Cellular Biophysics: A Framework for Quantitative Biology

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Energy and Life- Osmotic Engine

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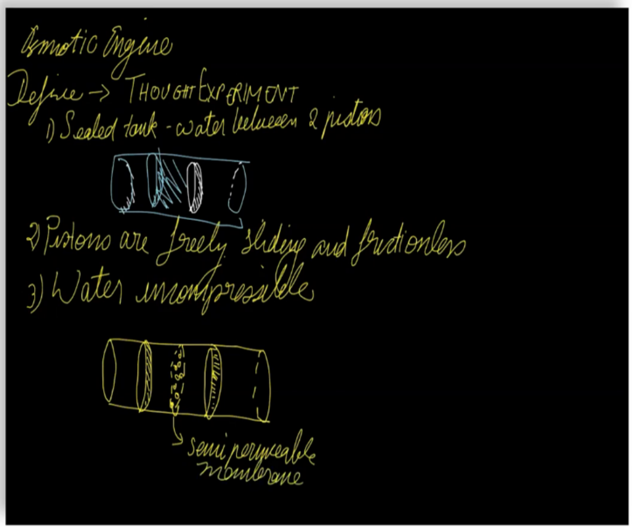

For this module, we are going to talk about the osmotic engine. Now, I am first going to define the osmotic engine as indeed a thought experiment. And like all thought experiments, this one has some idealizations in it. And this from an ideal spring, an ideal pendulum, in cell even that there are simplifications involved.

So, what are these simplifications? So, the first simplification is that we are using a sealed tank with water between two pistons. Now, let us just try to see if this can be made beyond our imagination into an actual drawing. So, we have a cylindrical tank, it has two pistons. These two pistons for this whole thing to work have to be frictionless.

In other words, they are freely sliding, which also in a way sense implies, they are frictionless. And indeed, that for our purposes the fluid that is in between these two, so the water over here, let me show, actually get it to be water, I got rid of my tank itself. The water in between in this region is indeed incompressible as per our definition. You remember from some chemistry and physical chemistry in particular, that indeed, while gases are compressible, classical fluids at least are non-compressible. Meaning to say, certain volume of water will not change its volume under pressure.

Now, in addition to this, we add a certain feature to our idealized sealed tank, which I hope I do not undraw now, which is the fact that the two pistons are now separated by a so called semi-permeable membrane. And I think some of you who have done their masters here, you are probably encountered the osmotic problem in the case of leaf osmotic shocks, and the definition of a lot of osmosis revolves around the fact of the existence of such semi-permeable membranes. Which in fact, bio membranes tends to be quite frequently. So, this is the semi-permeable membrane.

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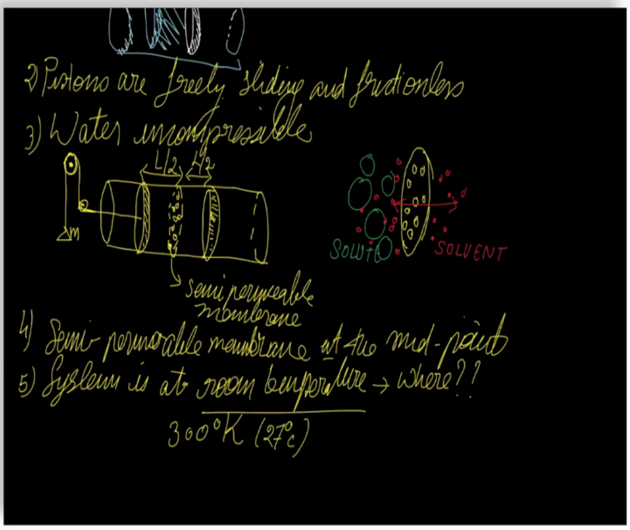

And indeed in this region, the two halves of the parts separating the, separated by the semi-permeable membrane of the tank, are equal. That is to say this is total length there. The one of the pistons on the left is now connected by a pulley system to a small mass m. These are freely spinning, again frictionless pulleys, and the mass is a tiny mass m. Under such a circumstance so, I forgot to add the fourth part of this structure is a semi-permeable membrane, at the midpoint.

