Neural Science for Engineers
Prof. Vikas V
National Institute of Mental Health and Neurosciences (NIMHANS)
Indian Institute of Science, Bengaluru

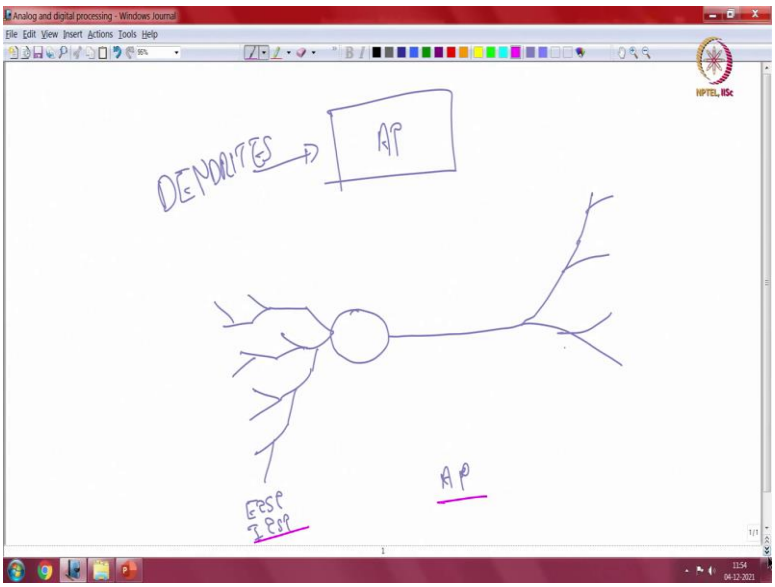
Lecture - 14
Analog and Digital Processing in the Neuron – I

Greetings back again, so we have titled this as Analog and Digital Processing in the Neuron. I am aware of controversies in the engineering field between analog studies and digital studies and how each has its importance and friends with engineers who vociferously back the analog side of the story vis-a-vis digital.

So, there are a lot of merits and demerits on either side of the story. Now, is it possible that the nervous system has been looking at the same issues for some time in its evolution and how do we look at it and how do we try to understand what is happening?

Now, some background on this, important place where you know processing actually happens within the neuron is always told to be the action potential. So, action potential is what actually happens, and it is the output of the neuron to subsequent. We saw muscles, we saw other nerve cells which take the output of a neuron and do something with the information.

(Refer Slide Time: 01:41)



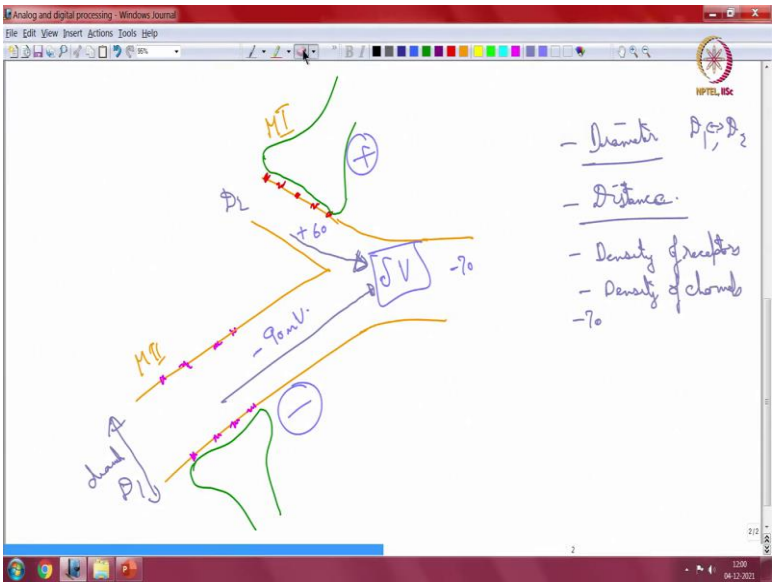
So, how do we generate the action potential is something which has been very sketchy. So, I have started with discussing that the action potential basically starts from dendrites. Now, there are lot of dendrites for a single neuron. So, some pictures would be shown here, and you can make out that the proportion of dendrites to axon is very high.

