Cellular Biophysics

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Energy and Life – Interconversion of energy

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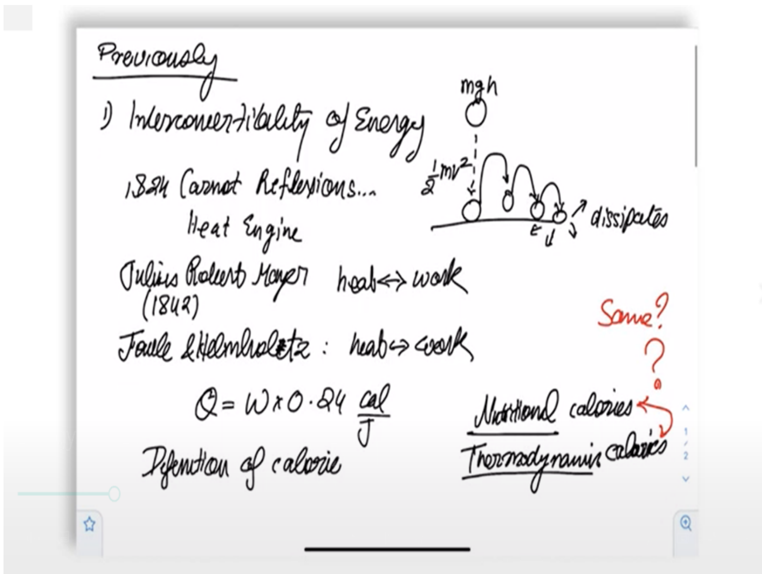

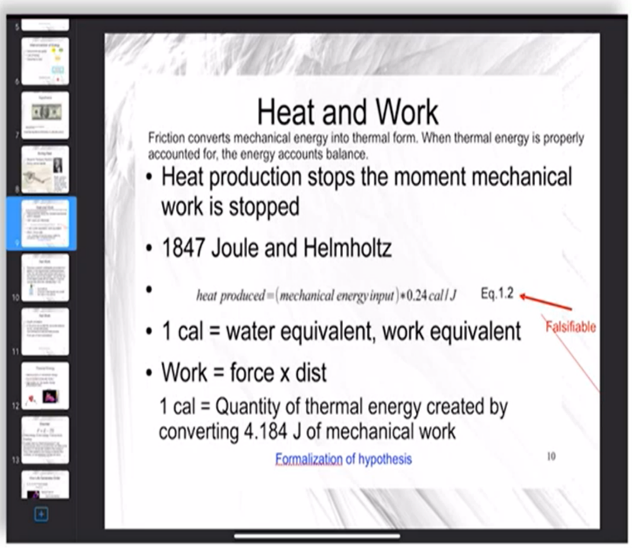

The fact that energy is interconvertible. And by this I meant your basic bouncing ball experiment. You experience this in your daily life if you do not, I will say you should be playing more. All work and no play make Ram, Raheem and Rehmat a sad person. Either way the idea was if you remember we talked about the potential energy the kinetic energy and the fact that eventually it dissipates in some form. And that some form we said was heat.

Now historically thermodynamics is an old field 1824 is when we can claim Carnot French physicist chemist wrote a book on reflections and I am not quoting the entire French title describing for the first time a heat engine.

Mayer Julius Robert Mayer came up with the idea of the interconvertibility of heat and work and that is what led us yesterday to discuss the account for Rumford’s and eventual formalization in 1847 by joules and Helmholtz. So Mayer was 1842 and Joule Helmholtz heat work equivalence where we said that the heat produced is mechanically input into 0.24 calories per joule.

So heat produced is mechanical energy input so we call that work into 0.24 calories per joule. This is obvious to you that work or energy in terms of units as in joules and therefore heat is in calories. 1 calorie is then defined as the thermal energy crate by converting 4.184 joules of mechanical work so that is sort of our definition of calorie.

Now since we talked about units earlier in the first segment I would like you to discuss with me next one-on-one meeting the nutritional calories that are listed on the back of a lot of food items now. And thermodynamic or we will say physical units of calories are these one and the same or are they different. You are going to look this up there is a lot of material on this and you may actually have chemistry physics textbooks that will tell you a bit more about it.

