# Neurobiology

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## Week - 02

## Lecture 2.2: Basic electrical properties of neurons

In the last video, we saw how electrical activity is generated in the brain by the movement of charged particles. And in particular these charged particles are basically various ions sodium, potassium, chloride, calcium which move between the inside and outside of the membranes, neuronal membranes. We saw the role of the membrane in controlling this movement, the role of ion channels and various ion exchange pumps. In this video, we are going to see how do neurons compare to various electrical basic electrical components. So, what is the resistance, what is the capacitance, what are the voltages that are present in neurons. And we will also try to build an equivalent representation of neurons in terms of these basic electrical components.

I will start by reviewing basic electrical concepts. So, the first thing we will look at is current. And as you probably already know from your basic physics courses, current is the movement of charged particles per unit time. So, how much charge is moving per unit time that is and that defines how much current there is.

It is typically denoted by the symbol I. The units that we use for measuring current is amperes. But one ampere is actually a lot of current and we do not see these kinds of currents in the actual neural circuits. But the levels of current that we more often deal with are on the order of nano amperes or pico amperes. So, a nano ampere is $10^{9}$ ampere and a pico ampere is $10^{12}$ ampere.

So, these are the levels of currents that we might encounter in a neuron. The direction of current is actually defined by the direction in which positive charge is moving. So, if you have a situation where the charge is carried by positively charged ions, then their movement will tell in which direction the current is moving. But you may also have a situation where the charged particles are actually negatively charged. For example, in the case of electrons in an electrical circuit.

So, this is a very simple electrical circuit with a battery and a wire and let us say a resistor here. So, the positive terminal of the battery is facing this side, then current will flow in this direction. But if you zoom into the resistor, you will actually see the electrons moving in the opposite direction of the current. So, by convention, the current is defined to move in the direction of the positively charged ions or opposite to the negatively charged ions. In the case of neurons, since we have both positive and negative ions, so depending on the type of ion, if the ion is positively charged like sodium or potassium, then the direction in which those ions are moving that will define the direction of current.

But if it is the chloride ions that are moving, then the direction of current will be opposite of the movement of chloride ions. The second concept we are going to look at is voltage also called the electrical potential difference. So, we saw a battery in the last slide. Let us say it is a double A battery. So, it will have a voltage of about 1.

5 volts and what that basically means is that positively charged particles on the positive terminal of the battery has higher energy compared to the negative terminal of the battery. And the difference in the energy is the magnitude of this difference is represented in the voltage rating. So, a 1.5 volt battery has a certain amount of voltage, a certain amount of energy difference. If you have a battery of 9 volts, then it would have 6 times higher energy difference.

Now, if we connect these two points by a wire or and every wire would have some resistance, so let us say a resistor, then we basically provide a path through which charge can flow from one side to the other. And if you have a positively charged particle here, it would like to go from this higher energy side to the lower energy side. And in that process, it can release some energy. And if you have negatively charged particles like electrons here, then they would move from this side to this side and again they can release energy in that process. So, this is how an AA battery can be used to generate energy.

So, you can use this energy released by the movement of electrons to power a clock or to light up a bulb and so on. The potential difference is denoted by the symbol V typically and the unit of it is volts. In neuroscience, we deal with voltages that are typically in the range of minus 100 to plus 100 millivolts. So, somewhat lower than a voltage but not very low. And now let us see where the voltages are present in a neuron.

So, as we saw in the last video, there is actually an uneven distribution of charged ions between inside of the membrane and outside of the membrane. So, if you have a neuron and this is the inside and this is the lipid bilayer, you remember the membrane is made up of lipids which are facing the polar heads are facing outside or inside. So, you have a bilayer and the middle of this layer is hydrophobic. So, it is an impermeable membrane and there is a differential distribution of various types of ions between inside and outside. And that difference in the differential distribution creates electrical potential.

So, we can say that there is a potential membrane potential. So, typically the outside is considered as the reference point. So, we can say that we will treat it as the reference point and then relative to outside we can say what is the voltage of the neuron inside and that is known as the membrane potential. Now, let us consider resistance. So, resistance as you know is the hindrance or impediment that is posed by any medium through which the current is flowing.

If the current can flow very easily through a wire, then we would say the resistance is low. But if the wire is thin or if it does not have enough electrons and if it poses more resistance or more hindrance, then we will say it has higher resistance. In the case of neural circuits, it is not the electrons that are flowing, it is the other ions and then the resistance will be how much hindrance is present for the movement of these ions. The symbol that is used to denote resistance is typically R and the unit is ohm which is typically shown by the symbol, Greek symbol omega. Now, in the case of neurons, let us see where the resistance comes from.