So, large number of dendrites integrate information and then produce output in a single axon. Now, that axon actually does some amplification because the axon may terminate on multiple second level neurons or dendrites and that is how information gets processed. But let us look at it in a little more detail and compare and contrast what actually happens between different parts of the neuron.

So, I think I will use this notation to depict for multiple reasons. And you have got a cell body, even for the axon it can be 2 or 3. I think of course, but you should remember that it is lesser.

So, we have so far discussed that you have EPSPs, IPSP, then you have action potentials. So, what is EPSP? I think we will have to go back a little to understand that these are currents which are generated. Now, we will look at the dendritic part of the story first.

(Refer Slide Time: 04:10)



So, we go back to membrane and then you have a different membrane. So, this is membrane 1 and membrane 2 and each of these have different kinds of channels on its surface and those channels are responsible for different kinds of inputs. I think I have

discussed this already. So, you can have inhibitory channels on a dendrite, and you can have excitatory channels.

So, I am using this in the membrane notations just to produce linkage. So, I think I will be more specific, we will make all of these as synapses signals, do not just randomly get generated on the cell. Of course, they do in some specific cells say for example, sensory cells in which say you know you stretch a particular cell it produces an influx, those are sensory cells which are there on our skin.

So, sensory cells they have mechanoreceptors. So, mechanical change say pressure, touch, stretch, they produce a change within the channels. Now, so far, I have discussed only voltage gated channels in which the change in voltage is responsible for that, also in some fashion discuss say calcium related channels in which increased concentration of calcium produces activation in some other kind of channel.

We will come back to the discussion at hand. So, we first say that this is producing a positive and this is producing inhibitory signals. So, inhibitory signals will be if we look at what actually happens within that, we are looking at voltages of something like 90 milli volts and we would be looking at voltages of this is stimulatory.

So, you are looking at some sub threshold sub threshold is between -70 and -50. So, we will put it at on +60. Now, what are the factors which determine the voltage at this area? Generally, there is something called as a resting state, and we have defined the resting state that it is -70 milli volts. It is a general understanding that a neuron at rest has -70 at all parts of its cell body.

There are if you apply your mind to it, does not look reasonable or seemingly feasible because you know there is there are hardly few neurons, which should be at rest some activity happening across the various neurons. I do not subscribe to the idea of only 5 percent neurons are active at any point in time.

So, what factors would determine the change in voltage from -70 at this point. So, if we put if we record voltage in this location, what are the factors? So, one factor which I told earlier was the diameter. So, the higher the diameter the faster is the rate of transmission across from the point of stimulus to the point of evaluation, I call this as a point of evaluation.

Because this is not the axon hillock where we are taking a call as to weather action potential has to be generated or not, we are looking at what is the local change in voltage.

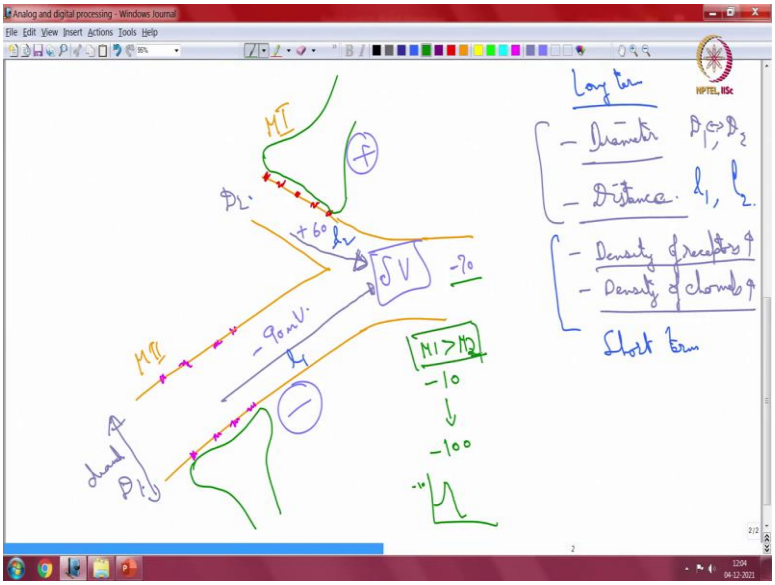
So, the diameter determines how fast this ionic current transmits from the point of origin to the point of computing. Similarly, we have diameter, so we have D1 versus D2 then which is diameter 1 is here and diameter 2 is here then even the distance is something which I discussed.

