Neural Science for Engineers

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Module - 02
Lecture - 08
Anatomy of a Neuron

So, we start with some structural idea of the nervous system. So far, we have been actually discussing function. So, the general idea of most medical curriculum as you start with structure and then go on to function in parallel. I have used it in reverse because as the title of the course suggests it is meant for a different class of people.

So, I do not have to follow the strict regulations of medical teaching to do that. The idea of starting first with function is that function is somewhat easier to understand and follow through; it is a certain logic which has been used in the discussion so far. And we can clearly understand how each part is connected to the prior and there is a particular flow through that.

Now, it comes to a certain level that you need to understand structure to you know ground the whole stuff. So, that is the idea of that and you cannot learn much about the nervous system without actually understanding how it is made up of and that is the purpose of this. So, I have titled this class as Anatomy of the Neuron.

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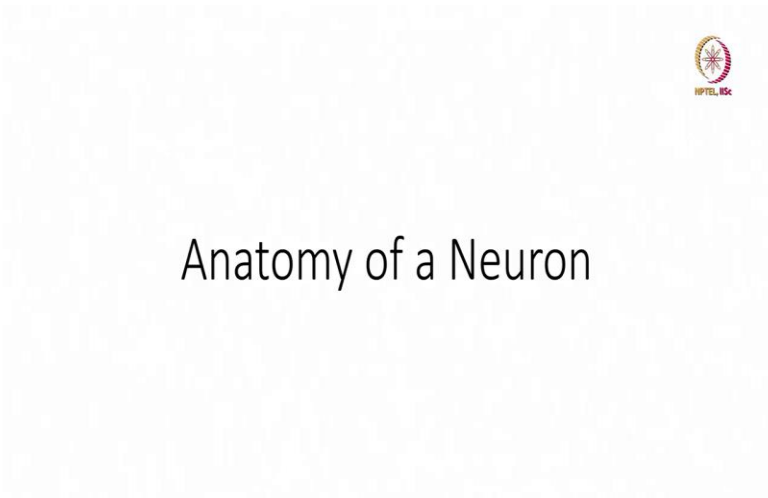

I will be focusing just on the neuron, and we will progress with further advanced structures ultimately reaching up to the brain in subsequent classes. So, over the course of this you may find things a bit unpalatable, but you need to know a little bit of structure. I would make attempts to ensure that there are easier methods of understanding this stuff and it is not by rote.

So, the beauty of having an online education program such as this is that you know I can spend a lot of time explaining which actually cannot be done in a regular class with fixed time constraints. So, we start on with that introduction to something about background.

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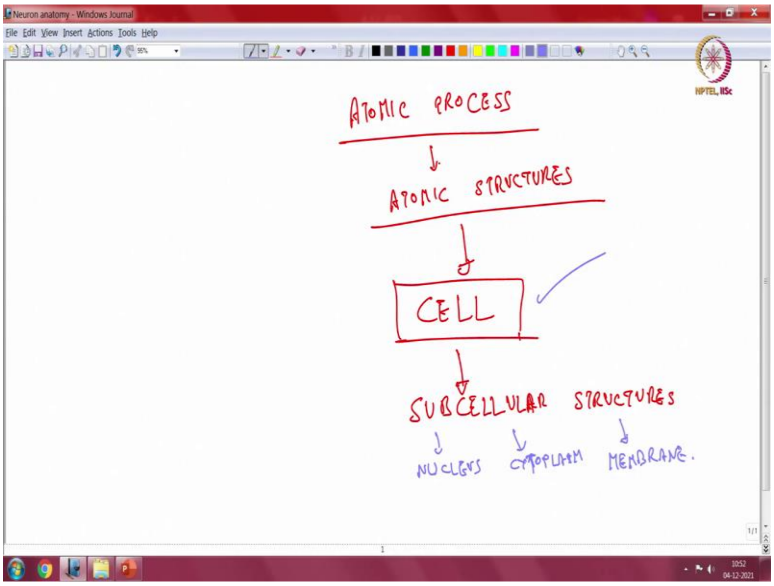

So, we look at atomic processes in most fields of engineering. So, we basically look also at atomic structures in most fields of engineering. So, what constitutes the single smallest entity, which is functionally independent, structurally independent and can do some work or has some responsibility attained with it. Now, the basic atomic structure in biology is the cell.

So, a cell is an entity which is considered as a fundamental unit of biology you know you have a cell we already discussed membranes which cover the cell; it is not that the cell has nothing further. So, you have sub cellular structures. So, that would include something called as the nucleus then cytoplasm and membrane incidentally. But we still discuss cell.

