Neural Science for Engineers
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Lecture - 03
Analogy between Living Systems with Semiconductor Structures

So, in the previous session we spoke about how information systems are present within various biological entities and these systems have evolved to various extents within the rich spectrum of life. So, you have single celled organisms which have very basic server systems within the cell with very minimal interaction with the outside environment.

They have very basic sensors which interact with the outside environment when we grow into more multicellular organisms we have seen that the cells have specialized themselves into different systems which can be either tissues or which can be organ systems.

Now, one of the organ systems decided that it is going to take care of all the management tissues within the organism as well as interact with the information, which is integrate the information which comes from the outside and also guide the effector system for optimal survival and propagation of the organism. So, that is the nervous system.

Now, with more sophisticated interactions with the environment there was the threat perception that external agents such as bacteria, viruses which are there within the environment and which try to delve in other organ systems, other living beings for their own survival, they need to be perceived and neutralized for the survival of the organism that is how the immune system develops.

So, evolutionarily this it is not one after another, they develop simultaneously at various time scales and that is how things have developed. So, hormones take care of the internal system. So, they keep the checks and balances within the body. So, these are four distinct entities which I thought should be highlighted.

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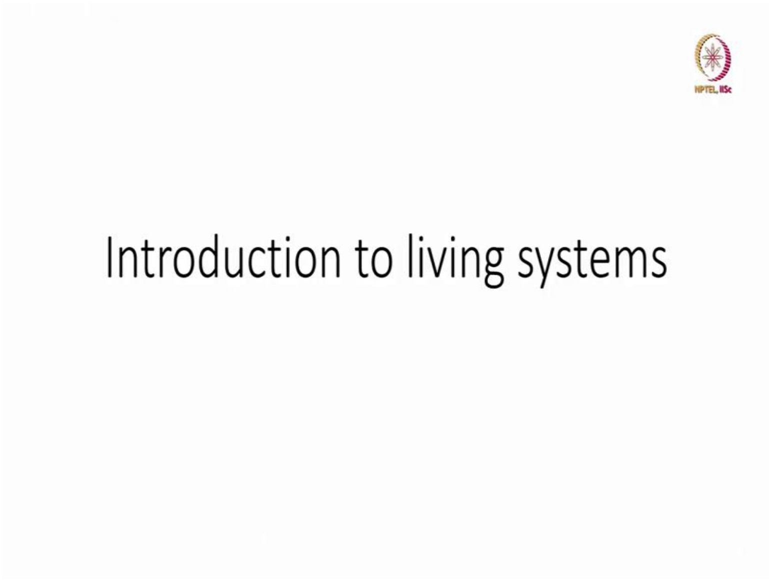

Now, after an introduction to the information systems I would like to give an introduction to living systems in general. So, living systems is anything which is life. So, what is the structural and functional basis of life as we understand and its importance? Because the nervous system itself has life and the mechanisms which guide living systems to live are directly responsible for the function of the nervous system as we progress later on. So, a deeper understanding of how living systems exist and the mechanisms of underlying that is necessary for progressing further.

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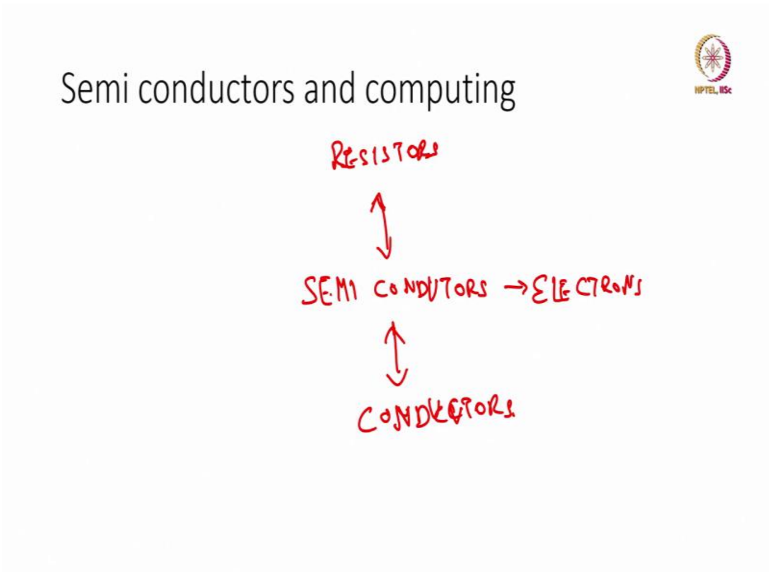

