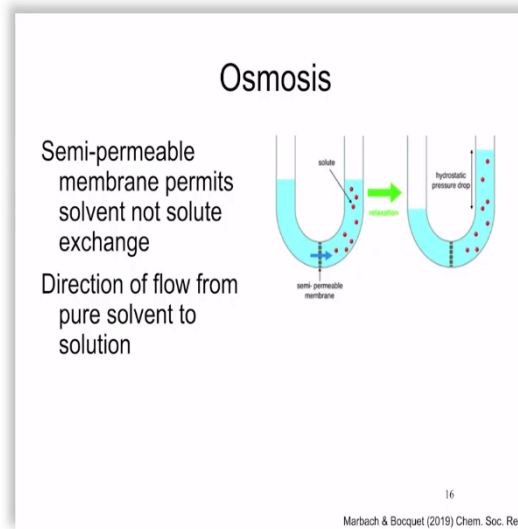**Cellular Biophysics: A Framework for Quantitative Biology**
Professor Dr. Chaitanya Athale
Department of Biology
Indian Institute of Science Education and Research Pune
Energy and Thermodynamics of Life
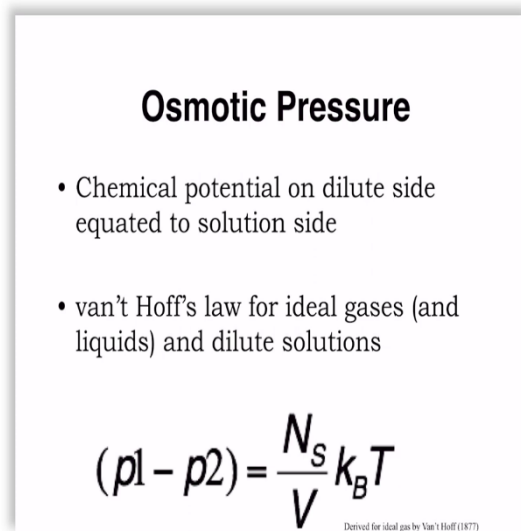**Part: 02**

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And we are going to lead to a model of living systems that perhaps mimic one of the most important criteria for life. And I urge you to go back and revisit what you wrote down as what is living, and what is not living. This is exactly the reason why we had that exercise. It was I think part of your quiz 1, take home quiz, sleep on your quiz, write it 2 minutes before the deadline quiz, same one. And that is the fact that most biological organizations, the smallest being a cell have a membrane that separates them from the environment. In fact, these membranes have a very peculiar property, that they are semi permeable.

In other words, they permit solvents to be exchanged, but not solute. And the direction of flow then, is from pure solvent into the solution. And this movement of the solution molecule, solvent molecules I am sorry, across the membrane, semi-permeable membrane into an arm of this structure, which looks a bit like a U manometer is a relaxation process, which ironically, results in different heights of the fluid column across the semi-permeable membrane. The height of that itself, as you remember, is then determined by the hydrostatic pressure drop. The force that drives this is osmotic pressure.

And the distinction between osmosis and diffusion is that diffusion has no direction. In that particular case of diffusion, the molecules indeed attempt to distribute themselves evenly. If

they were initially unevenly distributed, or even if they were evenly distributed, they will still move around, and could argue ensure uniformity. Whereas in osmosis, there is directional movement of molecules, and this directionality in some senses is given by the semi-permeable membrane.

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So, in that sense, there is this driving force can be defined in terms of an osmotic pressure, in terms of a chemical potential, which we can be equated on diluted solution sides. And this exact equation is given by van't Hoff's law, based on ideal gases, and liquids, and dilute solutions. Which states that the pressure gradient p 1 minus p 2 is equal to the number of solute molecules upon the volume times k_B T.

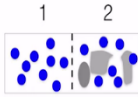And you have probably seen some other formulations of it, which involves the universal gas constant and not k_B. What is k_B? This is our Boltzmann's constant. Incidentally, van't Hoff derive this solution in 1877. Yes, also pre 1900s, we are in 2020 now.

So, osmotic pressure for the sake of that p 1 p 2 definition, defines 1 as the compartment with just the solution. While, 2 is the one with the solution and solute molecules, I am sorry, 1 is just the solvent, 2 is the solution.

And the semi-permeable membrane results in a fluid flow to compensate for the entropic cost. This entropic cost is a funny one, because it suggests that there is some degree of order in compartment 2, where there is a concentration of solutes. And this order by the second law of thermodynamics tends to get more disordered, and the only way to do it is to create more redundancy in the positions, and that is what drives the fluid flow.