So, how much distance is there between, we should have a different metric for that. So, what is the length at which this is happening? Small length, but that would actually cause a change in the current and that would produce a different kind of signal right, why does that happen?

Because now the faster this +60 reaches over here if we look at -70, so the distance I told you about the distance. So, point of stimulus to point of evaluation. So, diameter distance of evaluation density of receptors. So, I think we should start introducing the concepts of learning over here.

So, you must have heard of Hebbian synapse and even in back propagation in which you know you change the weighting based upon; of course, back propagation you do not change the weightage based on this one, but you know a pathway in a neural network which is getting repeatedly stimulated needs to be facilitated. So, facilitation happens how? So, facilitation can happen by increasing the density of receptors by increasing density of channels. So, that is the other method density of channels.

(Refer Slide Time: 10:16)



So, you can in various ways change this density of receptors and density of channels. So, you have multiple stimulations happening over a period of time. There is an increase in the density of receptors and that in turn would cause an increase in the density of channel. Now, diameter and distance are sort of immutable because they have been added from the time of origin of the neuron.

So, you have got long term, and these are sort of short term. Short term in the sense that say you are learning a new task, or the neuron is learning a new task and then there is this neuron is getting recruited into that new learning pathway. So, the neuron gets stimulated, stimulated, stimulated. So, in order to facilitate the signals much more, you can increase the density of these receptors which in turn increases the firing in turn increases this ionic current which is coming through, that is a method.

Generally, the diameter and the distance can be changed of course, because the synapse is prewired. So, all synapses what is conventionally known are sort of fixed at birth or at around after pruning happens at around 3 or 4 years of age something like that.

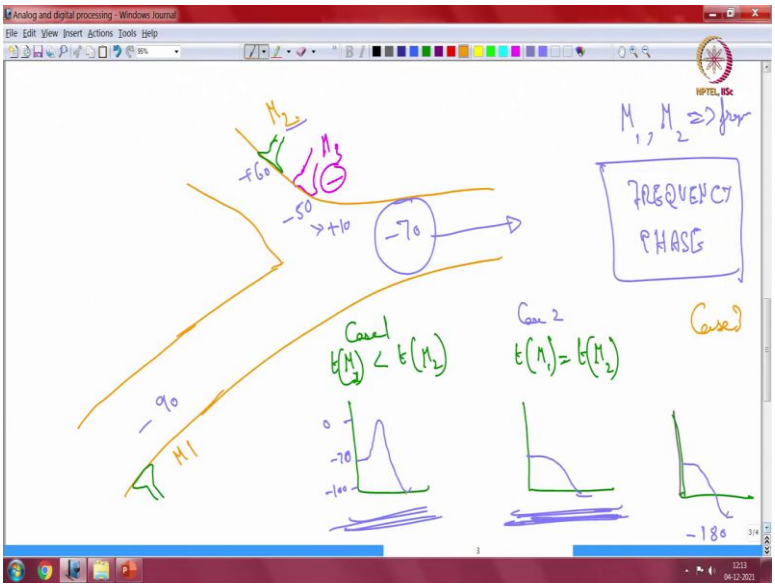
So, they do not change you cannot change the distance from the signal origin which is the synapse to the point of calculation which we are having here. So, also the diameter of the tubules are also constant. So, they you cannot keep on changing, but a given tree can have differing diameters based on the location of the tree and the branches and things like that.