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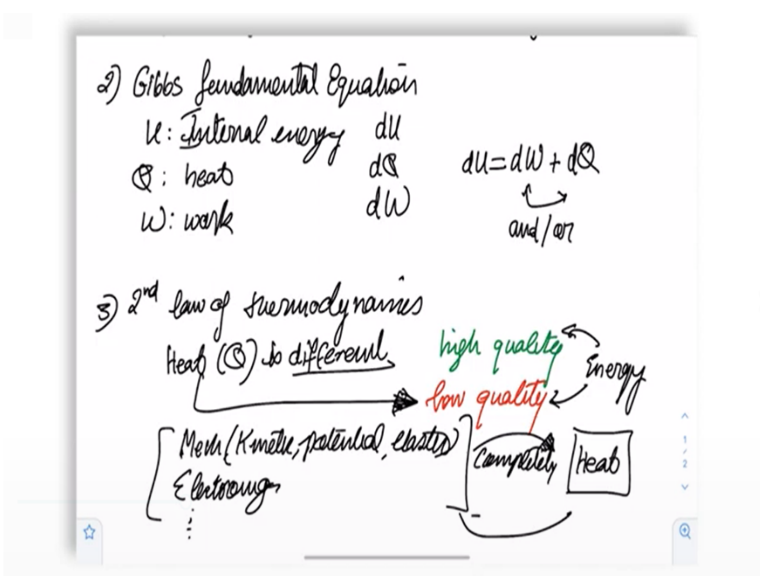

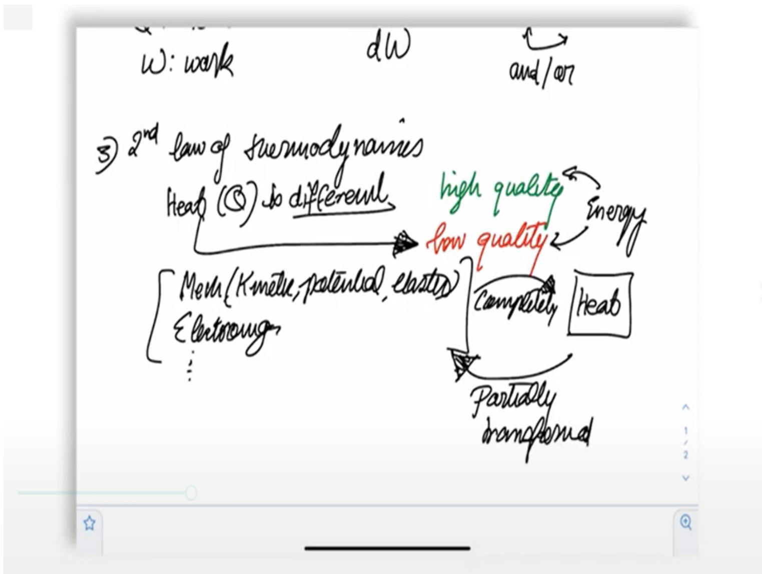

So, I then went on yesterday to discuss an equation which I put out there but it is formally written as Gibbs fundamental equation that equates internal energy heat and work. We have already seen heat and worker interrelated but what about this internal energy.

So it turns out that if you imagine a total differential of internal energy of heat and of work then the internal energy by definition in terms of its change consists of the summation of change in work and or change in heat. In other words internal energy will change when either work is done on or by the system or heat is done added to or by the system and one or the other needs to change in order for the du to be non-zero.

The second principle of thermodynamics goes a step ahead and tells us that heat is different from other forms of energy, it is different. How is it different? I kept talking about something called high quality and low quality energy. So if you were all into metaphysics you might have more things to say about this but in a physical sense this is a precise meaning in terms of energy that is either high quality or low quality.

And we attribute heat to be of low quality, why do we do that? It is because all forms of energy let us say mechanical energy, kinetic energy which is part of it kinetic, potential, elastic, electromagnetic and a long list which I can sit around enumerating. Can completely transfer can be completely transferred to heat. But heat itself is only partially transformed into these forms of energy.