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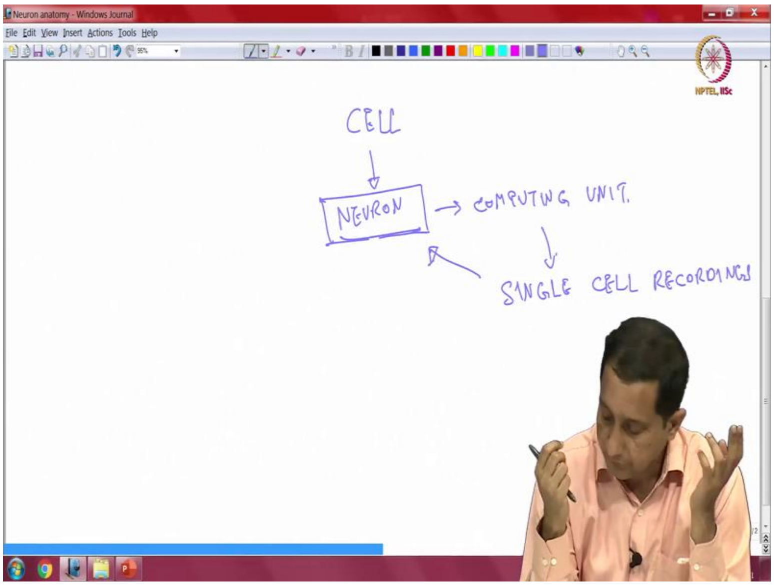

So, in terms of nervous system biology we have to discuss the cell. Now, why do we discuss the cell? Because neuron which is the fundamental cell of the nervous system is the is a computing unit in itself. Now, how it compares to ANNs and CNNs? I think we will understand during the course of the study.

But for the purpose of introduction, neuron is the fundamental computing unit of the nervous system and you would, for those people who have biological or biomedical backgrounds, understand something called as the single cell recordings. So, you do single cell recordings from a neuron. So, the output of a neuron is what is called as single cell recordings.

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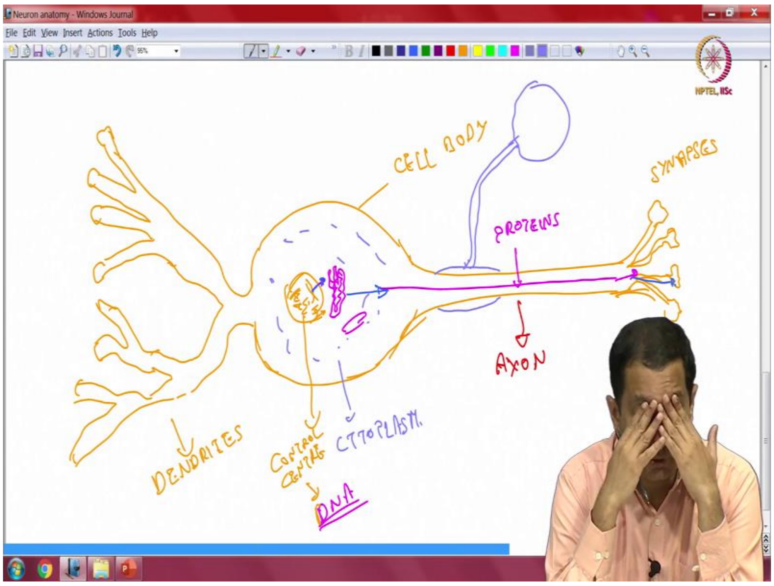

So, let me first draw what constitutes neurons. So, you would have a central part called as a cell body. Now, a cell body contains a nucleus, and it also has cytoplasm. We spoke about membrane so far. So, what are those membranes? The biggest membrane is the tubule. So, the biggest tubule is something called as the axon then the axon is not an entity in it does not end blindly, it ends in some other things called as synapses and there are multitudes of them.

So, one axon can give rise to multitudes of endings and these endings we will come to that in some while. The other part of the so, this would be synapses, the other side of the neuron. So, we are looking at a very simple idealized neuronal structure, the other side is like a tree. So, when I say tree, it obviously means; it has got an architecture and then there is a tree which half rises and it goes like that.

So, this whole complex would become something called dendrites and so this constitutes the structural unit of computing. So, there is an axon which is the central part that is the sort of integrating center for the cell. It contains the cell body which contains the nucleus, which determines the long-term function of the cell and the day-to-day management of the cell.

So, nucleus is sort of the control center; why control center because it has the all-powerful DNA. So, DNA produces RNA, RNA produces proteins and proteins are responsible for several things. If you remember how important proteins are, you can actually control the density of the channels on the membrane.

