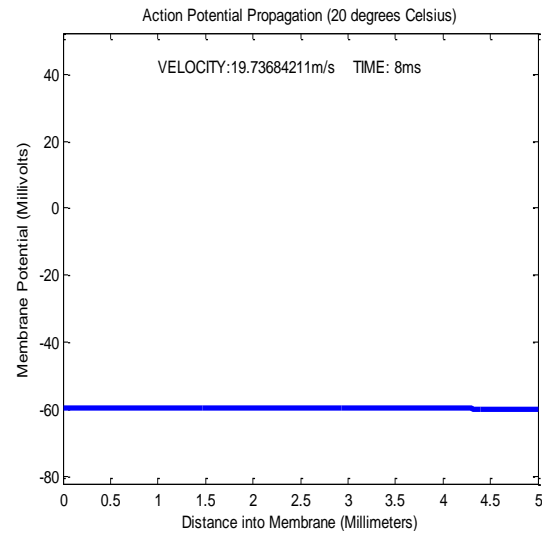


Fig. 19 Propagation of the Action potential 8ms after the application of the stimulus.

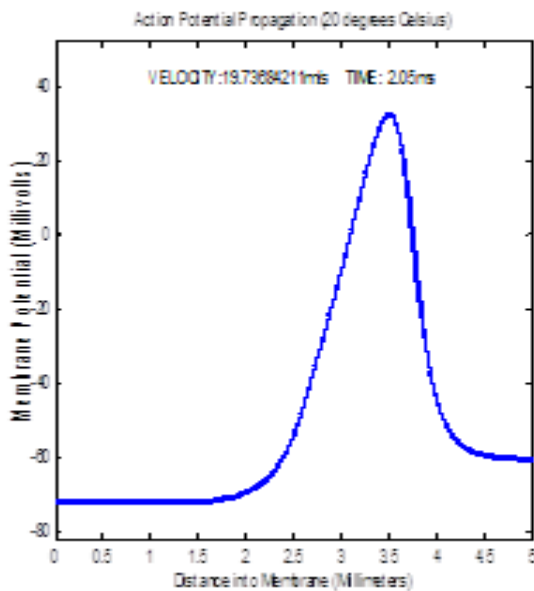


Fig. 17 Propagation of the Action potential 2.05 ms after the application of the stimulus.

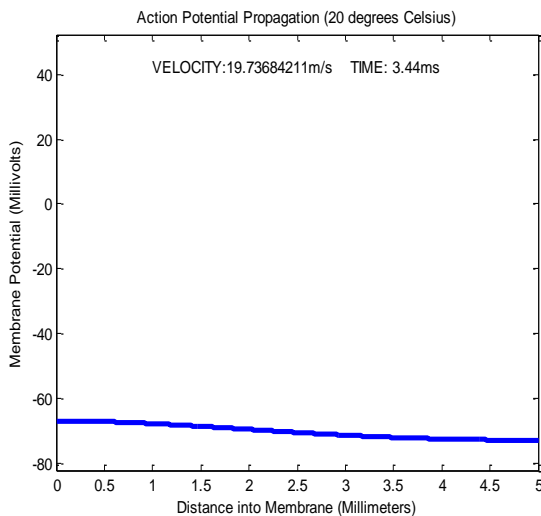


Fig. 18 Propagation of the Action potential 3.44ms after the application of the stimulus.

In the above simulations we have shown the propagation of the action potential through the axon for 8ms. we observed that the membrane potential raises from a negative resting potential of -60mv towards a positive value and reverts back in the negative direction and becomes more negative than the resting membrane potential and finally retain the resting potential at the end.

It also makes sense to check if the conductances match the plots shown above. A plot of the time versus the gate probabilities is given below.

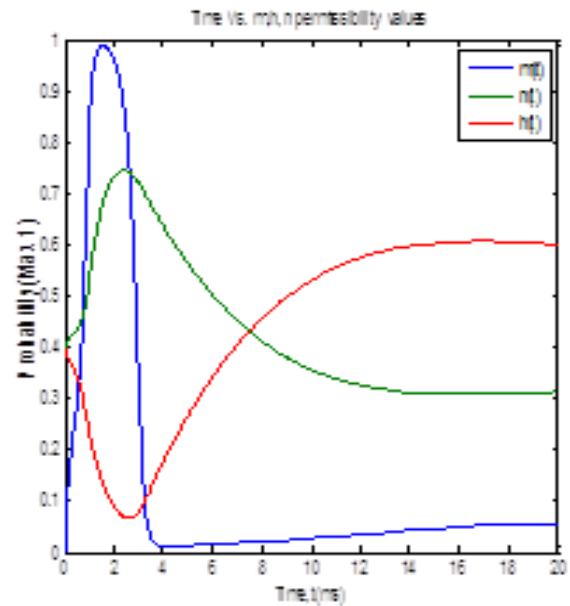


Fig. 20 Getting variables vs. time.

When the stimulus is present, since g_{Na} is much more dependent on m than on h , it shoots up, which describes the peak of the action potential. As m increases, n increases as well, which peaks as m shoots back down; this describes the undershoot of the action potential. Graphically, this picture makes sense.