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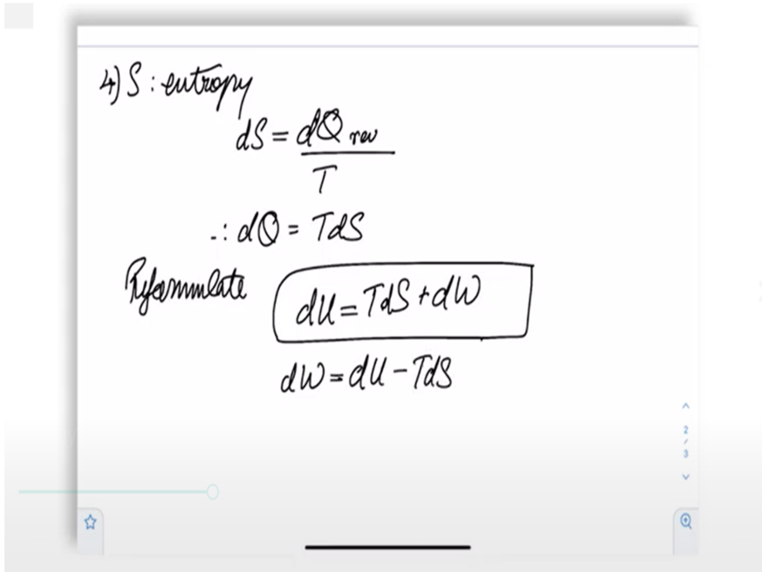

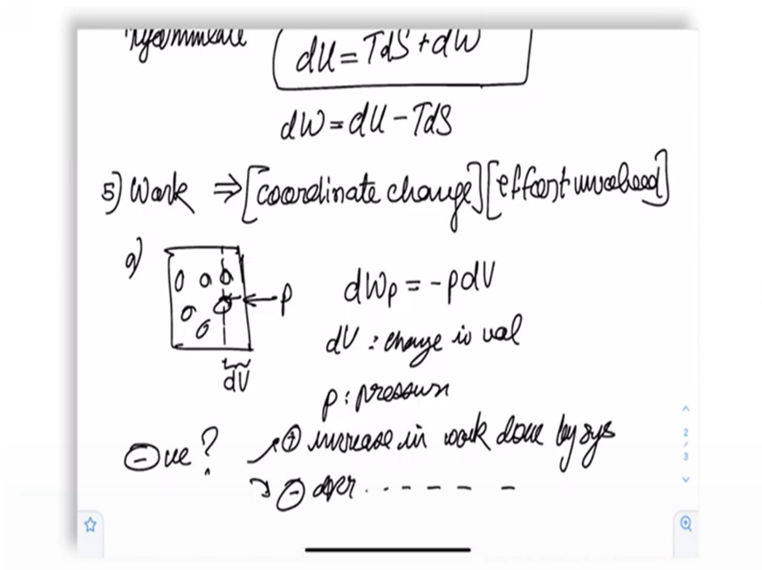

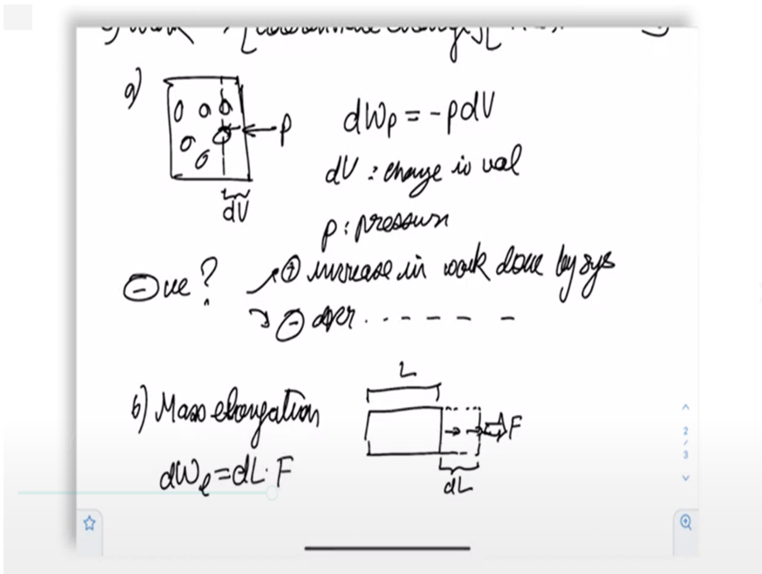

And this leads us to this term which we discussed previously entropy. Because, as it turns out that the differential of entropy or the change in entropy can be defined as the change in heat by temperature. Which of course leads us to therefore write dQ is equal to T Δs. TdS and reforµlate the Gibbs law as now du is equal to not dq but TdS plus dw and this is what I used last time I think you remember it probably in terms of dw is equal to du minus TdS that is depends on what you are trying to say.