So, I did promise in my introductory lecture that we would look at systems in engineering and try to develop concepts which can link between the two fields. So, that is how I feel like it is easier to understand in terms of things which you have already understood in some part of our academic career or work.

So, I will start with semiconductors and computing. So, people from engineering realize how important semiconductors have been to the development of electronics. And in general, to the entire computing hardware and software which we have now. So, if you look at what semiconductors are, semiconductors basically are entities which can conduct electrons, electricity and they are halfway between resistors and conductors.

So, resistors do not transmit electricity, electrons and conductors transmit or conduct electricity. So, semiconductor is halfway through. So, only the discovery of semiconductors which happened quite late in our evolution help the development of these various scientific fields associated with information technology as well as computing and several other branches of study.

So, what I would like to highlight is the development of semiconductors was a very important landmark and that forms a landmark where you have a before semiconductor era and then after semiconductor era and that makes a lot of difference. So, the beauty of semiconductors is having properties of both resistors and conductors.

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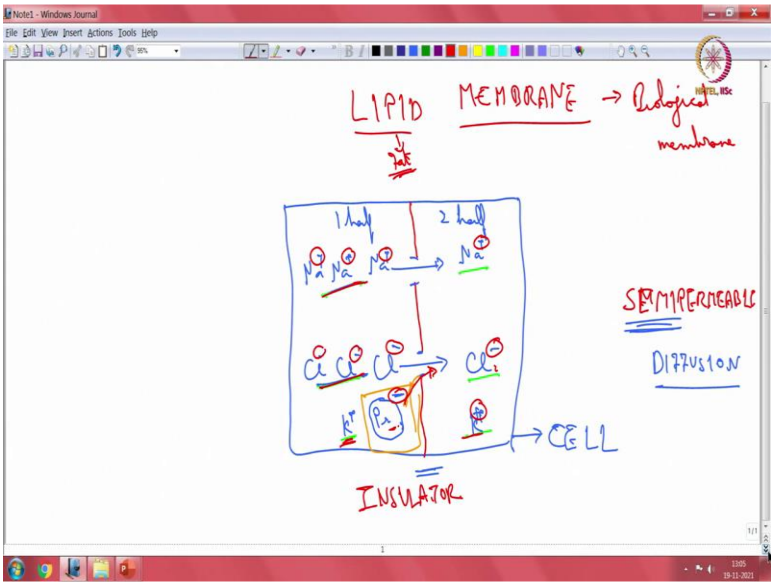

What is similar to biological systems and semiconductors is something called as a lipid membrane.

So, lipid membranes are the classic examples of biological membranes and lipid membranes are fat and as such act as an insulator. So, basically what happens is if you keep a lipid membrane within a container. So, the container is an example for the cell. So, we will develop the model within the cell and then progress on to other entities.

So, you have a membrane which divides the cell into two halves. So, there are 2 halves and then you have ions within that. So, the conventional ions which are there are sodium and chloride. So, you have sodium and chloride and you also have potassium. So, most of biological electricity is ionic electricity.

So, we will be using a lot of ionic electricity as opposed to electrons which form, but partly form the base entity for all electronic study and engineering study. So, the entire work which is done by the nervous system by living systems are through ions which is so, ionic electricity forms the basis of the functioning.

So, as long as the lipid membrane exists, you have entities which are different, and you can have differing concentrations of both on different things and the membrane is basically an insulator. And there does not exist any transfer of material across the membrane.

