Cognition and its Computation

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Lecture - 11
Introduction to Computation

Hello. So, you have been already introduced to the cognitive aspects that we will go over in the course. And, today I will introduce you to the computational aspects that are associated with the aspects of cognition that we will be talking about throughout the course. The Holy Grail in neuroscience is that computation occurs through spikes in neurons. What we mean by spikes, what a neuron is let us go over those things first.

So, neurons are the main cell bodies involved in computation in the brain. They are not the majority in the brain. There are other many other cell types that are present in the brain, but the computation is performed mainly by neurons. So, the other cell types are glial cells, astrocytes and so on. And, they are there for supporting mechanisms is what used to be thought earlier.

But, with recent discoveries we are learning more and more roles played by the other types of cells that is astrocytes and glial cells in the brain in terms of computation also. Here, we will restrict ourselves to computation done by neurons and by neurons we will mean primarily the neurons in the cortex which is the cerebral cortex. And, some of the other structures in the brain that we will talk about in detail in later lectures.

So, the means of computation done in the brain; when I say computation done in the brain what we mean is given some inputs to a neuron and these inputs; so, by these inputs we will mean activity of previous neurons ok.

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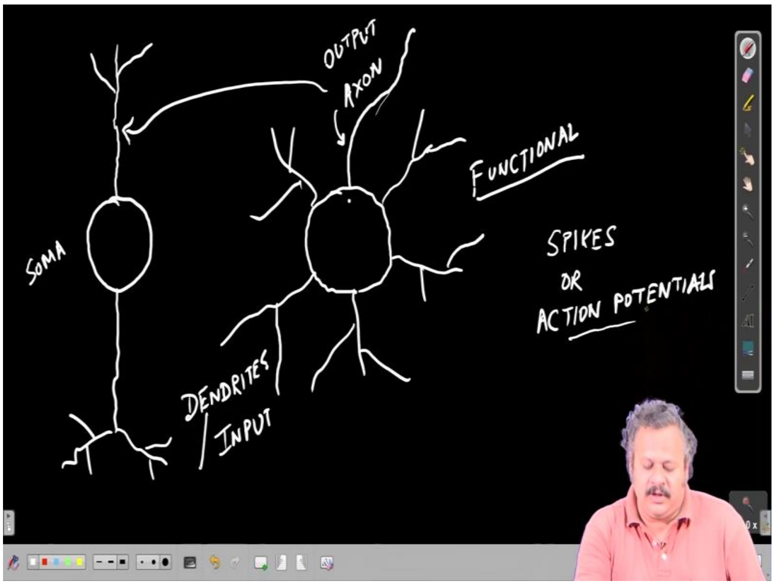

So, let us look at the structure of the neuron. So, they have a cell body and can have different morphologies. So, we will try to draw this as a circle, it does not matter for our purposes. It has usually two sides to it, two functional sides ok. When we mean functional; that means, it does not mean two physical sides, but in terms of the input and output there are two different sides.

One is the input side which is the dendrites which has structures like this. They can have many different morphologies and morphologies often correlate with function of the neurons. And so, this is one kind. There may be other types where we have the neuronal cell body which is all we call it the soma. And, they may have large long dendrites and then break out into smaller branches. And, these are called dendrites and they are the input side of the neuron.

So, these are the input sides and there may be other kinds of shapes also which we do not want to go into detail here. But, the main purposes of this course what we need to know is the dendrites are the input side. And, there is an output side which is thinner neurite growing out of the soma which carries the functional output of the neuron to next stage neurons. And, these may branch out and may make connections with many other neurons.

So, in this may be the axon goes out this way. So, this is the axon here and this is may be the axon here for this kind of a neuron and this is the output side. So, as you can see the input is all around. So, there is no real side physically. So, functionally again I repeat that there will be two sides. Now, there are exceptions to it, as you will see that there are many neurons that are actually without any axons even. And, they make dendritic synapses on other types of neurons or other neurons and that is how they performed their computation.

So, coming back to computation what we mean is that these axons when they are projecting out, they carry the information from a particular neuron on to the next stage neuron ok.