Work itself which we are constantly talking about here can come in many different forms and it generally takes the form of some kind of coordinate change into some kind of effort involved in the coordinate change. So let us take some examples so when we have a gas in a compartment we have gas molecules and we compress the compartment by exerting some pressure on it. Changing the volume by some dv then the work done on the system is given as the pressure work Wp is equal to minus P dV, dV being the change in volume and P being is the pressure let us stick with small P.

Now what about the negative sign as it turns out that this depends on definition a positive sign usually is indicative of increase in work done by the system and therefore negative is when it is decreased and this is effectively what is happening here. In other words it is also work done on the system we can sort of define it.

But you can also have other kinds of work and you are familiar with this such as mass elongation so I have let us say a block of rubber and I extend it by some length dL then the force I needed to exert on it to perform this work becomes dW linear is equal to dL times F.

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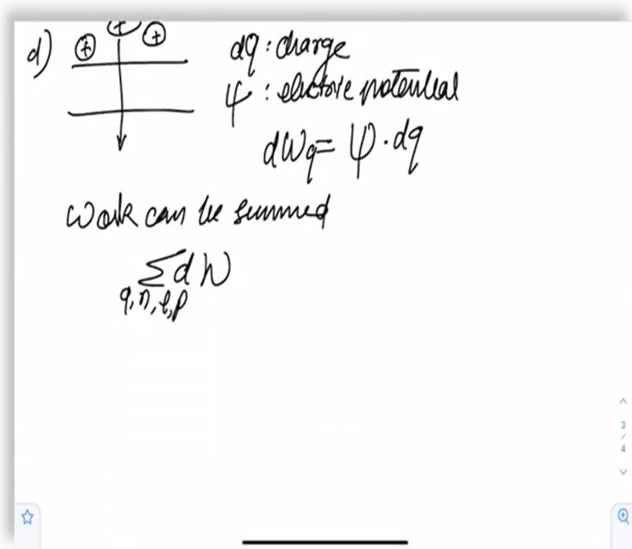

Now cells also do work and many of you are familiar with molecular motors walking on cytoskeletal elements transporting cargoes which may contain some molecules. In such a case even maybe against a concentration gradient or a chemical potential in such a case we define the chemical potential that pre-exists and dn as the change or change in number of molecules at a across the system giving us dW_n equal to μ dn. We can also do the same thing with charge transport across some membrane in terms of dq being the charge and ψ indicating electric potential.

Then the dWq is equal to ψ times dq. It turns out work can be summed together summation dW of all kinds q, n to give us the total work done by the system L, n, p and this then plugs into our Gibbs equation to give us a sense of what the total work is.

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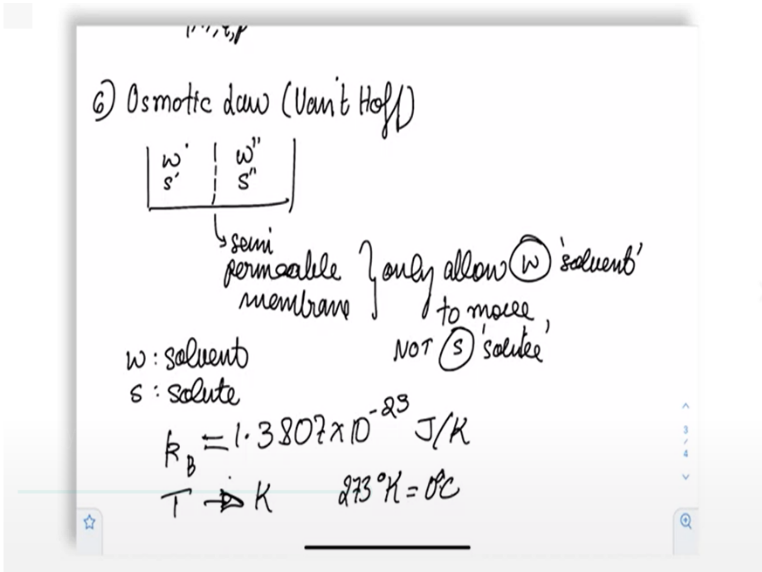