Now, it becomes interesting if we make this membrane semi permeable; when we have a semi permeable membrane what happens is you have openings within the semi permeable membrane. And then there are these ions which diffuse from one direction to another direction. So, say for example, we have excess of sodium and chloride and one of these ions move over here because of the concentration gradient across the membrane.

So, these follow laws of diffusion and by which the concentrations become equal on both sides of the chamber. Now, when we use the term semi it also indicates that it need not be permeable as such to as such to different kinds of compounds.

Now, biological compounds I already introduced to you, entities called proteins which are fairly large molecules, and they are also charged molecules. So, we have a biological scenario in which the proteins which are large cannot go through the membranes which are there within the membrane. So, what happens is though there is free diffusion between sodium, there is free diffusion between chloride.

So, there is free diffusion between sodium, chloride and potassium, the protein cannot go. So, the protein is not able to go from one part of the chamber to the other part of the chamber. So, that is because the membrane is semi permeable and the protein molecule is large and the protein is not able to go from this part of the chamber to the other part or 2nd half of the chamber.

So, we have a concentration gradient for proteins across the membrane into two halves of the container. So, this changes the scenario a little bit, because initially we were looking at concentration gradients of sodium, chloride, and potassium. So, and these can freely move from one side to the other side, but here actually we have made it a little more tricky because there are some entities which are not able to go, but which are charged.

So, not only is the there are multiple factors in play, but we need to achieve equilibrium across both halves because there is a closed chamber. So, there is a closed chamber and there is a semi permeable membrane across the two and then you have differing concentrations of charged particles within both halves. So, that is the initial state of affairs.

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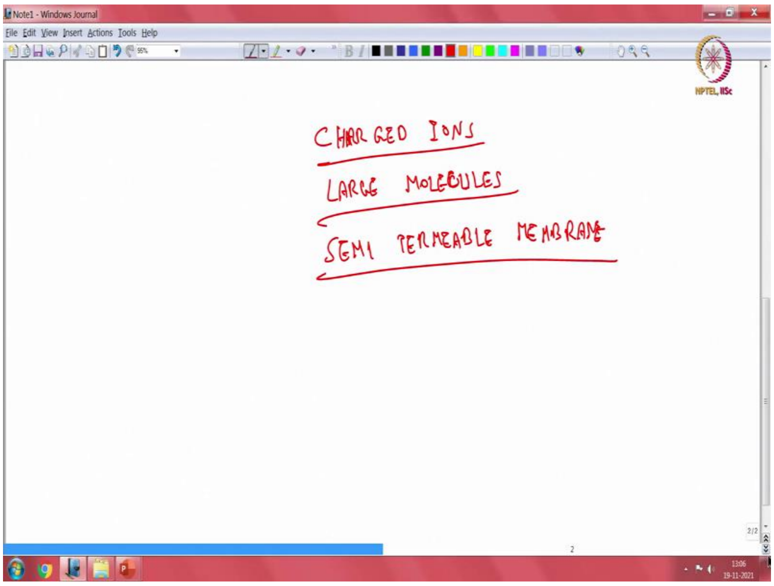

So, let us list it out. So, we have charged particles, molecules, ions, then we have large molecules and then you have a semi permeable membrane. So, these three things bring about a very interesting interplay of these agents I think which we will discuss now.

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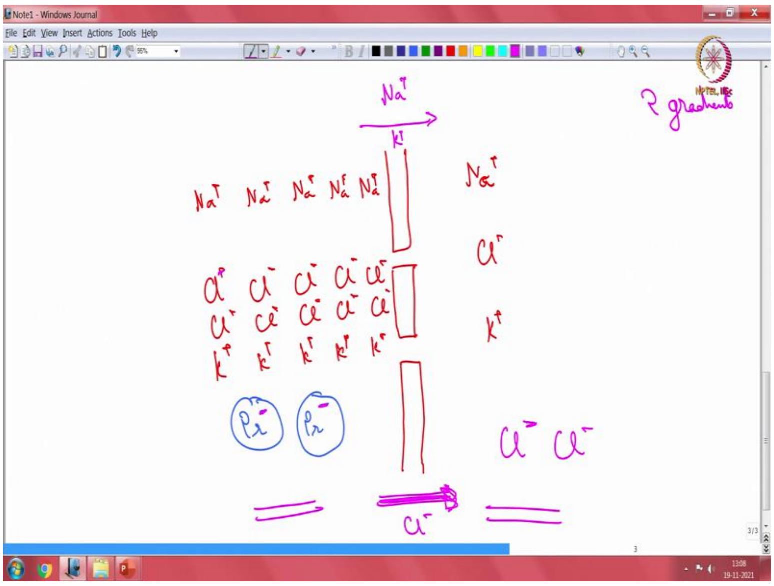