So, basically it indicates that the neuron has the power to change the rate at which things happen. So, you can actually change slightly the velocities of transmission across this one. So, it can form a part of learning; it can also form part of you know modulating responses, modulating signals across various large neuronal pathways.

So, the cell body contains the nucleus, it also contains something called endoplasmic reticulum; it contains several other components mitochondria, endoplasmic reticulum, which are again protein-based structures useful for protein development, protein transmission and then there are dedicated paths through the axon by which you can actually transmit the proteins too.

So, protein pathways exist from the nucleus through the DNA, RNA endoplasmic reticulum and into the tubules of the axons and then it goes into the periphery into the synapses. So, this is the general way in which things happen within the neuron; if you have breakdowns in any part of it, you have very horrendous diseases which happens in the nervous system.

So, this neuron is incidentally the computing unit of the nervous system, but it does not mean that there are several kinds of support structures. I spoke to you about myelin. So, myelin is produced by other cells and these cells actually you know they wrap around the axon.

So, it is not that the neuron produces this thing. So, you have other cell, supporting cells which provide these structures, and they are an integral part of the processing system of the head. You cannot consider each of these things in isolation. So, you do not look at only the neurons; look at also the mechanism of how they interact with other glial cells such as Oligodendrocytes and Schwann cells and many other supporting kind of cells.

So, these cells have both normal and abnormal function. So, in normal terms they produce the myelin which covers the nerve, but they are also responsible for brain tumors because neurons per se do not divide except in exceptional circumstances. So, what we know as brain tumors generally arise from the supporting cells which are known for division.

So, that is something about the medical side of the story. So, we need to look at a little more detail, again in terms of the action potential as to what happens to the action potential and how things happen? What is the destiny of an action potential? So, we go back to drawing the same neuron.

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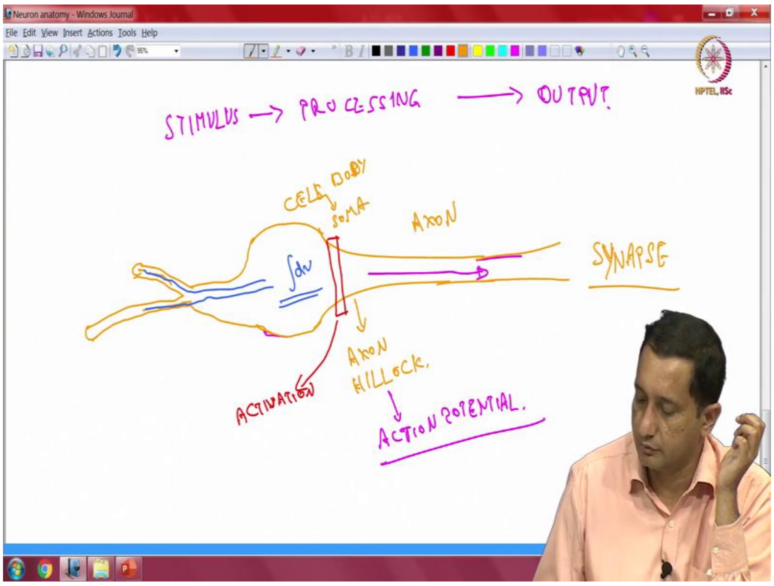

But in a smaller fashion and I think I will use a different notation. Now, the junction between the axon and the cell body or the soma is called axon hillock, and that is the place where the action potential is generated. So, what actually happens is you cannot provide electric changes into the inside of the brain.

So, you need to have a stimulus and you need to have processing and output right. So, you need to have stimulus. So, we start with we know that the unit of neuronal computation is the action potential. So, action potential is generated at the action axonal hillock, and it goes through the axon. Now, the stimulus as such comes from a different location that is the dendrites.

So, for simplicity I think I will just draw 2 dendrites this is the reason why I am drawing it unequally because it is that richness which is responsible for the functioning of the nervous system. So, I am just drawing it. So, the stimulus actually starts from the dendrites, and I told you about the currents which come through this one.

So, you have different currents which come through here and these currents are averaged, you have average of the volt summation of the voltages integrated over here in this one and then here is the threshold. So, that is the gate. So, the activation as such happens over here. So, different current gradients which are generated in the dendrites and these currents are summated within the neuron.

And then the action potential is then decided whether you need to propagate the signal further or not. So, that it is an all or none phenomenon. So, the neuron decides whether the signal has to be generated and the action potential which is again constant amplitude is generated and transmitted. So, now, what actually happens on the other side of the story is something called as a synapse.