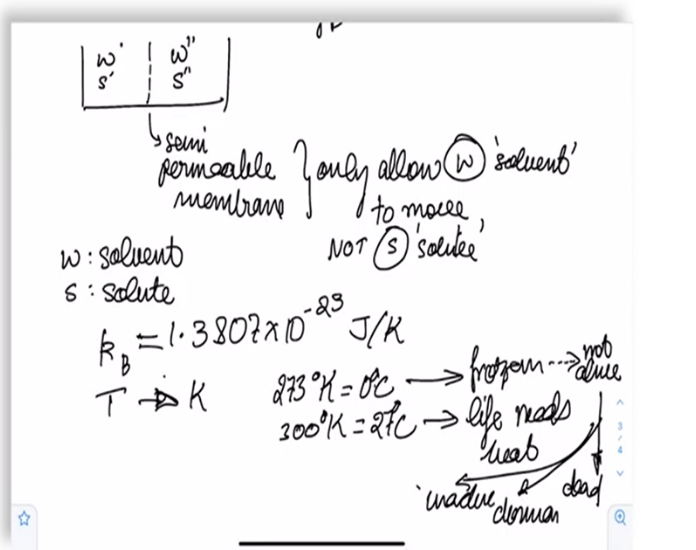

I then spoke about the thought experiment I am sorry the concept of osmotic law which was attributable to Van't Hoff, please bear in mind that this is not the same as simple hydrostatic pressure which you see in plants. The idea is that if you have two compartments separated by a semi-permeable membrane where W is the solvent and S is the solute then the semi-permeable membrane only allows S molecules to move across it not. I am sorry only allows the solvent molecules W to move along across it not S. One of the terms that we keep encountering in this is Boltzmann's constant or K_B.

Now most of you remember this, this is a physical constant that is mentioned at the beginning of most physical chemistry and physics textbooks it is given as 1.3807 to 10^{-23} joules per kelvin. Temperature itself is in terms of absolute temperatures in kelvin units and as you remember 273 and some simplifying degrees kelvin is equal to 0 degrees Celsius.

Therefore, for the purposes of biological assumptions and calculations we are going to continue referring to 300 degrees kelvin as our reference temperature which is 27 degree Celsius. Because if you remember life needs heat and frozen is at the least not alive at worst it may even be dead or dormant or inactive that is not like no that is not like hence the motivation point.

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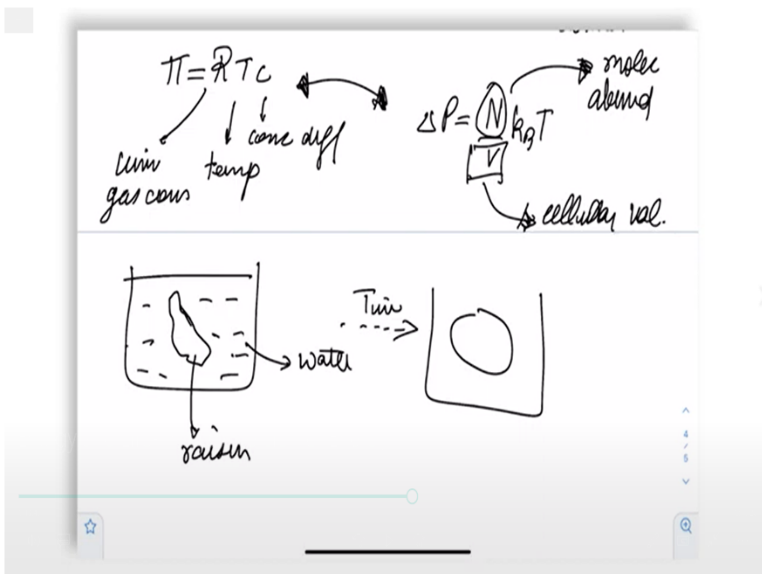

So the Van't Hoff law in its most simplified form tells us that the pressure gradient is Π is RTC, c is concentration difference, t is temperature, r is the universal gas constant. And we had also written it as equal to N by V times K_B you can write either or and for the calculations that we are going to do which consider molecular abundances and cellular volumes this is a more useful approach to take for us. So you know this experiment so if you take a raisin kishmish, sugar dried raisin and put it in water after sufficient amount of time it swells up.