This is a mechanistic explanation and we will get to some more details of this in a bit. But the van't Hoff's law then is indeed as I said, Δ P is N by V times k_B T or C R T that is your C being the concentration, R being the universal gas constant, and T being temperature.
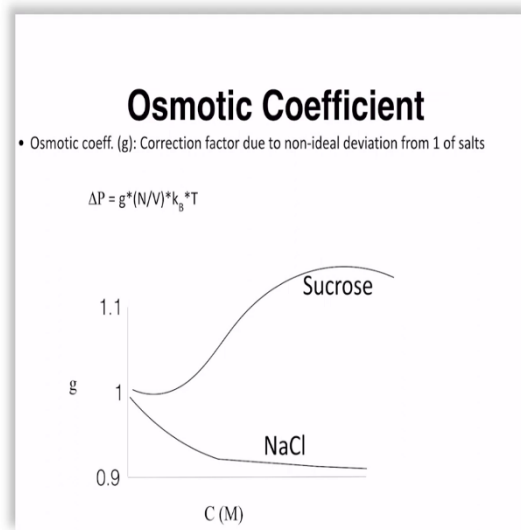
There is a slight modification to the van't Hoff's law, which requires a correction factor g. Because van't Hoff derive this for ideal gases and dilute solutions which states that at higher and higher concentrations of a solute, this value of g deviates from 1. So, as you see in the case of sodium chloride it decreases, and in the case sucrose it increases. Indeed, in addition to all this the calculation of concentration of or number of particles N of the solute itself gets complicated when you have ionic solvent, solutes, which are capable of complete dissociation into Na and Cl minus leading to a factor of 2. And you are aware of this.
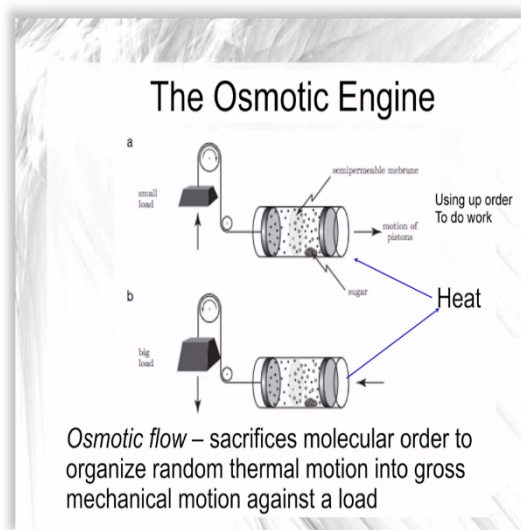
And this brings us finally, to a thought experiment, which is called the osmotic engine. So, the osmotic engine thought experiment is framed as follows. Consider a cylindrical chamber

separated by a semi permeable membrane, in which there are two frictionless distance. Those grey blobs, the distance. The left side piston is connected via pulley system to a small mass which can be lowered or raised in height. Since these pistons are frictionless, their movement is not hindered by anything it is an ideal thought experiment. And they will respond to what happens in the cylinder, in the chamber where the solute and solvent are placed.

Now, in across the semi-permeable membrane on the right hand side compartment, a small amount of sugar is added into it and assuming that this is an ideal system, it instantaneously dissolves and forms the solution. So, right hand side as solution, left hand side as solvent which basically means that there will be flow as we just discussed. Due to the osmotic pressure from left to right. Now, given that in the simple meaning to say classical regime fluids are incompressible, which means they cannot, their pressure cannot be reduced, or increased.

Therefore, the fluid, the solvent will flow left to right, in order to conserve volume, because otherwise there will be less dense water, and that does not exist, that is the meaning of incompressibility. When that happens, as you can imagine, the motion of the piston drives that small load up, because the pistons have both moved rightwards.

Now, this is nothing but work, it is mass acted upon by gravity which is force, moving through some height, z let us say. In other words, the work is defined by force times distance. And funnily enough, this work was done by adding sugar into one side of the piston that is crazy. How did that happen?

And we argue that this is primarily due to the fact that the tendency of a thermodynamic system to go from order to disorder is the prime driver. In other words, the entropic maximization, second law of thermodynamics is the prime driver that uses up order to do work.

In a similar sense as what I had asked earlier, what is this order? Whose order are we talking about? Well, we are talking about the order of the molecules in both the compartments, where on the right hand side solute is arranged in some fashion at some concentration. And how it happens is through the absorbance, absorption of environmental heat and movement of molecules.

Now, there is an opposite scenario you can imagine, where the mass is very large, and it acts downwards. And the sugar is still in the right hand side compartment. But, because the mass

opposing this osmotic pressure is so large. We are still talking qualitatively, that instead of going right, both the pistons move left. Which means that the water from an already, from the solution compartment moves into the solvent compartment, making the solution compartment even more concentrated, the volume reduces. This process gives off heat, and is also then the reverse of osmosis, or otherwise known as reverse osmosis, this is exactly what is used in some kinds of filtration systems.
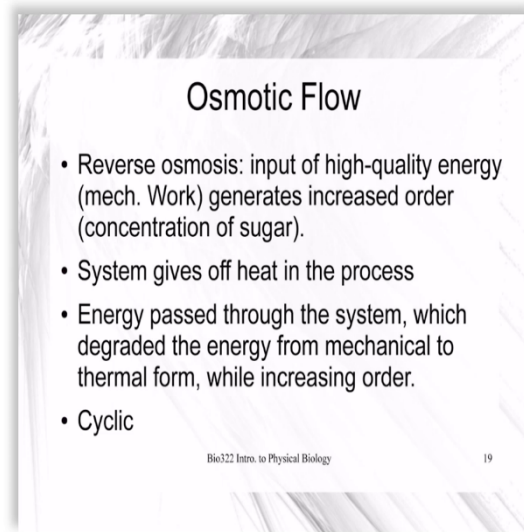
So, to summarize osmotic flow sacrifices molecular order to organize random thermal motion into gross mechanical motion against a load. So, remember what I said earlier about high quality and low quality work, this is what we were talking about. In other words, we can in this particular case, convert random undirected pointless motion of particles into nice directional, unidirectional force times distance kind of work, if we set it up correctly, as in the osmotic case. Is a sort of like the role of guide in a PhD. Lots of enthusiasm needs to be directed.