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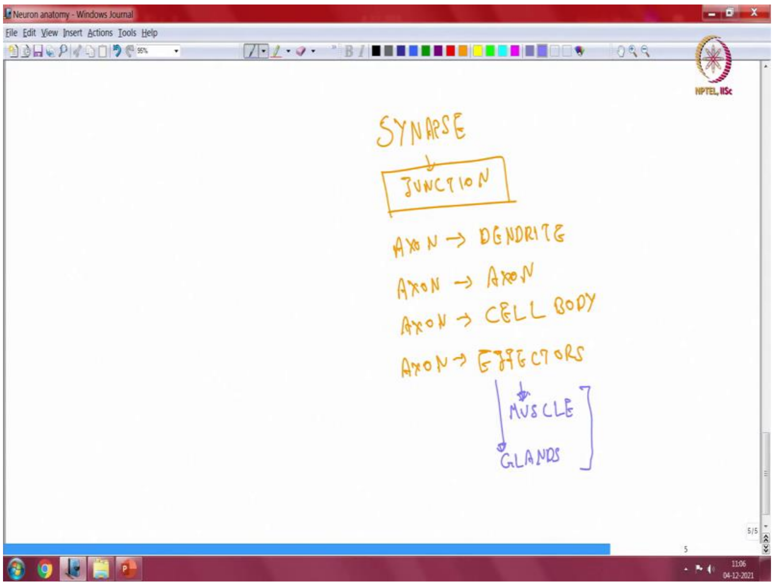

So, synapse basically means a junction. So, a junction is between any 2 computing entities. So, 2 computing entities in terms of biology should be between axon to dendrite, then it can be axons sometimes to another axon or axon to cell body. Each thing has its relevance it is not the same as connects in a multi layered neural network it is completely different.

So, that is the first principle. So, you have axon as the output of a neuron and that is what ends in these junctions which are called synapses and this synapses go and meet other places within another neuron or maybe other cells say for example, muscle and things like that.

So, it also can be to other things called as effectors. So, what are effectors you have muscle, you can have glands. So, these these form the important effector system. So, skeletal muscles, cardiac, I think we discussed this earlier. So, muscles are the output structures, where electrical activity is converted into mechanical activity.

Muscles basically are mechanical agents of transferring electrical data and that is what is responsible for whatever we do, whether it be talking, walking, anything and everything which is done by a human body is generally through various kinds of musculature. So, that is how that is the destiny of an axon and that is the destiny of an action potential.

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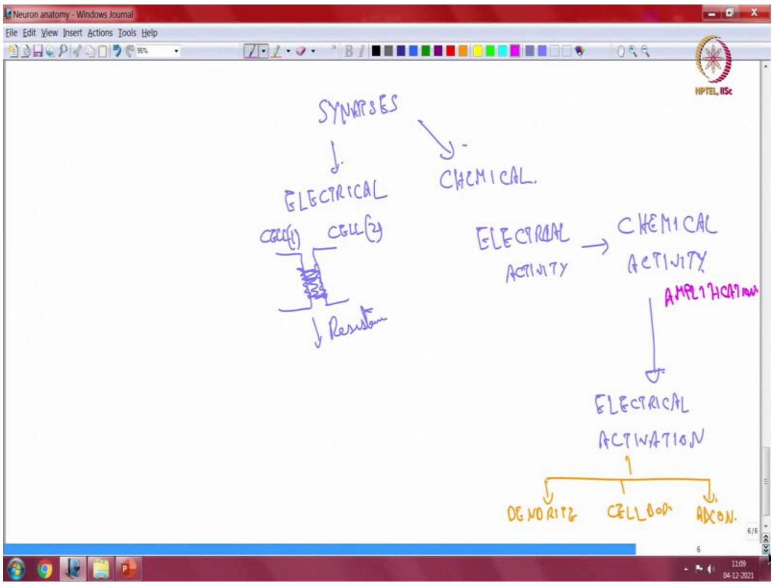

So, going further down into what happens with synapses you have different kinds. So, you have for people who are electrically, electrical synapse, then you have chemical synapses. So, electrical is you have one junction and then there is an electrical connect between the 2, cell 1 to cell 2.

So, cell 1 and cell 2 have electrical connection; obviously, it is a low resistance pathway and there is seamless integration between 1 cell to the another, but surprisingly for something which should be thought to be as the most efficient way of doing things. Most or majority of the synapses are chemical synapses in which the fundamental principle is that electrical activity is converted into chemical activity and chemical activity in turn generates electrical activation.

Electrical activation again please do remember like what I have told it can be at other dendrites, cell body or even maybe on the axon. So, that is how things work within synapses; chemical synapses are you transfer electrical data into chemical data and then back again into electrical data and that is one of the methods by which you can fine tune processes and do computation within that.