So, going back to the semi permeable membrane. So, semi permeable membrane has got small openings and two chambers where we have sodium, chloride, and potassium in solution.

So, we will have larger numbers. So, and then to mix and make the things trickier we have got protein, need not be the same protein, there are different kinds of protein and you know on the opposite side we have lesser concentrations of sodium, chloride and potassium.

So, if we look at what happens with this thing, we see that there is a concentration gradient for sodium. So, sodium moves from here to here, chloride also moves, but for a different reason, potassium moves from this direction, now chloride actually even has a problem with the negative ion of the protein. So, to achieve parity there will be a larger amount of chlorine moving to the other side, now this is to achieve net ionic equilibrium. So, you have two concentration gradients.

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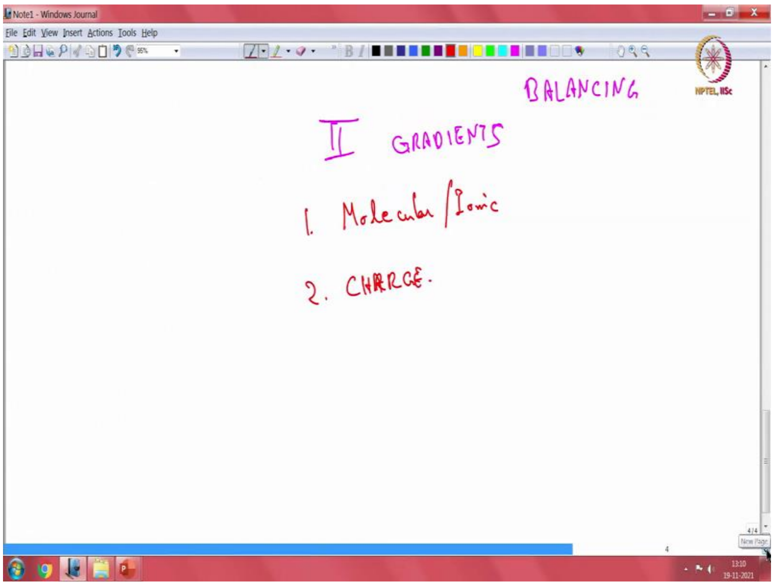

So, we know we have come to the conclusion that balancing has to happen for two gradients. So, the first is the concentration of the entity. So, molecular gradient or ionic, then second is the charge. So, we understand from the previous one that it is completely asymmetrical. So, you have a membrane which prevents the free diffusion of entities from one side to the other side.

Now, entities are used to, because sodium is very different from proteins, proteins are large molecules with charge. Sodium has got a single positive charge, proteins can have larger amount of charge because they contain various kinds of, they have amino acids which can produce large amounts of charge on the surface of the protein.

So, now there is an imbalance between two parts of the cell, parts of the container and this is when at equilibrium you will have different concentrations of chemicals that is the ion versus protein in both the sides, one based upon diffusibility, say protein cannot go from one side to the other side, ions can go from one side to other side, but the ion cannot freely go across the concentration gradient because there is a charge variation between both the sides of the container.