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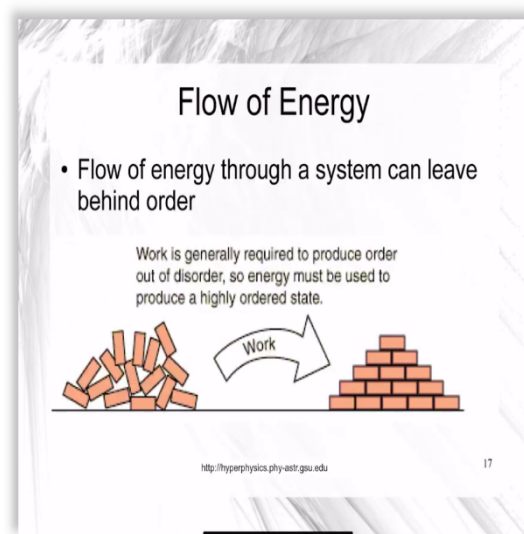
Now, conceptually, this is an idea that the flow of energy through a system can leave behind order, and work is required to produce order out of disorder. So, energy must be used to produce a highly ordered state.

So, reverse osmosis, which is the opposite of the standard osmotic process, takes the input of high quality energy, mechanical work because of mass is larger it pushes the pully system down, and generates increased order concentration of sugar. And that is exactly your analogy for a living organism. Where, by the investment of some high quality energy, or expending high quality energy, you can create order against the very law of thermodynamics as stated by the second law.

In the process, the system gives off heat. You can say it dissipates heat, and the energy that pass through the system degraded into thermal form in the process of increasing order. And you can imagine that this can be done cyclically. And that is life. So, to answer the question, what is life, this is the thermodynamic conception of life.

So, in summary, the conservation of energy, which corresponds to the first law of thermodynamics states that the change in internal energy is the sum of energy transferred as heat to a system, plus the work done on a system, and you are familiar with this. At the same time, spontaneous change of physical and chemical systems can be measured by entropy. And in the words of Kelvin, no process is possible, in which the sole result of the absorbent, absorption of heat from a reservoir and it is complete conversion to work, you cannot perfectly convert heat into work it is inefficient.

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At the same time, the second law of thermodynamics states that the change in entropy is nonzero and positive of an isolated system increases in the course of spontaneous change.

And as total is the entropy of the system as well as its surroundings, which gives us back our non-vitalist. In other words, integration of thermodynamics and biophysics.

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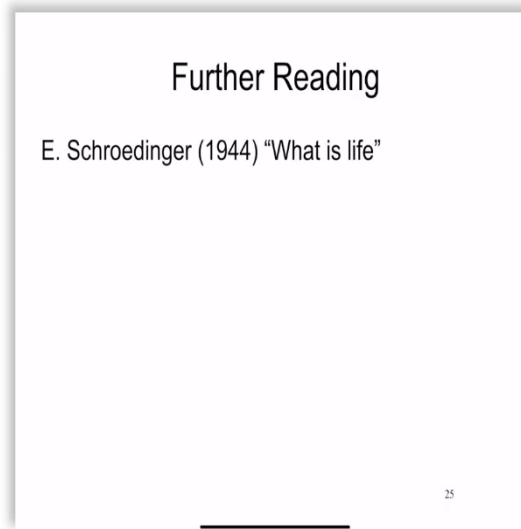
So, for further reading on the topic, I refer you to Erwin Schrodinger, what is life? And this theme ends here because it was a short prelude. And we will keep returning to thermal energy again and again in the next few lectures.

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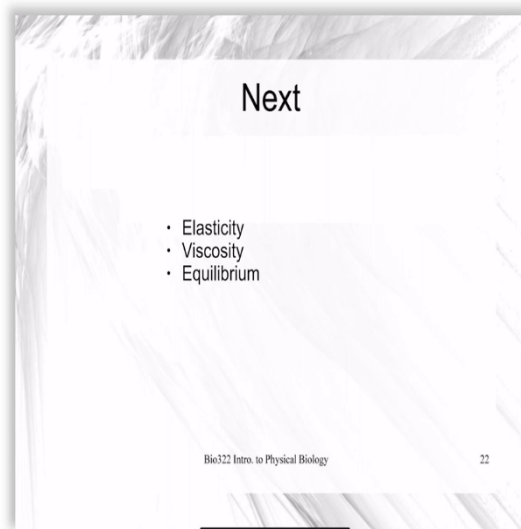
When we visit the topics of elasticity, viscosity and equilibrium, thank you.