General idea is that chemical is responsible for something called as amplification of signals. So, we look into a lot more detail into the synapse, see synapses what is connecting an axon to a dendrite. So, the axon of one cell goes to the dendrite of the other cell and that is where neuronal computing happens; when it goes into a muscle it is called as an NMJ, neuromuscular junction.

So, it can be neuromuscular junction is where it is a connect between a neuron and a muscle. And so, neuron produces a signal, muscle acts and that is how muscular activities happen, but the principles remain the same. So, how does that happen?

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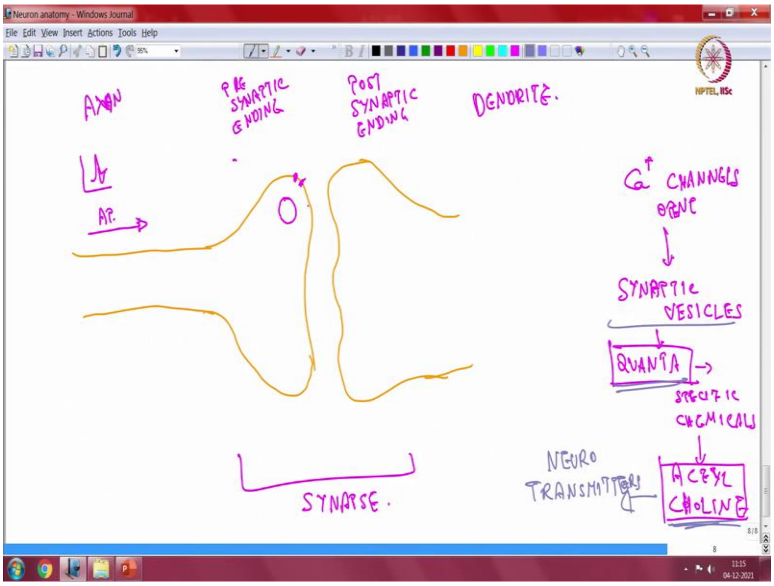

We go back to the membrane which was producing the action potential and then it produces something called as a nerve ending. I will be looking at one synapse over here. So, we will label this, this is axon, this is called the presynaptic ending, post synaptic ending. So, the whole thing is a synapse; axon this should be a dendrite.

So, what actually happens to an action potential? So, the action potential is generated within the cell body due to the processing of the neuron and that action potential is transmitted across. So, reiterating again the amplitude of the action potential does not change, the frequency of the action potential changes based upon the input parameters which are received at the cell.

So, we will consider one single action potential which arrives at the synapse. Now, what it changes in the synaptic area it opens up something called as the voltage gated calcium channels. So, we have so far looked at sodium channels, we looked at potassium channels, but an important channel which is especially important within the inside of the cell, the sodium is the currency by which transactions happen across the cell boundary inside and outside of the cell.

But within the cell the major important ion which is responsible for computation and all further activities is calcium. It is very tightly regulated element because you make slightest of mistakes, anything from cell death to cell degeneration can happen and that is an important reason why calcium is very tightly regulated.

So, what actually happens within the synapses. So, calcium channels open and these calcium channels actually produce, there are this things called as synaptic vesicles. So, synaptic vesicles are packets. So, there is a quanta containing specific chemicals, the general example, which is quoted here is acetylcholine, you can have various kinds also.

We now reach some important steps. So, these chemicals which are present within the quanta within the synaptic vesicles are the method by which information is transmitted from one cell to another cell. The mechanism is what is being discussed over here and these are these formed general class of molecules which are called neurotransmitters.

So, the neurotransmitters are classes of chemical compounds fairly conserved across biology, across several kinds of organisms and these are the general method of serving as neurotransmitters. I think people would have heard of dopamine and serotonin and adrenaline.

So, these are examples of neurotransmitters, and you would have heard about the relevance of dopamine in the Parkinson disease and things like that. So, they are fundamental entities within the nervous system. So, deficiencies, excess, all of these are responsible for various kinds of diseases. So, that is the importance of the compounds.