So, one of the things that we always talk about in terms of semi-permeable membranes is that they have such tiny pores. And in order for my visualization to work, I actually have to make the pores quite large that while one set of molecules is prevented from going through by simply by the size of those molecules, another set which is tiny is allowed to go through.

And typically, in these kinds of cases, the tiny molecules are the so-called solvent molecules, whereas, the large molecules are typically the solute molecules. This is the classic example when you take a dried raisin, Kishmish and put it in water, it swells up and the argument is it is driven by osmotic pressure that is why. Due to the fact of concentration of sugars inside it.

So, the similar sugar analogy, we now say that one perhaps last statement of the assumptions is that the system is at room temperature. Now, room temperature you should ask where, which room temperature? We just simply are going to assume which is 300 degrees Kelvin. That is, I think I have made the sort of slight misstatement, it is approximately 27 degrees Celsius.

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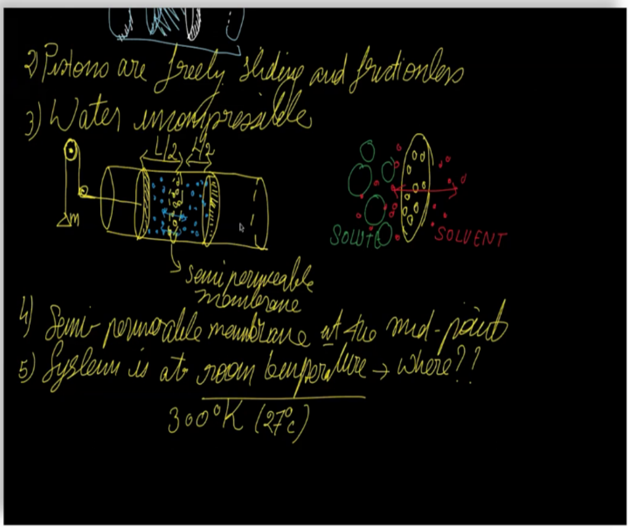

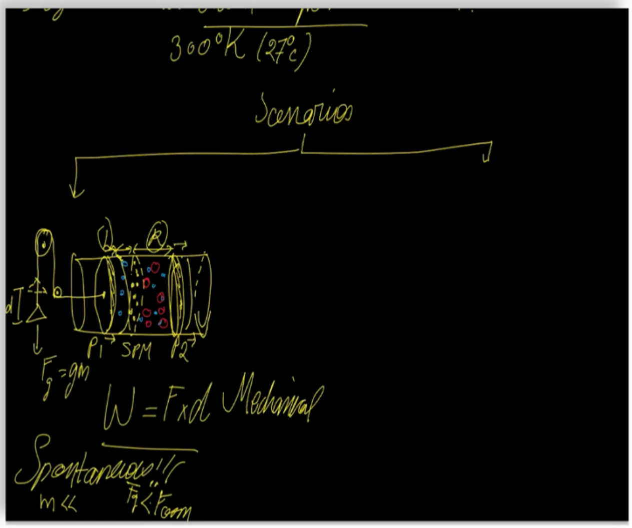

In such a system now, we introduce back to our diagram here, we introduce some additions. So, we said already that our cylinder has water in it. So let us just add some water, some water molecules tiny, and they are everywhere, and because water is incompressible, and the semi-permeable membrane allows the free flow of water, these molecules can go back and forth.

In such a system, now, we have one of two scenarios. So, the first scenario is that we introduce on one side, particularly the right hand side of our hypothetical tank, some sugar molecules. So, we are still stuck with our midpoint with the semi-permeable membrane, piston 1, piston 2, left, and right chambers. And along with the water molecules that we had already in both chambers, we introduce some sugar molecules into the right hand side.