And, what we mean by information here is information in terms of the activity of the neuron. And, that we by activity what we mean is the membrane potentials excursions, large excursions for a brief period of time which are called spikes or action potentials or action potentials. So, these are the means by which the neurons communicate with each other. And, there are cases where neurons communicate with each other not with action potentials, but with other graded potentials. There are cases like that which we will not discuss for now and focus on what we mean by the action potentials.

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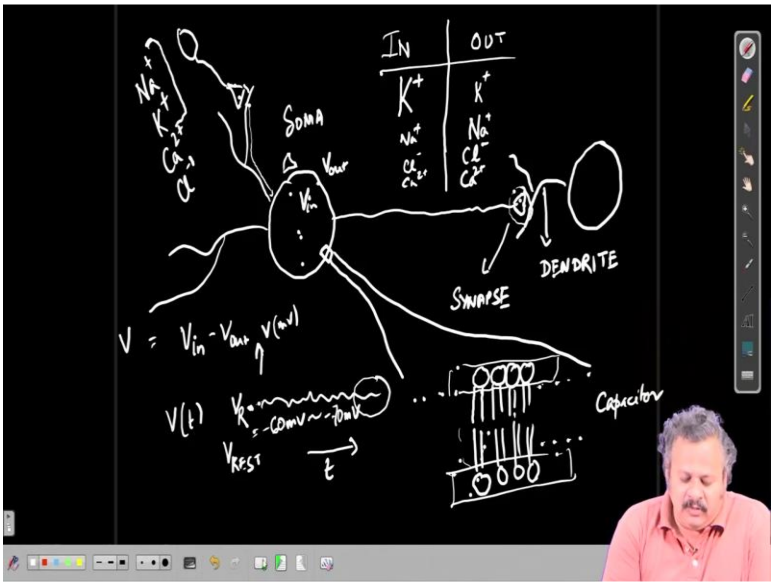

So, axon; so, if I talk of a neuronal cell body which is the soma here and let us say its axon is going on to project, what we mean by project is make a connection with another neuron on its input side which is the dendrite. So, this is the dendrite of the next neuron here. So, this is the first neuron and this is the second neuron and what we form here is what is known as a synapse.

So, an action potential is if we are able to record the membrane potential of a neuron, that is if we are able to measure the voltage inside the neuron and outside the neuron. Then, this over time this V in minus V out we will call this V. This as a function of time if we are plotting for a neuron, they may be because of some noise at some particular voltage fluctuating around it and which we call V rest or V R, which we say V rest that is the resting membrane potential.

So, this axis is voltage in let us say millivolts, this axis is time. And so, neuron at rest remains at a particular voltage; what we mean by remains at a particular voltage is this. V as a function of time is fluctuating around this V R and this V being the V in minus V out. The inside potential and the difference between the inside and the outside potential of the neuron.

So, why at all is there a difference in potential inside and outside of the neuron? So, if you recollect from your chemistry in your 11th and 12th or even earlier, you may remember that is there is something called an electrochemical gradient or electrochemical potential. So, the in the inside of the soma of a neuron has many different types of ions and the external medium that is the outside of the soma has also the same ions, but at different concentrations.

So, the this V rest turns out to be around minus 60 millivolts for the kinds of ions and kind of concentrations they are in or and this can vary. This is an approximate number. This can change based on the different types of neuron, different kind of concentrations up to minus 70 millivolt or even lower. So, the ions that cause this difference in potential in the inside of the neuron and the outside of the neuron is are rather sodium ions Na plus, potassium ions K plus, calcium ions, chloride ions.

And, these are the main players in determining this voltage. And, actually we will see that even with sodium and potassium, we may be able to explain most of the behavior of this spiking and this membrane potential. So, inside the neuron we have a very high, if I make a table here small table inside and outside of the nerve. So, inside we have a very high potassium concentration and outside the potassium concentration is low.

Inside we have a low sodium concentration and outside we have a very large sodium concentration. And, similarly chloride is low inside, calcium is low inside and they are large outside by even an few orders of magnitude for calcium actually. So, this imbalance of ions creates a difference of potential across the membrane. So, now, what is the membrane? The membrane is made up of phospholipids and they form a bilayer.