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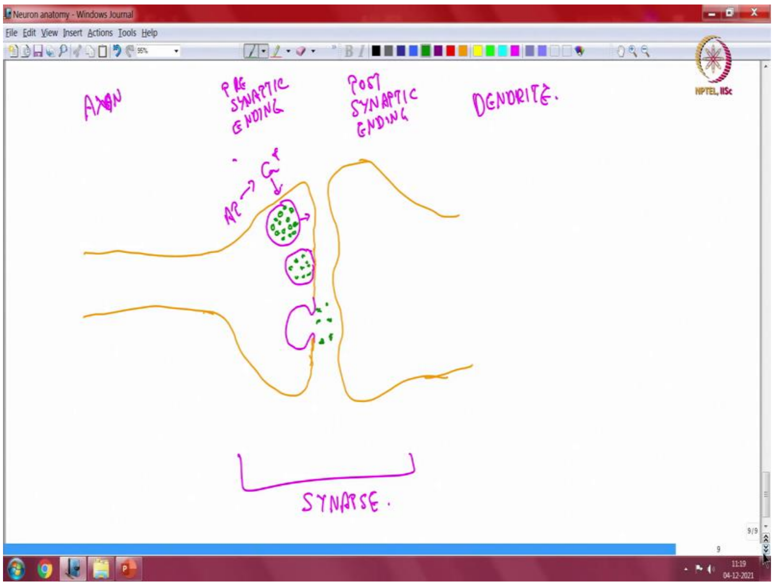

Now, what actually happens is these synaptic vesicles which contain acetylcholine molecules are present within this presynaptic membrane and each is quantized. So, you have a vesicle containing a fixed amount of acetylcholine molecules. And what is done over here is the AP triggers calcium, this calcium actually causes this to move towards the synaptic cleft and then bind with it.

So, let us see how it happens. So, in the first stage you have binding which happens and then, in the second stage they actually fuse with the membrane and in the third stage they actually open to the synaptic cleft. Synaptic vesicles are basically again double membrane entities like what they are for the cell membrane and the calcium provides a binding site for these synaptic vesicles.

So, what happens is these single quantize packets of information get released into the synaptic cleft. Now the synaptic cleft is important because it is not a general open space; it is a very tightly regulated junction. So, the nature has ensured that information which is to be transferred is tightly regulated within that there are mopping systems which take care of these molecules, there are insulation systems which prevent transmission of this very important neurotransmitters from one part of the cell structure to another cell structure.

So, this is the importance of having those supporting cells. So, supporting cells do all this housekeeping jobs for the neuron. The neuron just takes care of a lot of the processing, but the housekeeping cells do a lot of the other things, you know it includes say housekeeping cells I told you about large potassium currents, which go and stabilize the membrane and things like that.

So, the discrepancy between which happens between the discrepancy, which happens between various parts of the nervous system if it is not tightly controlled. So, coming back to the synapse; the molecules are generated and poured into the synaptic cleft. So, that is what has happened so far.

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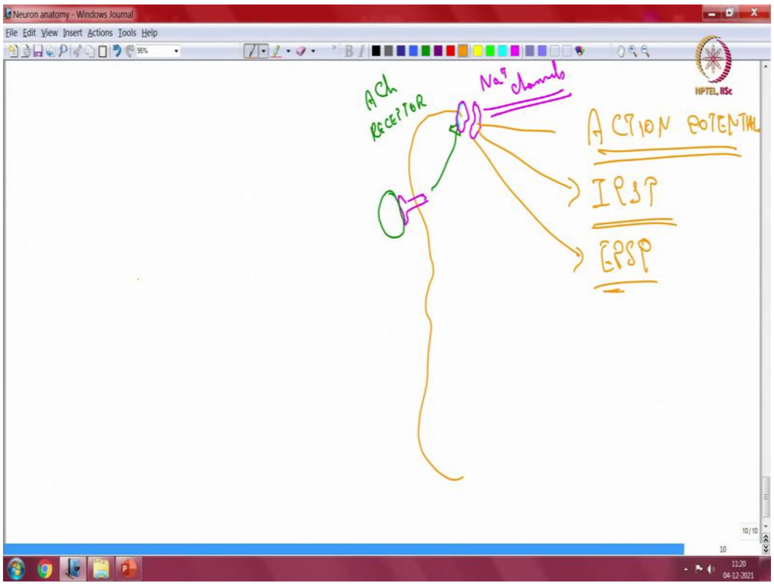

Now, what happens on the post synaptic membrane is the inverse of this stuff. So, in the postsynaptic membrane you have acetylcholine receptors. So, each of these quantized acetylcholine molecules will go and bind to an acetylcholine receptor and this in turn triggers or sodium channels.

So, when sodium channels are triggered and when they are triggered in sufficient enough quantity you have an action potential, which is generated, or it can even be an IPSP or an EPSP. Why? A lot depends upon where this synapse is happening right, as I discussed earlier.