Here the converse is also true if or rather if I now take a non-dried raisin a grain and place it in water and wait for some time there is a small chance if the water is pure and I have waited for long enough that the grape might burst. We are going to revisit this but the fundamental point is that something is acting to pressure to break this or to swell this up yes and that pressure is nothing but osmotic pressure.

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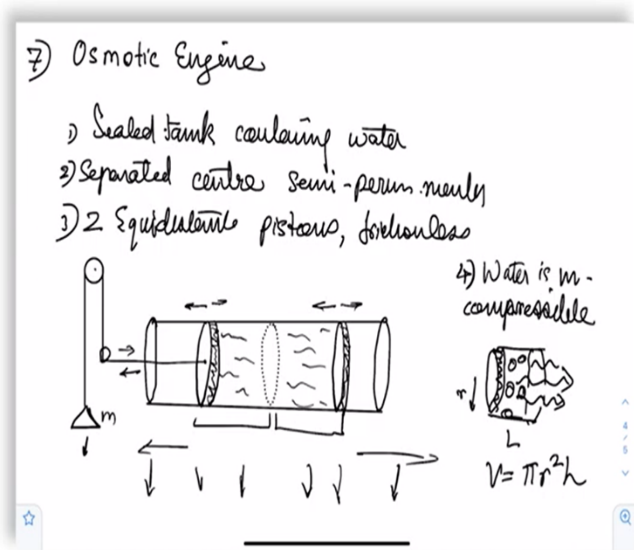

And in order to further illustrate this we spend some time discussing the very basic thought experiment of an osmotic engine which serves for us. Not just as a way to understand osmosis but also to think about thermodynamics and the meaning of order disorder and work. So what is this osmotic engine? We say that we have a sealed tank consist containing water separated in the center by a semi-permeable membrane and has two equidistant pistons that are frictionless.

So let us see if I can draw this so my drawing needs to improve in the traps not nonetheless if you get the picture this is a cylinder cylindrical tank. Maybe this is easier I have my semi-permeable membrane here against the dash line then I have my pistons here. At initial position they are equidistant from one another. But they can move back and forth they have freedom of movement. Now in between is water, what I now do is I attach to one of those pistons a pulley system that goes over wheel and in turn suspends some small mass m on whom gravity is acting.

So the pulling is horizontal pulling or pushing image argue gravity is equal in all directions for the osmotic engine system. But for the mass there is unidirectional pulling which results in this direction of motion if it is pulled down or this direction of motion if it is pushed up you understand the setup.

We also said that for this system to work water is incompressible what does it mean it means that if the piston in contact with the semi-permeable membrane is placed here and the water molecules move in some one direction then the volume which is nothing but $r \pi r^2$ L, will obviously reduce because molecules go away suggesting that there will be a reduction in pressure but because it is incompressible the piston itself is forced to move. And that is the fundamental principle on which all of this works.