Now if we increase the current injection from small to large value the firing frequency increases as shown in Fig. 21

REFERENCES

- [1] Stuart Russell, Peter Norvig, (2010). "Artificial Intelligence: A Modern Approach", Pearson education inc, Prentice hall, USA.
- [2] The Man Behind the Google Brain: Andrew Ng and the Quest for the New AI By Daniela Hernandez, Available: <http://www.wired.com/2013/05/neuro-artificial-intelligence/>
- [3] Neuroscience, Available: <http://en.wikipedia.org/wiki/Neuroscience>
- [4] Mostafizur Rahman and Mufti Mahmud, (June 2013). "Deciphering Brain Functionality through Brain Modeling: A Review on Single Neuron", JU Journal of Information Technology (JIT), Vol. 2,
- [5] The nervous system, Available: <https://www.boundless.com/biology/the-nervous-system/how-neurons-communicate/synaptic-transmission/>
- [6] How stuff works, Available: <http://health.howstuffworks.com/human-body/systems/nervous-system/nerve4.htm>
- [7] William W. Lytton, (2002), "From Computer to Brain: Foundations of Computational Neuroscience", Springer-Verlag Inc, New York.
- [8] Refractory Period (physiology), Available: http://en.wikipedia.org/wiki/Refractory_period_%28physiology%29

Eshita Afrin has received her B.Sc Honours degree in Applied Physics, Electronics & Communication Engineering from Islamic University, Kushtia-7003, Bangladesh in 2014. She is currently an M.Sc. Thesis student of the same department and working in the Laboratory of Remote sensing and Satellite Image Processing under professor Dr. Md. Shahjahan Ali. Her research interest include, Biomedical Imaging, Bioinformatics, Bio-signal Analysis, Medical Technology, Computational Biology, Satellite Image Processing

Dr. Md. Shahjahan Ali has received his B.Sc. (Honours) and M.Sc. (Thesis) in Applied Physics and Electronics from Rajshahi University and joined Islamic University as a lecturer in 1997. He obtained his PhD in Satellite Image Processing from University of Dhaka, Bangladesh. He is currently serving as a professor of the Department of Applied Physics, Electronics & Communication Engineering of Islamic University, Kushtia-7003, Bangladesh. He is doing research in Satellite Image Processing, field of Applications of Remote Sensing in Energy and Environment, Wireless networking. His areas of interests are - Cloud detection and analysis, Solar and thermal energy estimation, Surface energy balance, Land cover and Land use, Environmental change studies

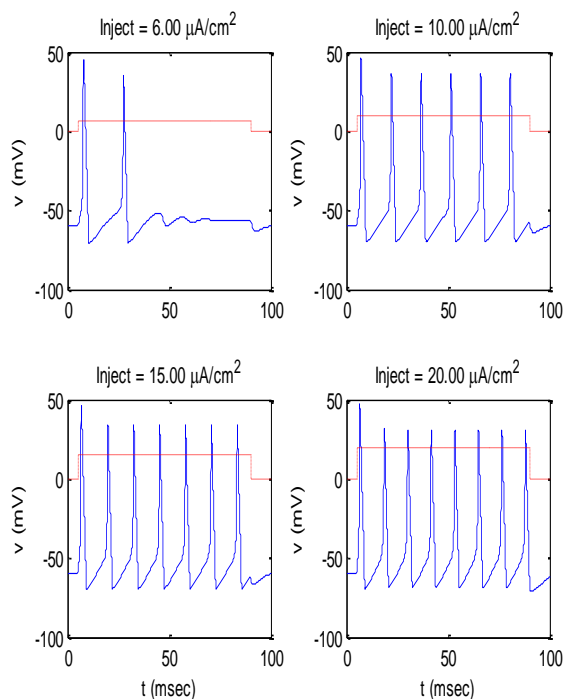


Fig. 21 Firing frequency increases with the input current injection.

We know that information is encoded by the frequency of action potentials, much like FM radio. A small stimulus will initiate a low frequency train of a few action potentials. As the intensity of the stimulus increases, so does the frequency of action potentials, which is consistent with the above simulation.

Thus we can say that we have successfully demonstrated the behavior of a neuron by electrical analogy i.e., an artificial neuron which is the building block of artificial neural network.

VII. CONCLUSION

Throughout the above discussion it is observed that an effort was made to construct an artificial neuron which is the building block of artificial neural network. Introduction was made by making analogy between a simple neuron membrane and RC network and results of simulation yields that its behavior is the same that of a RC network. Then one of the simplest neuron model the IF model which consider the neuron membrane as an RC network and synaptic input as current injection is discussed and simulated. The model was made more realistic by using alpha functions as current injection and addition of noise. But a neuron is not as simple as IF model. Thus a more realistic model, the HH model which closely approximate the behavior of a biological neuron by modeling the behavior of the action potential and gating variables was discussed and simulated to study various characteristics. It was observed that the behavior of the neuron described by the model closely approximated by the behavior of the biological neuron. Thus it can be said that the paper successfully described the behavior of an artificial neuron which is the building block of artificial neural network. i.e. a successful effort was made towards the introduction of brain inspired AI.