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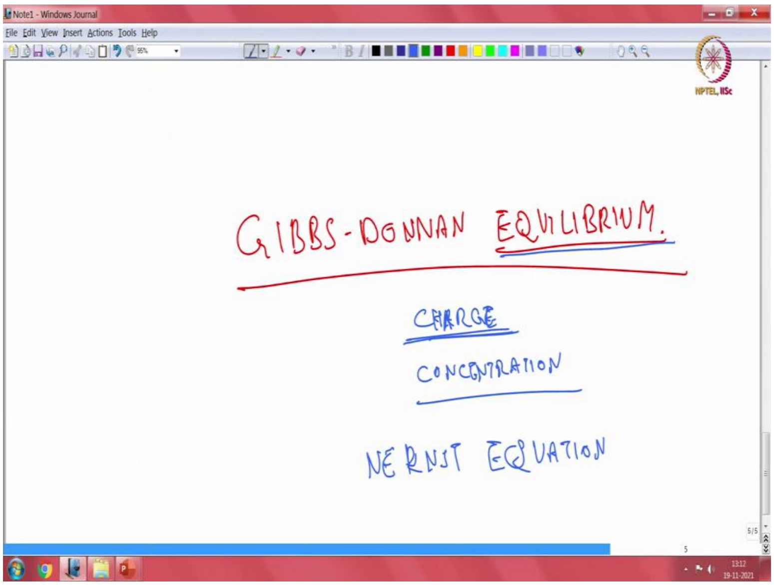

So, the balance which is generated is called as the Gibbs-Donnan Equilibrium. So, Gibbs-Donnan equilibrium refers to the state of equilibrium between charge and molecular concentration. So, this is the equilibrium which happens because of the balancing of two different kinds of entities you have charge which is differing on both the sides, you have ionic gradient. So, you have an ionic gradient and then you got a concentration gradient.

So, for differing entity, differing concentrations of proteins on both sides and differing concentrations of ions on both sides, charged ions on both sides, you have an equilibrium which is established based upon this thing, and it varies. So, there are chemical formulas for calculating that and then, that is what is called as the Nernst Equation you can look upon that I will project it at the end of this slide.

So, the Nernst equation determines the method by which charge is generated on one side or the other. So, you have ionic concentrations, you have molecular concentrations and then there is an equilibrium so; obviously, there is going to be some discrepancy in the charge between the two sides and that charge can be calculated by something called as the Nernst equation.

So, this is the semiconductor equivalent theory in biology. So, what is the relevance of semiconductor, the Gibbs-Donnan equilibrium has the same importance in biology. So, the introduction of asymmetry across two biological cavities by a single semi permeable membrane is what is being reflected by the equilibrium and that is the state in which all living beings exists. Now, I will make it a little more interesting and a little more tricky.

So, where is life in this you know, you have just two containers and you have got something called as a protein on one side and you got ions and then they move across. You have equilibrium and you have inequality on both sides. So, there is a concentration inequality because of the protein being on one side and the charge inequality because charge has to match with the ionic concentration. So, that is the concept of equilibrium versus this. So, life or the living cell does one extra stuff.

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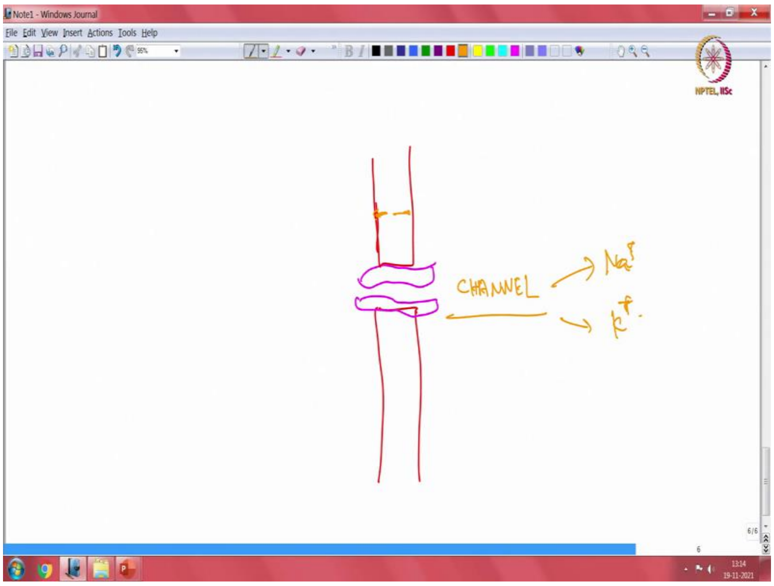

So, we go back to the entity. So, these pores as such which I have written in very simple as a hole over here will actually be controlled by something else. So, you have a protein, and that protein has got an opening. So, this is called as a channel. So, you have a channel for sodium, you have a channel for potassium, you just increase the complexity of this stuff, but still it is the same.