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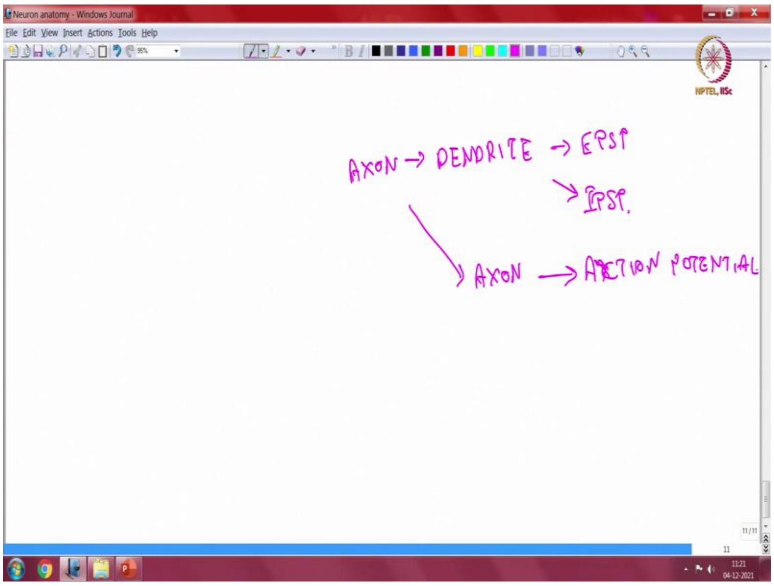

Axon to dendrite it should be EPSP or an IPSP. Now, if the same axon is to another axon, it can or cannot result in a axon action potential, right. So, the location of the synapse actually is important for that reason. So, the information which was there in the presynaptic neuron need not always generate an equivalent response.

So, that is the beauty of the system because it is not just that one signal is getting transmitted, it is not a cable through which information runs from one side to another side. There are actually very complex translations which happen.

So, one is one single action potential resulting in multiple quanta of acetylcholine vesicles released; we are looking at amplification. So, one action potential can generate may be subsequent several currents of IPSP or EPSP. EPSP generally because acetylcholine is a stimulating neurotransmitter.

So, that produces currents of varying durations in the distal dendrite. So, it may also end up in an axon, where you know it is pre distant. So, if the neuron postsynaptic neuron is ready to accept the action potential it fires an action potential the frequency of which can be modulated based upon the kind of acetylcholine molecules which is released.

So, various kinds of computation are happening one based on the location, second based upon the frequency of the stimulation or frequency relationship between the presynaptic neuron and the postsynaptic neuron. I think I should explain this with a few more examples. So, we will look at each of these case scenarios in detail.

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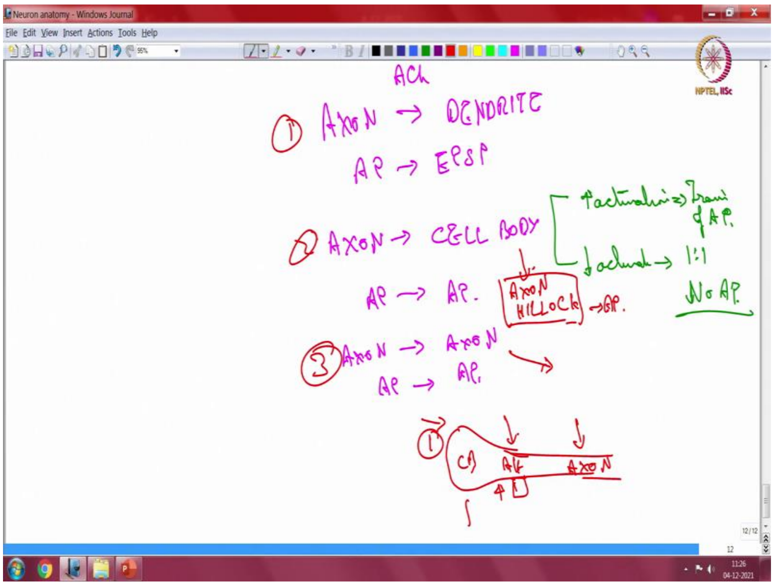

So, axon to dendrite AP to EPSP. So, we will just look at acetylcholine. So, EPSP axon to cell body AP to AP and axon to axon. So, AP to AP again, but there are differences. So, if the cell body is primed. So, what I mean by primed is there is prior stimulation within. So, if it is in an increased sense of activation you can have, which includes to train of action potentials in the distal. So, it is in the axon.

So, you are directly translating axon, one single signal into multitudes of signals. So, you have done an amplification in the process. So, if it is in a state of decreased activation, you may have 1 is to 1 or it does not produce an action potential; no action potential. So, even those two things are possible.

So, there are 3 options which happens. So, you can increase the frequency of the output signal, the same signal gets transmitted at the same frequency or you can actually downgrade the frequency of the signal. I started with 1 action potential, but you imagine it has to be a frequency of signal.