So, essentially what we have is in the membrane polar head group with non-polar tail groups, two tails like this. And, they are arranged in this form across the cell body and they form a bilayer like this. So, what I am drawing here is a small chunk of the membrane expanded out into this region which is made up of these lipid bilayers. And, this is the whole surrounding and that is what is present even in the dendrites and along the axon everywhere. The entire neuron is covered with such lipid bilayers forming sheath all around it.

So, a lipid bilayer like this with this part polar and this part being non-polar. So, what essentially it acts like is a capacitor because, this part is almost like the plates of a capacitor and we have an insulator in the middle. So, this causes the separation of the charge and this is a very low permeability kind of structure with ions very little possibility of ions to go in and out, but it is semi-permeable. So, ions can flow across.

And so, at equilibrium the concentrations of sodium and potassium are such that the final rest membrane potential at rest when there is no other inputs on to the neuron, no current coming into the neuron or so, it is around minus 60 millivolts to minus 70 millivolts around that region. So, now when I said input, I meant input currents and that happens through these synapses that we have drawn here.

So, for this neuron also there are dendrites and there may be synapse formed by a previous stage neurons axon which ultimately in through a process of neuro transmission which we will discuss in detail later. It injects a current either a positive current or a negative current into the dendrite which travels along the dendrite to reach the soma.

And, there may be tens of thousands of synapses or even 1 synapse on a neuron and the non-linear weighted sum I say non-linear weighted sum of these each of these inputs. Because the way this inputs act finally, on the soma can have many different processes involved. And, it is not a linear or even a simple non-linear transformation from the inputs to the outputs. Simplified versions of those do exist and that is what is used in neural networks, but it is far more complicated than even a weighted sum of what inputs are coming in.

So, a current input that comes into the dendrite through a synapse or this synapse may be directly on the soma. The current that finally, reaches this cell body is what determines what the neuron is going to do with it and that is what we mean by what computation the neuron is going to perform. It is the structure of the dendrites, the different inputs that are coming in at the different locations in the dendrites, what kind of inputs that are coming in.

All these things together matter in terms of what resultant current is going into the soma. And, then based on those inputs the neuron may or may not produce a series of action potentials. And, what we mean by that action potential is if we are recording this membrane potential; let us go to a new page.

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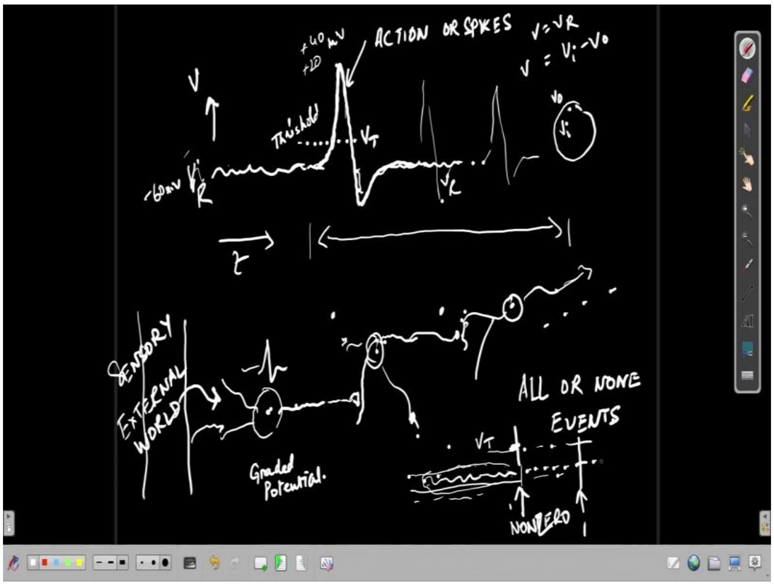

So, we had the membrane potential at V R and so, that is going along. This is around minus 60 millivolts as we said and this axis is the voltage axis, this axis is the time axis. And, at times there will be large excursions of the membrane potential like so. These are what we called action potentials or spikes.

So, remember we have this soma and we are somehow recording this V in minus V out which is our V and at rest this V is equal to V R. So, this voltage can jump up because of the inputs through the dendrites that reach the soma, such that it may cross a threshold. So, I am introducing a new term here which we call threshold which is let us say threshold, which is let us say some particular voltage V T ok.