Now, with time we expect that our mass m, which is because of the gravitational acceleration being pulled downwards, will actually be displaced. Now, for a few seconds, just think about it, there is sugar on one side, it is a semi-permeable membrane, water is equilibrated, what should happen? Now, you know this again from the same example I mentioned earlier about dried raisins, Kishmish. You expect that the concentration of the sugar is higher here, that there will be some tendency to re-equilibrate concentrations. So, essentially, what we are going to see is a displacement of piston on the left hand side to the right hand side.

But if the piston moves and the water is incompressible, you will also get a displacement of P 2, to the right. Essentially, implying that this moves here, this moves here and the volume of the right chamber increases, and the volume of the left chamber decreases. But because the piston 1 is connected to a small pulley, it is also at the same time going to raise the mass by some height, by some height, d or h. This is pure and simply nothing but work done against a load, and work in this case is force into displacement. So, in a way, we find that the presence of some solute molecules on one side leads to what we can call modified mechanical work.

And this surprisingly, is spontaneous. Why surprising? Because all we did was change the concentration of the solute on one side, what is important is that m is somewhat small, because if the opposing force that is to say the force due to gravity is excessively high, higher than the force that this is capable of generating, then we will not be able to perform this action, so so-called osmotic force. But the real question then becomes where did this force come from?

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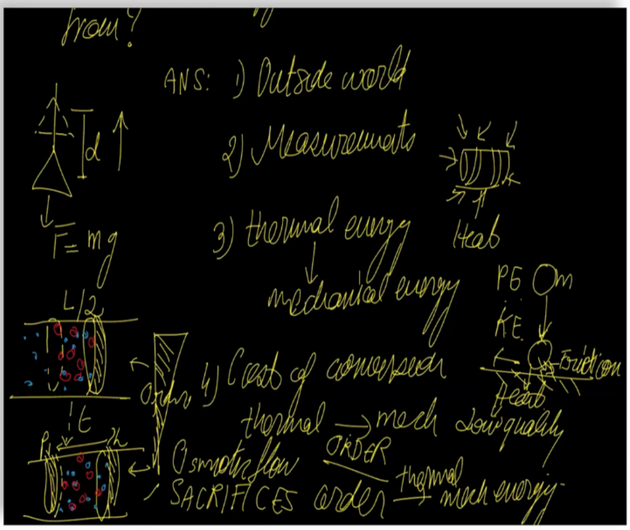

So, interestingly enough, or let us say where did the energy to move the mass come from? Remember, I mean when you want to lift a load through a certain height, d. That has to oppose, and exceed the gravitational force, or the weight of the system and that is like any kind of lifting process.

So obviously, it is clear that we did not put in any in, we did not actually pull at it. So, the energy it appears in terms of what the answer to this question is, is coming from the outside world. Indeed, careful measurements when they are made, if they demonstrate that such a system, the piston spring, piston mass system actually absorbs heat from the environment. This therefore means that this process is driven essentially by thermal energy, which in fact, is converted into mechanical energy.

Now, I do not know if you remember, in the previous module, previous segment of this module, we talked about a ball falling and that it has a potential energy, and kinetic energy associated with it. And when it falls in does not move anymore, we asked where the energy went off. And we said that friction in a way dissipates this into heat. And in some other statements I have made, I had implied that heat is a kind of low-quality energy. In other words, it sort of it seems to correspond to processes that cannot do mechanical work anymore, they are dissipative in other words.

And yet it seems like here we are capable of doing mechanical work, mechanical energy, which is sort of good bonafied, easily measurable displacement through time some height through some distance against a force, and it seems to be done by some method. And it turns out, that this is this method or the cost of conversion of thermal energy to mechanical energy is at the cost of order.

Now, you may ask, what is this order that we are talking about? Think about it like this, in our initial setup, at the beginning of this thought experiment, when our piston in the right hand side chamber was of some length L by 2. The sugar molecules were restricted to the volume corresponding to that cylindrical volume that matched this L by 2.