So, there is a frequency of AP which ends up in the presynaptic, but because it is ending up on an axon it can step up the frequency, give the same frequency output or it can even reduce the frequency or no output. So, there are a lot of decisions now that in turn depends upon the activation state of the postsynaptic neuron.

So, between cell body as I told you there is one more step in a cell body. So, cell body has to reach up to the axon hillock to generate the action potential. So, there is one more level of decision making between that, but say for example, if it is between axon to axon, it integrates with an already existing signal which is coming out from the axon so, axon hillock.

What I mean is, cell body, axon hillock, axon. So, the first one is here, first one just produces current which is integrated over here; the second one is on the cell body which is integrated over here. Integrated in the sense that there is a decision step in this place. So, the decision step here actually it is modulation. So, there is already a signal passing through the axon, you can reduce the frequency or increase the frequency. So, that is the relevance of how location matters for the synapse.

So, where do these synapses determine the output function of the neuron? The output is just based upon the location and it is one of the methods by which you know actual processing happens within the nervous system; you got one single neuron which can end up on multiple neurons. So, it is not that one neuron ends in another neuron or one single dendrite, if you look at various architectures of neuron which I will be sharing in a slide.

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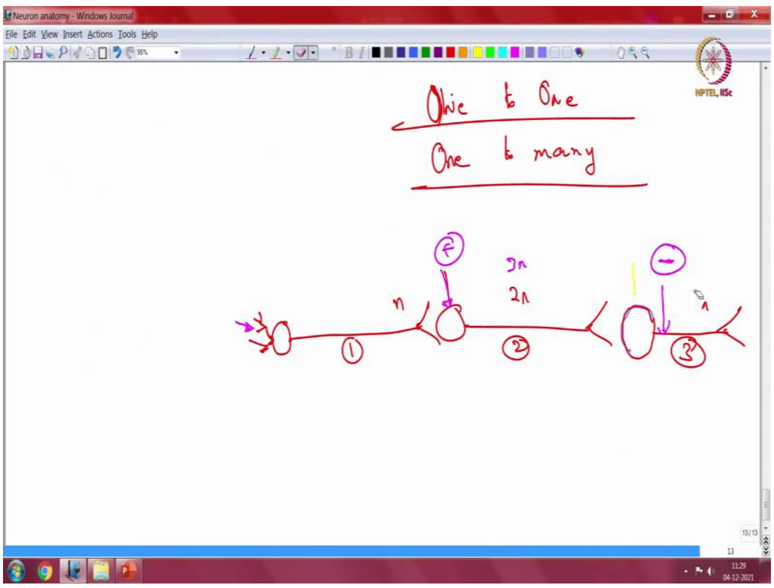

The way pattern of one to one; one to many and this is a very important concept for everybody who is listening to this. So, that determines a lot of how the output signal varies in relation to the input signal. There is a lot of modulation happening on the way because we are actually looking at changing the frequency of the output.

So, how action potential which is an all or none, yes or no function gets transmitted into a modulating function is one of the mechanisms is this. So, you have an axon which comes into various parts of the cell body, the synapse is there on various parts of the cell body, the synapse determines how the post signal exists within that.

So, let us see how it sort of happens. So, you have cell 1, cell 2, cell 3; then you have a dendrite which is coming over here. So, one of the signals. So, I will start calling this as a signal gene, input signal coming into the dendrites. So, what it causes is an EPSP or IPSP and then the neuron decides to fire with a particular frequency in.

Now, that frequency can be changed into 2n and then changed into 3n. So, this is just the transmission; now if you got signals here if it is excitatory, you are looking at an output of 3n and suppose you have a inhibitory signal over here sorry not here ok, too light inhibitory signal.

So, this is a positive excitatory signal you are looking at 3n inhibitory converted into 1n. So, that is how changes can happen. So, this is the relevance of the synapse, the location of the synapse and how the transmission occurs across that; so, retreating stuff which we have gone through so far.

We have axon, we have a whole neuron which is a computing entity, we got dendrites and then the cell body, the axon hillock and the axon hillock is the originator of the accent action potential which is an all or none phenomenon and you have only one entity which can be changed; one parameter which can be changed which is the frequency of the action potential nothing else.

So, frequency can be anything between 0 to some maximal frequency for that output neuron based upon the resting membrane for the duration of fatigue which is there for the membrane at that region; the output so what signal is generated within a dendrite like an EPSP, IPSP gets summated within the cell body.

It gives an activation function at the axon hillock where the action potential is generated, the action potential goes through the axon, comes to the synapse. The synapse in turn can combine structurally with some other part of the nervous system and that produces excitatory or inhibitory signals. So, we will stop at that.