So, coming back to our discussion, we have differing diameters, we have differing lengths. So, let me call this l1 and this should be l2. So, distances and diameters determine also density of receptors and density of channels in the respective synapses.

So, if we plot what is happening to -70 because we assume that the density of receptors and density of channels is same between M1 and M2, we would say that -70 goes to; so, -70 if we take it in numerical terms -70 should go to -10 and then because the signal is arriving a little later than that it should go to -100 right. A very linear calculation may not happen in the exact same sequence of events it is just to tell.

Suppose you have -70 if you plot this graph it should be the signal reaches up to -10 and then goes all the way to -100. Suppose both of them reach at the same time. So, M1 > M2.

(Refer Slide Time: 13:48)



Case 1: M1 arrives it should be t(M1) < t(M2), so graph is like this -75. So, we had decided that +60 and -90. So, we start with -70 this is 0 this is -100. So, how did the signal look like it started at -70 because the signal at M2, M2, M2, M2 arrived earlier M2 arrived earlier.

So, we would have I said that it will go up to -10 and then it drops down to -100. So, that is one thing now both case 2 time taken for M1 is equal to time taken for M2. What

would happen to the signals? So, -90 + 60 = -30. So, -30 - 70 = -100, but the signal changes completely.

So, it would not have the biphasic peak it goes directly from -90 to -100. So, 2 cases in which I have just used one single unitary signal of one single current change, ionic change produces two different signals. So, there are you know you can imagine the possibilities which exist in terms of permutations of you know calculating different frequency of if you look at M1 and M2 in terms of different frequency.

So, both frequency and phase of the dendritic signal determine the local output. Now, and I am just using two branches if you look at the purkinje neuron you can just imagine the amount of computational power one single cell can generate with just the architecture. So, it is a huge amount of computational power which is located within the EPSPs and IPSPs, the beauty of it is, its completely analog.

So, here 2 graphs which I drew showed how same signal which differ only in terms of the time of you know time of onset of the stimulus through the time of recording can produce completely two different graphs.

So, that is the beauty of you know the processing capacity of a dendritic network. Now, a dendritic network is deliciously analog you know it computes ionic gradients. The ionic gradients are passed from one branch to the subsequent branch and that goes along literally I think hundreds, or thousands of gradients and these gradients are summed, destroyed and you know made irrelevant, stepped up in one single neuron.

So, we are just speaking about one small part of a neuron, which is just a dendritic bifurcation containing just two synapses. Imagine a single neuron with literally hundreds of thousands, millions of dendritic inputs to the cell and then all these local calculations happen at each bifurcation and then comes.

An important thing to note here is, what are the parameters for this change. So, parameters are diameter of the wall which is from birth literally and then you have the kind of synapse which is also sort of pre wired which is whether it is excitatory or any inhibitory.

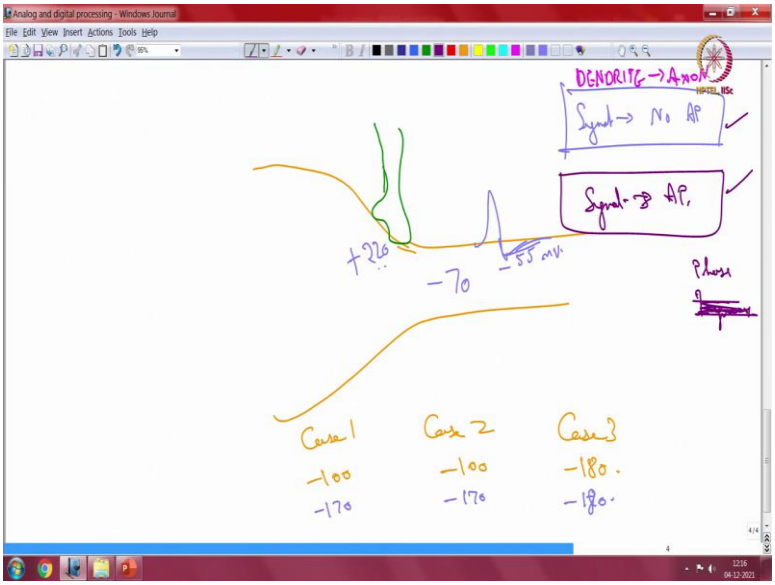
And you know that is it. I think I can draw that and show once more to make things clearer. So, I think it is easier to make it in the same thing if we change the input signal. So, M3 which is minus, and you are generating a voltage of -50.