So, instead of having a random opening in a lipid membrane lipid bilayer so, incidentally it is a lipid bilayer. So, you have lipid molecules in both the sides and there are lots of theory I do not think which is relevant for the current discussion. So, you have channels which go across the membrane, and which allows different things to go across and they are specific for specific ions. So, sodium channel allows only sodium ions and potassium channels allow only potassium ions.

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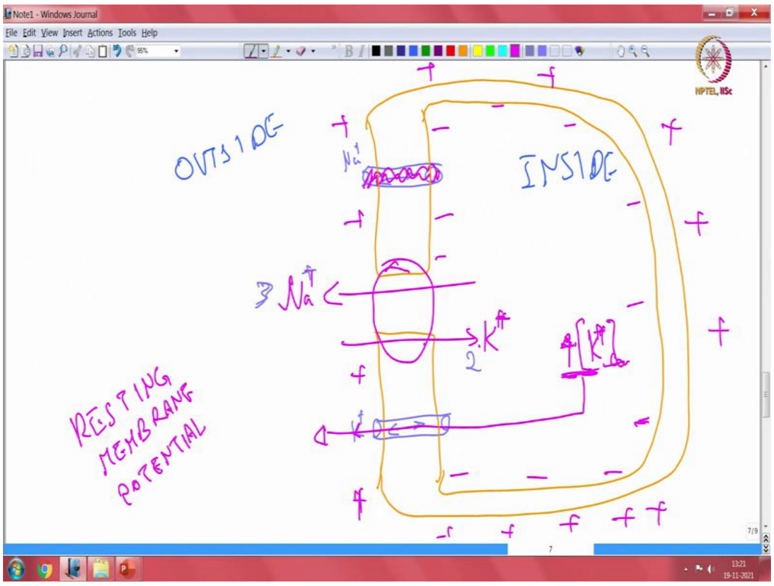

It becomes a little trickier in the next slide where we introduce the concept of pumps. So, a pump does a little more complex stuff. So, it does an exchange. So, we now we have to expand our knowledge. So, when I started the discussion, I started with a container with a single permeable membrane in which you have ionic equilibrium on both sides, we stepped it up a little more with the same container with a semi permeable membrane which allows only some stuff from one side to another side.

In the third part of the development, I started with a container with a semi permeable membrane, but with unequal stuff on both sides. So, that is the basis of the ionic equilibrium and the molecular equilibrium concentration and so that is the Gibbs-Donnan equilibrium.

So, what has changed is first I told that the ion channels are specific. So, it is just not that there is a pore through with sodium potassium or calcium chloride goes through, but it is very specific. So, sodium channels allow only sodium, potassium channels allow only potassium, chloride channels allow only chloride.

So, it becomes a bit trickier, but when you put in this thing. So, you have pumps now, I did not complete my previous statement. So, we started with a single container, now if you imagine one of the parts of the container to be the cell and the outside to be the general outside then we are looking at a cell and the extracellular part.

So, in higher organisms you have something called as extracellular fluid and then you got something called intracellular fluid. So, what is within the cell is what is within this thing. So, this forms a cell ok and this forms the outside and this is the inside of the cell. So, we have created the pitch.

So, as I told earlier so there are openings for sodium, there are openings for potassium. So, the gradient determines, say concentration gradients or the ionic gradient would determine whether these things go in either direction, but the pump is different, the pump pumps out potassium, sodium and takes in potassium.