So, I am drawing back my water molecules and so on and so forth. With the passage of time, we seem to find that eventually the second the p 1 as I called the piston on the left side, p 1 will come so close to the semi-permeable membrane that there is practically no more volume left in the left compartment, and this entire thing is L, since radius does not change, this is the volume, sort of a surrogate of our volume. We can consider this L as a marker for the change in volume. So, this seems to suggest that if the number of molecules 1, 2, 3, 4, 5, 6, 7. So, 1, 2, 3, 4, 5, 6, 7, 7 molecules of water have a larger space in which they can exist.

So, we are basically saying that the state in which they were on in the initial position was more ordered. And in the final position with time, that is the order has decreased over here, as compared to here. And this in some senses is the reason to state that osmotic flow sacrifices molecular order to organize, to in a way convert thermal to mechanical energy. Indeed, this only can happen if the system has a opposing mass that is smaller.

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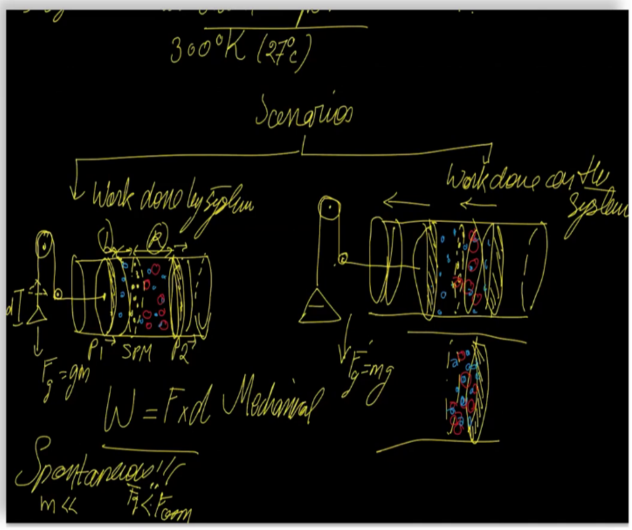

Now, you can of course, go back to our scenarios and ask what about the alternative? Because, I did not say much about it, which is the right of this diagram here. So, in such a system, you can also imagine the opposite, that is to say our CH tank is as it was, our sugar molecules were moving around in the right-hand side compartment, they were introduced at some time t_0. The pulley system still exists. But our mass is much bigger now, so this is the opposite of what I have said earlier. Or, in other words, there is a small mass and we add an additional force.

In such a case, where the mass is exceeding the force that the osmotic engine can now generate, then you will reasonably expect that instead of moving rightwards as our pistons had done earlier, they will now experience a force that drives them leftwards, what that interestingly enough means for our sugar molecules is that as the pistons move right wards, the volume available for the sugar molecules becomes less and less. This also means that they are now stuck in a much smaller region.

And therefore, they are more ordered. And this is essentially what reverse osmosis is about, which is where due to the increase in order of a system, because of an external force forcing this osmotic engine in the reverse direction that entropy, that order, disorder, the tendency to disorder would drive it, the reduction in order. You would get local ordering at the cost of mechanical work being done.

So, now, in this case, in the first case, that we discussed, work was done by the system, in the right-hand side case with an excess weight the work is done on the system. And this is the crux of what we have been trying to get at in terms of the second law of thermodynamics. Because, by the regular statement of the second law of thermodynamics for a closed system, energy of that closed, the entropy of that, the degree of disorder of that closed system is bound to increase.

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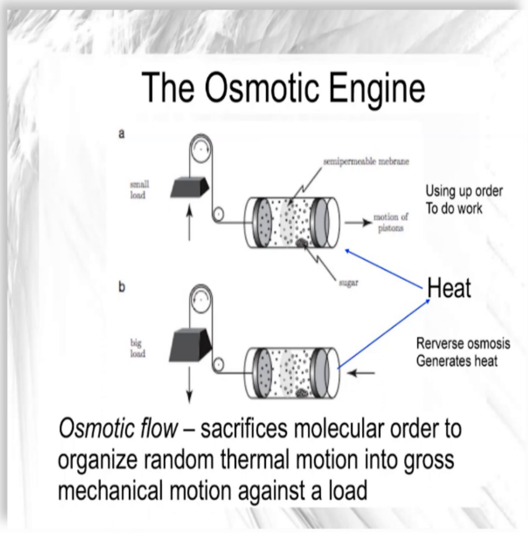