So, the graph is completely changed, so how did the graph go? So, if we put a -50 over here so it starts at -70, so my +60. So, sumatted amount to a coming over here in this junction is +10, which is the equivalent current at this location combines with -90 and then you have that will be -80 and -70. So, that is hyper polarization, so it goes much further.

That is by inclusion of just one more synapse into the circuit. So, we started with two synapses. I included one synapse, I showed how changes happen in terms of the phase of the stimulus. So, what point of time does in each of these individual signals arrive at this synapse and how this arrival at the synapses causes a change in the computed voltage at the distal thing.

The beauty of this thing is it goes further down and there is dissipation which happens over the dendritic pathway. So, there are mechanisms by which it can reduce and there are also mechanisms. So, if you have a current of minus how much was this -1, I do not know if it actually happens in real life, so -180 is too low. So, if in case that happens what would happen at the axonal this one?

(Refer Slide Time: 21:22)



So, axonal side we will go to that same story. So, continue the same story in the path. So, previously we have discussed several entities in which in case 1 and case 2 we had -100 as the output and in case 3 we had -180 as the output. So, this is with 2 synapses and 3 synapses respectively.

So, what actually happens at the axon hillock? So, case 1, case 2 and case 3, remember the graphs are different in all three ,which is in itself important thing, but I will discount the graph. We look at net voltage which is there at the time of reaching the axon hillock.

So, in case one we had deduced that it is -100, -100, and this is -180. So, I think should make it a little more interesting. So, I think I should introduce it here. One more synapse over here. So, -100 reaches the axon hillock membrane potential is 70. So, case 1 -70 -70 is -170 cell is hyperpolarized -170 cell is hyperpolarized -170 hyperpolarized. What happens to signal generation at the axon? All these input signals of varying currents.

So, signals do not result in no action potential which is from dendrite to axon. So, from dendrite where we calculated the individual EPSPs and IPSPs which in turn is a summation of currents which are generated due to excitatory and inhibitory activity, it results in no activity at the AP, but suppose we have a big synapse, which is sitting over here and produces, I need some large current.

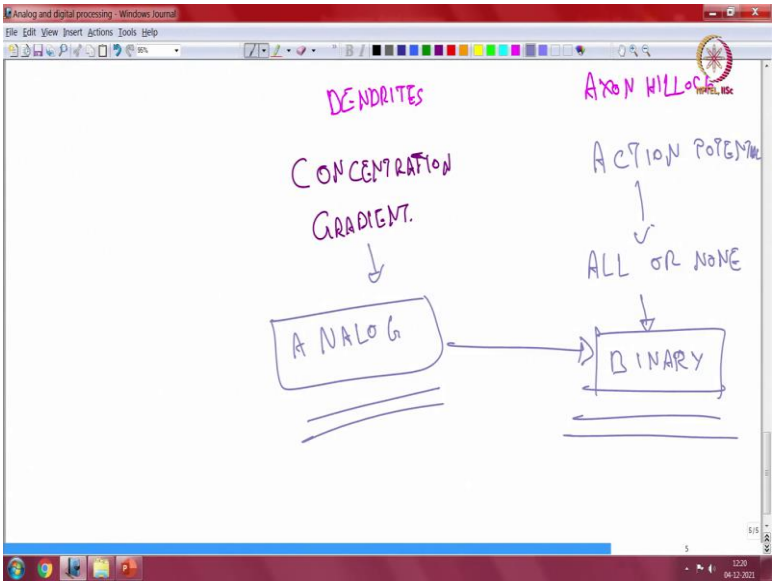
So, we look at something like + yeah it should be high 220, so what happens see. So, all 3 signals produce a change in voltage beyond -55 and that in turn produces an action potential I think I have got my numbers slightly off here, but the concept is what I have tried to highlight it is not arithmetic.