So, what happens ultimately is that it not only pumps out potassium it also pumps it out unequally. So, you have 3 sodium for every 2. So, there is a discrepancy. Now, we already realized that there is a discrepancy because of the semiconductor membrane not transferring ions equally, but this is also added problem that we have a pump which is doing a very funny job. So, it expends energy and then it throws out sodium and then takes in potassium.

Now, ultimately so what happens is the potassium concentration increases. So, we do not have such kind of channels for free flow of sodium, but there are channels for free flow of potassium. So, this extra potassium tends to leak out through here and ultimately what happens is because of the high concentration gradient. So, this is the basis we are applying the Gibbs-Donnan equilibrium at this stage.

So, we noticed the basis of the equilibrium to be concentration gradients and electrical gradients, now we are seeing that the pump is skewing the picture. So, the pump not only changes the ionic picture, but also is changing the net charge. So, sodium is pumped out which is positive, potassium is pumped in, but potassium again has got a gradient to the outside. So, higher potassium ions so that is the concentration of potassium which is increased and that causes potassium also to diffuse out beyond a certain limit.

So, what happens is net generally the charge on the inside of the membrane is negative and the charge on the outside of the membrane is positive and thus we have something which is alive. So, a single pump which uses energy to control the equilibrium of the ionic equilibrium of the cell is what is actually responsible for life, now as I told you it is an energy process.

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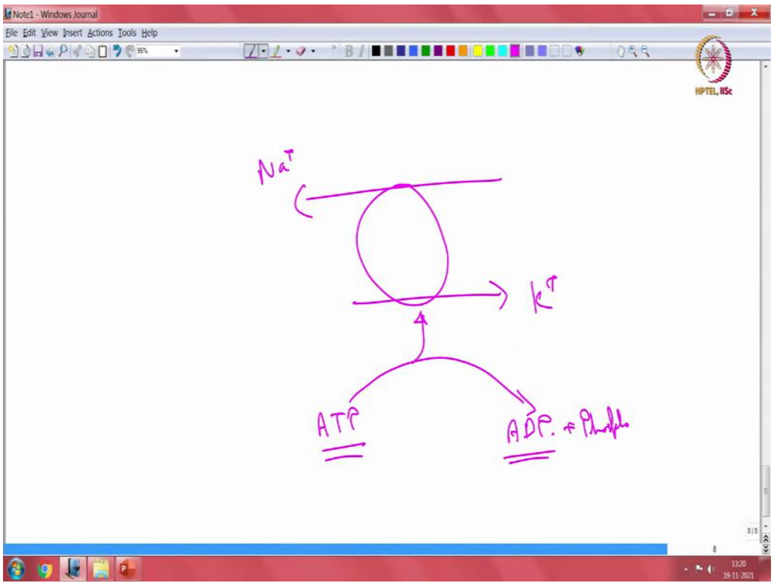

So, it the resource of energy is something. So, you have this sodium and potassium is through the chemical reaction of ATP to ADP. So, adenosine triphosphate gets converted into ADP + phosphate and the energy is what is responsible for this action. So, the generation of energy is coupled with the generation of charge. And the generation of charge is what is responsible for the negative charge over here and that actually is called as resting membrane potential.

So, the generation of resting membrane potential is the function which says that a particular cell is alive or not and when the power source, the source which generates the ATP. So, it requires both oxygen and glucose fatty acids and things like that. So, when that function is lost the ability of the cell to maintain its charge disequilibrium.

So, there is an equal loss of equilibrium between the outside and inside and inside is being kept negative and once that equilibrium is lost the cell is thought to be dead. So, that is the connection between life, maintenance of charge and ionic concentrations across cells and this forms the basis of all living organisms except viruses.

So, now this is a very fundamental topic in biology and it has the same value as I understand with semiconductors in engineering. So, you need to understand how semiconductors are to have a fundamental understanding of electronics and maybe even computer science.

It is the same level of understanding which you need to have between how equilibrium and inequality exist across a semi permeable membrane within and outside a cell and how the membrane potential is generated. Now, once this is understood I think we can progress on to excitable tissue which is nervous tissue and muscle tissue which we will deal with later.

Thank you.