However, because of the fact that we are talking about a system that is in contact with its environment, we expect that like in this diagram here, that the order will drive, the ordered state will be driven to disorder by the translocation of the pistons through the harnessing of heat. And in contrast, heat will be given off when mechanical work is done on the system. And this is reverse osmosis or ultrafiltration. So, in one case heat is absorbed by the system. And in the other case, heat is given off by system.

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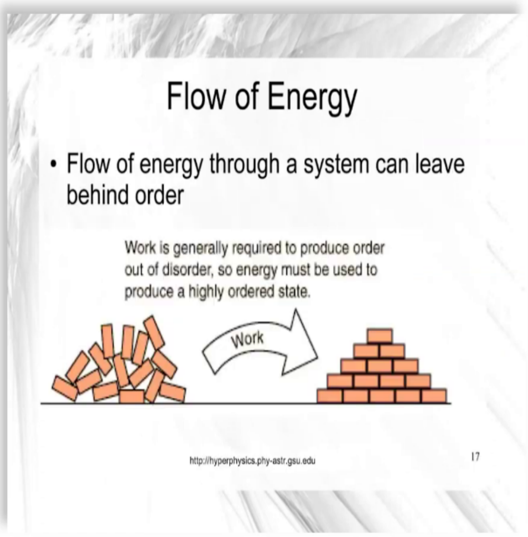

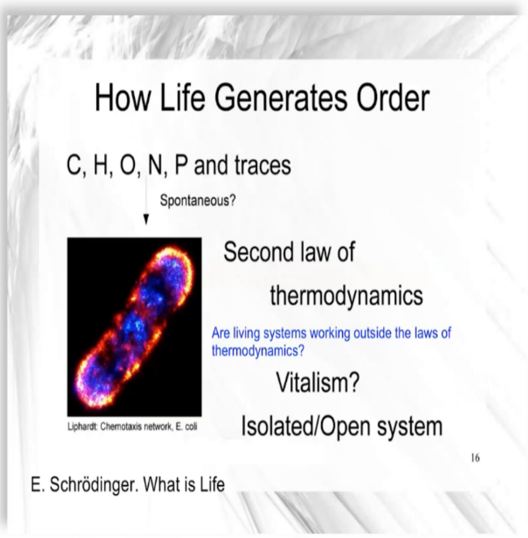

In that sense, you could argue that you cannot make an ordered system thermodynamically speaking, unless work is done on the system. And so, this energy must be coming from somewhere.

And in the context of what we talked about earlier, which is this business about the organization of living systems through the molecular components. Our idea now in consistency with the second law of thermodynamics is that they are open systems. That is to say the system itself is not just the living organism, but also its, in its surroundings. And the fact that it that the work done by the system, I am sorry, the work done on the system is what continues to preserve the order of the system.

So, in that sense, any entropic system should go to complete disorder, we should stop existing. Meaning to say from cell division to cell division, there should be increasing disorder, but we do not see that, and there are many complex processes the genetic and so on and so forth. But from the thermodynamics perspective, the idea is that with the investment of real mechanical work that is how that order is maintained.

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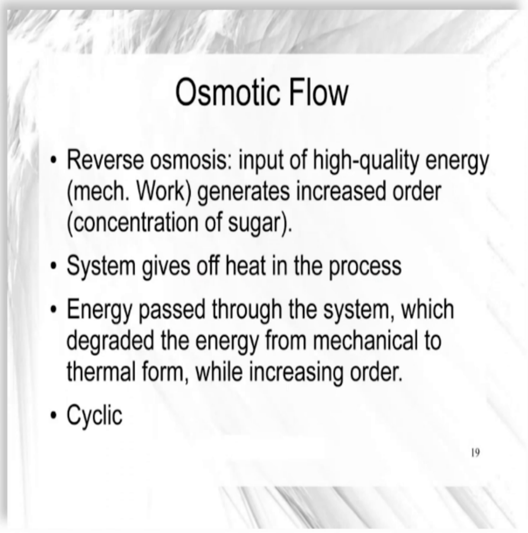

So, to summarize, reverse osmosis is the process of the input of high-quality energy mechanical work to increase the order as in the concentration sugar, and giving off dissipation of heat in the process. Energy passes through the system and is degraded from mechanical to thermal form. And you can cyclically do this to give you your so-called maintenance of from generation to generation.