So, definitely not arithmetic and it does not work arithmetic terms also, you should imagine that these are ionic currents and gradients flux everything matters. And I am not in fact, even aware of computations which have been done to a very fine degree to you know even showcase stuff, point is clear. So, in the first scenario when we go from dendrite to axon, we saw that the signal did not produce an action potential, but when we add the signal does produce an action potential.

So, there is an important concept over here, action potential again is in terms of phase frequency we discount frequency here, because we are looking at one single action

potential which has been generated by one single gradient which has come over here. So, here is an interesting concept.

(Refer Slide Time: 25:51)



So, what is concentration gradient in the dendrites at the axon hillock produces the action potential, which is we have discussed this extensively, which is an all or none, which basically is binary. This is a profound statement of the computing power of the nervous system, remember when hinted about single cell recordings and how single cell information is generated what we look at is the action potential, which is the output which is generated.

Because the action potential is the large change in voltage which happens because of the thresholding effect which is due to the property of the sodium channel and things like that. But the action potential is unique because I told you amplitude is constant, frequency can change. So, for a given single action potential it is a yes or no its a binary event.

So, you have no where there is no signal which is transmitted yes in which one single action potential is transmitted. Now, if you look at the dendritic gradients, they are chemical gradients. So, the gradients generated along tubes of varying diameters, the gradient depend the gradient transfer is determined based on ionic concentration. Ionic concentration in turn is determined at the time of stimulus, the diameter of the membranes and the intensity of the stimulus.

So, you have repeated stimulus in one part of it, there is a gradient which is generated favorable and unfavorable. Favorable is an EPSP, unfavorable is an IPSP. So, this is computed and at the cell body, at the axon hillock it there is one single decision. So, that is the beauty of a single neuron.

Now, if we look at ANNs and CNNs and things like that a single neuron computes one activation function and it is actually a lot of numbers which are computed and there are of course, there are techniques incidentally which I have read in the ANN philosophy in which you know they incorporate some of these things. But I intuitively figured out that they have not used it because they have read this and figured it that the nervous system uses it like that.

But you know I found it as a mathematical trick by of utilizing some of the nervous system concepts, but the nervous system on the other hand has deliciously mingled and integrated the analog system which is there in the dendrites to the binary system or the digital. So, called digital system which is there in the axons and the cell body is the fundamental integrating part, but having said that dendrites do most of the computation is what I figured out.

Because the sheer number density and richness of stimulation you will just have to look at one single purkinje cell neuron to feel ashamed of all the neural networks which we have generated and the GPUs which are dedicated for all kinds of tasks. So, that is the richness of the nervous system, which I have kept highlighting and this is a very interesting phenomenon which is there within that.

So, analog signals in one part of the neuron get transmitted into binary signals in another part of the neuron and the language is such that each of it has its importance. So, in the dendritic side you also have phase as important, you have intensity of stimulation which is important, but in the axon side you only have phase and frequency. Phase incidentally is a secondary thing you have multitudes of neurons you can determine phase differences between neurons.

But for a single neuron you have signals of different frequencies which come through. So, between two neurons you can have phase differences. So, I think I will stop here because this is a this is something which I always wanted to discuss in a forum. I have not come across this discussion in other kinds of neuroscience discussions unfortunately

and it’s something which I would like to you to dwell upon and think and tell me your comments on that.

Thank you.