Once it crosses this threshold, that the membrane potential reaches this threshold; it absolutely must produce this action potential. It will go up in voltage reaching about plus 20 or even more plus 40 millivolts depending on the neuron type and then come back down. And, then there is a period where it goes below the resting membrane potential and then finally, it gets back to its V R. And, remember depending on the input in its synapses and what is reaching the soma, there may be a series of action potentials like so.

So, given a set of inputs onto a neuron the series of action potentials it produces as output, this transformation is essentially the computation the neuron is doing. And, to understand that what we study is different numbers of action potentials that are produced over a period of time by a neuron and how it is related to the input. And, also we are in we know that even the time at which the action potentials occur that also is part of the can be part of the computation not always.

So, there are cases where only the rate or rather the number of action potentials is performing the computation. Sometimes, it is also when these action potentials occur relative to a stimulus onset or an event onset that carries the computation that performs the computation of the inputs that are coming in and transforming it to an output for the next stage neuron.

So, essentially we have a hierarchy of neurons where the first neuron is getting some input. See, when I say first neuron is getting some input we already are saying that there is another neuron before it. So, what does the first neuron get then? So, the first neuron what we mean by the first neuron is something in the periphery and usually it is the receptor some kind of receptor in the periphery, where the first inputs from the natural world comes in. And, this is specifically for the somatosensory circuits, not somatosensory sorry sensory circuits.

So, and for the we will talk in detail about the sensory circuits in a later lecture. And, there we will talk about the first conversion from the physical world into this world of action potential. So, from the world of let us say the speech, sounds or any kind of sound that we are processing or whatever we are seeing in front of our eyes and whatever we are feeling in terms of what we are touching and something that is vibrating and so on in the somatosensory world. And, also something that is smelling like a rose which we can perceive by it is sweet smell.

Similarly, taste of food these are all the sensory inputs that are coming in, in the physical world. And, they are getting converted somehow into this domain of action potentials or spikes which carry the information of the external world. And from there up in a hierarchy it is processed to finally, form the percept of the different things we have. Along with the sensory circuits there will be other circuits that we will talk about.

And so, in that in those other systems we will always see that ultimately the things start from some kind of sensory input. So, going back to our hierarchy. So, there is some external world here that we are talking about the sensory world, sensory external world. Somehow this gets compute this gets converted into electrical currents that produce spiking activity mostly, like the action potentials that we talked about here.

It is the action potentials mostly there are cases where it is not action potentials, as I said there are graded potentials. We will discuss that in a later lecture when we talk about the visual system. So, these action potentials are what are carried forward by the axons to the axon terminal which makes a synapse with the next stage neuron. And, the next stage neuron may be getting many many such inputs as we talked about.

And that may finally, produce a series of action potentials that is carried forward to the next neuron through a synapse and so on. So, it is these action potentials that are getting transmitted after some computation is performed on all the inputs together, that goes on to the next neuron. And, there in the next neuron it is getting integrated with many other inputs and the next stage does some computation and goes forward.

So, this is the general architecture that we will be talking about when we discuss the things related to cognition and sensory inputs and reward circuits and everything. So, the action potentials turn out to be the currency by which neurons communicate with each other and by which actually signals the next neuron about some computation that the previous stage neuron has performed.

And so, in this lecture we will start, we will conclude by discussing a little bit about the action potential process and this the way this action potentials are generated. And, that is because we have certain kinds of channels on the membrane that we have talked about like sodium channels and potassium channels that cause that can explain this behavior of action potentials or spiking.

And, the presence of a threshold which can be shown theoretically also tells us that these action potentials are actually all are none events, all are none events. So, what we mean by that is that it is either occurring or not occurring. So, basically the voltage that we have that can be essentially converted into regions where it is at rest or around rest or when it spikes, that is it crosses threshold and causes a spike and that is basically non-zero and so on.

Wherever there is a spike it is an event or a 1 let us say or a non-zero and the rest of the regions it is 0. But, there is also a lot of information in the region where it is non-zero which is what we call sub threshold. If this is the V T then whatever is happening within the voltage threshold, the threshold voltage is what we call the sub threshold region. And, that also carries a lot of information about what computation is actually being performed by the neuron.

So, with this we will conclude the lecture on the introduction to computation here. And, we will carry forward with more about the details of the neurobiology of computation in the next lecture.

Thank you.