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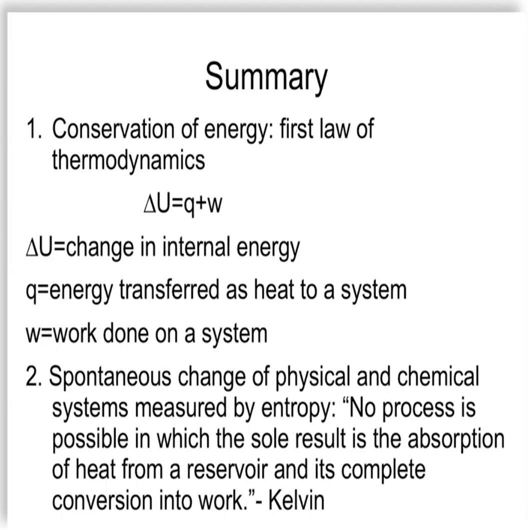

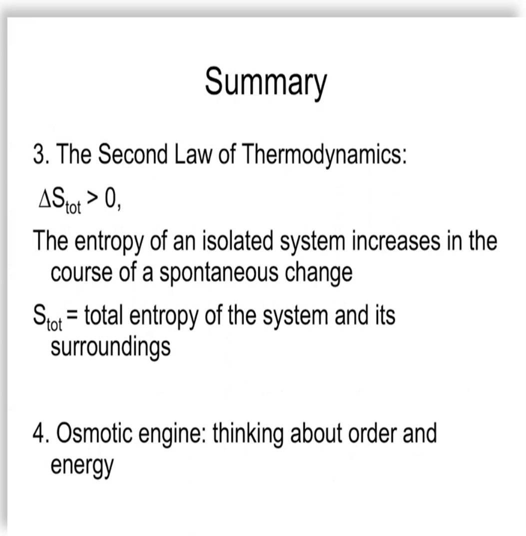

So, the thermodynamic laws do apply to biology. There is conservation of energy, as stated by the change in internal energy as the sum of transfer of heat and work done on the system. And the second law applies to living systems of the spontaneous change as measured by entropy, which is increasing. But the fact is that this refers to an isolated system, whereas living organisms are not isolated systems.

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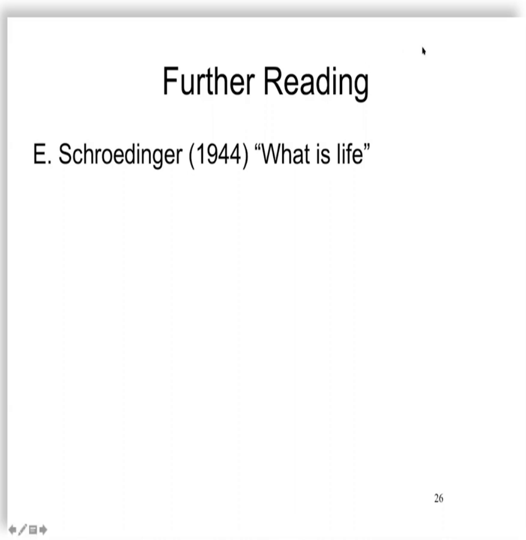

This is exactly the point at which we now need to discuss what Erwin Schroedinger try to say this what is life, and since you read it at our next live meeting, we are going to be going through it. This may actually happen that this live meeting will happen at a time you may not have had a chance to watch this video, I am posting it anyway. And I encourage you to watch it. Thank you.