So, of course, the membrane itself is impermeable to the ions. So, we could say it has infinite resistance and we typically do not even think of the membrane as a resistor because it can simply be thought of as an impermeable barrier. The region where the current flows through are the ion channels that are embedded within the membrane. And because these ion channels are proteins that have a finite sized pores through which the ions flow, these pores are not completely open or it is not that the ions can flow freely without any hindrance at all. Because of the finite size of the pore, there is certain hindrance and that is where the resistance comes into play.

These channels present certain resistance to the flow of current and different channels would have different resistance values. And now let us see if you can guess what kind of resistance values we would encounter in neuroscience. Pause your video and see if you can guess it before I show the answer. Okay, so the values that we see for resistance are actually pretty large. So, we can see resistances that are on the order of a million to a billion or even more ohms.

A million ohm is also known as a megaohm and a billion ohm is also known as a gigohm. So, we typically say the resistance are in megaohms or gigohms. So, now we can update our representation of the membrane. So, we are thinking of a piece of a membrane here and the membrane itself the lipid part is impermeable, but there are ion channels that we can represent as a resistor. So, now we have we can put a resistor between these two points.

So, we saw that there is already a potential difference between inside and outside and between those there is there are resistors which are basically representing the ion channels. For building an intuition about current flow, I sometimes find it useful to compare it to the flow of water. So, let us say you have two containers that are filled with water and they are kept at different heights. This one is at a more height and this one is at a lower height and these two containers are connected by a tube through which water can flow. Now, you can imagine the water in this container will be at higher energy compared to water in this container.

So, water will flow from here to here from high energy state to lower energy state and in the process it will release some energy. So, this hydraulic pressure difference is similar to voltage difference in electrical circuits and the current will flow from higher voltage to lower voltage. We can say that the quantity of water is similar to charge in an electrical circuit and the rate of flow of water is analogous to the current in an electrical circuit. And what would be a resistor in the case of this analogy in water system? So, the resistor is the tube. If the tube is big and water can flow through it easily, then we can think of it as having very low resistance.

It is like a conducting wire, but if the tube is narrow or it has some narrowing in middle, then it will offer a lot of resistance to the flow of water. So, it can be thought of as a resistor. So, overall we can say that the rate of flow of water will depend on two things. How much height difference there is? So, what is the hydraulic pressure difference? If the difference is large, then the current will be more. So, flow is proportional to the pressure difference or current is proportional to voltage.

And the other parameter that will affect the rate of flow is the resistance. So, if there is more narrowing or if there is more resistance, then the current will be smaller. So, current is inversely proportional to resistance. And with appropriate units, we can say V is or I is V over R or V is equal to I R. In the SI units, 1 volt is equal to 1 ampere times 1 ohm.

And a corollary of that is if you have 1 nanoampere current and 1 mega ohm resistance, then it becomes equivalent to 1 millivolt. So, and because these units are commonly used in neuroscience, it is sometimes useful to remember this shortcut. 1 millivolt is equal to 1 nanoampere times 1 mega ohm. The next property that we will look at is conductance. It is actually not an independent property.

Conductance is actually just the inverse of resistance. The reason we use conductance is that sometimes it is easy to talk in terms of how convenient it is for current to flow through a medium or through a wire rather than talk about how much hindrance that wire or medium poses to the flow of current. So, conductance is the ease with which current can flow. It is denoted by symbol G and we can write that G is equal to 1 over R. The unit for conductance is Siemens S, which is equal to ohm inverse.

So, if you have a wire whose resistance is 10 ohms, then you already know that the conductance of the wire is 0.1 ohm inverse or 0.1 Siemens. And in the case of neuroscience, since we deal with resistances that are on the order of 1 mega ohm or 1 giga ohm, so the corresponding conductances would be 1 micro nano Siemens. Now our ohms law says that V is equal to I is equal to V over R.

We can replace this 1 over R factor by G and the ohms law becomes I is equal to V times G. And what that essentially means is that if you have two points that have a certain potential difference V, then for the same potential difference if those two points are connected by a larger conductance, then you will see larger current. So, current is proportional to G. The more conductance there is, the more the current there will be for a given voltage. In the case of our neuronal membrane, we have a certain potential difference inside relative to outside and the current can flow through these ion channels.

So, these ion channels can also be described in terms of their conductance. If the conductance of these ion channels is more, then we will see more current flowing through the neuron. One advantage of looking at conductance rather than resistance is that conductances add up when they are in parallel. So, you know that resistances add up when they are in series, but when they are in parallel, then you have to do 1 over resistance becomes 1 over R1 plus 1 over R2. But in case of conductances, conductances add up when they are in parallel.

So, it is easy to find the total conductance if you know the conductance values of different channels that are connected in parallel.