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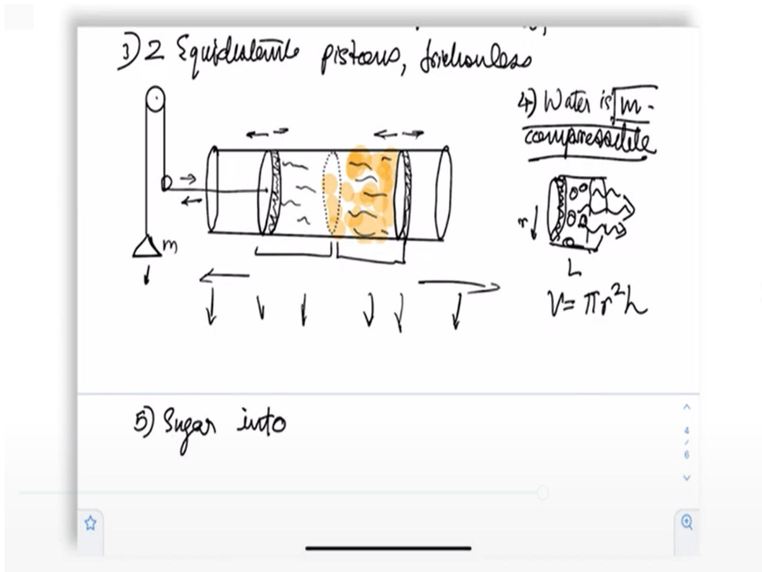
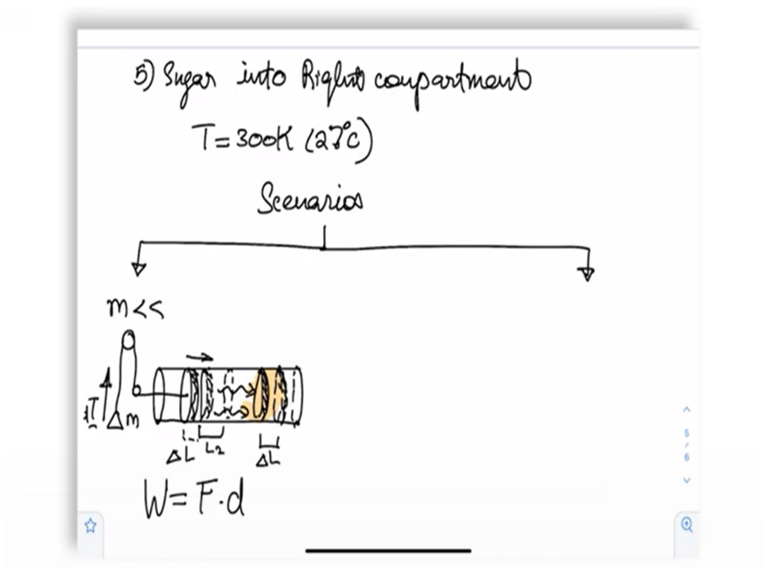
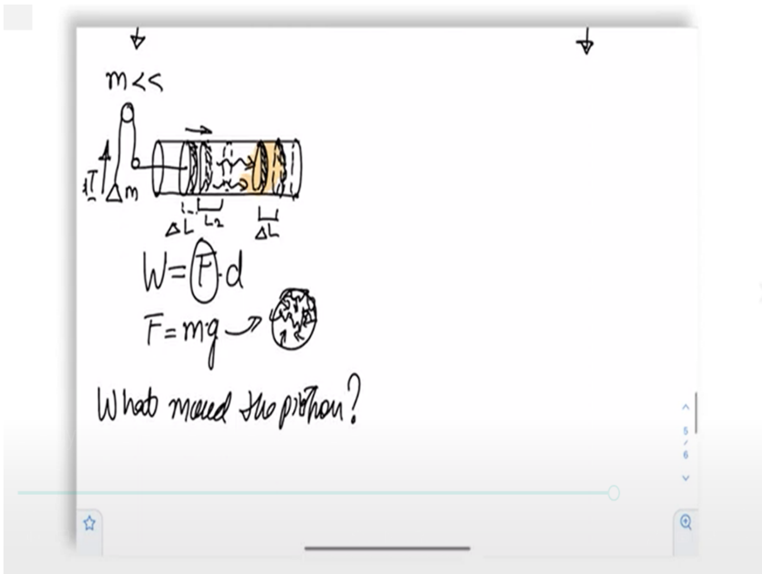
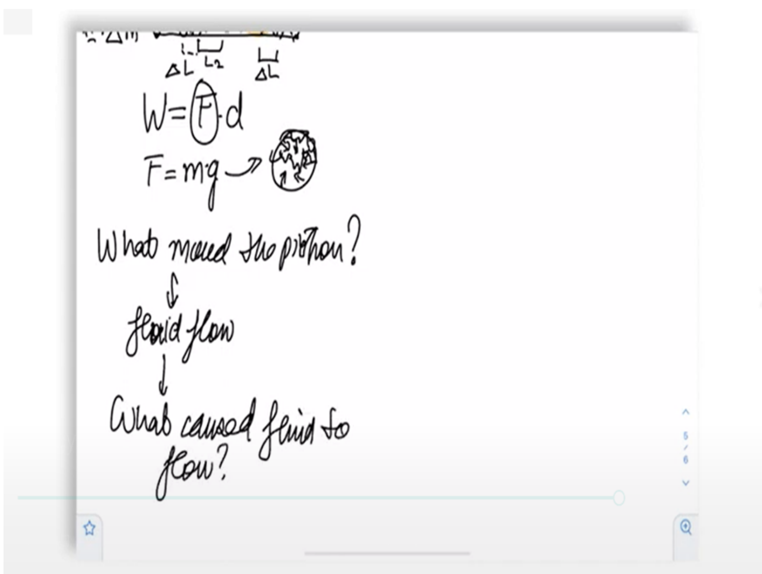
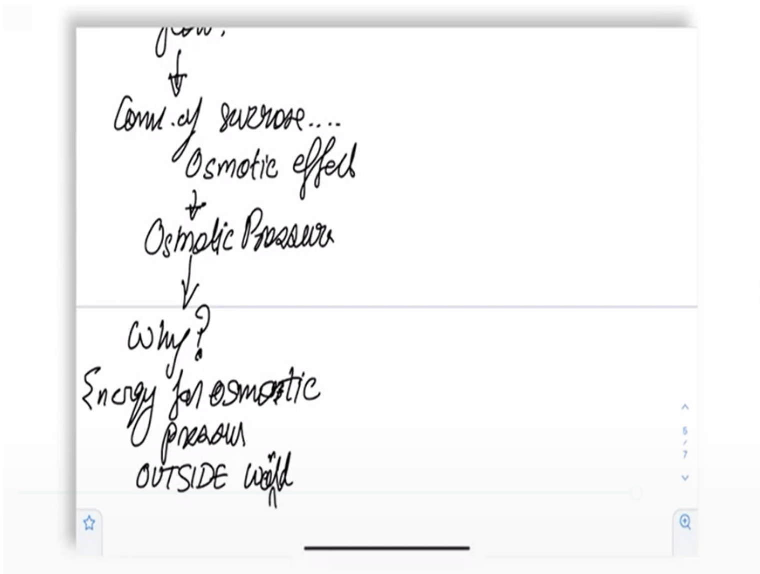
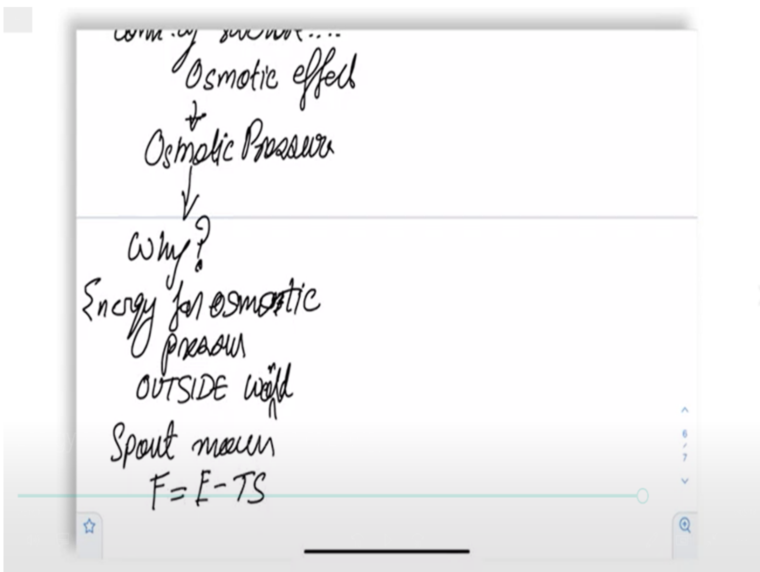





m<<
T
Δm
ΔL
L2
ΔL
W=F·d
F=mg
What moved the piston?


ΔL
L2
ΔL
W=F·d
F=mg
What moved the piston?
fluid flow
What caused fluid to flow?





At this point we add sugar into the right compartment somewhere here and it diffuses around and fills up the space. And when we do that, we know that at room temperature sugar into the right compartment, the temperature is 300 degrees kelvin 27 degrees Celsius as we said. There are two possible scenarios, one scenario is that the mass is small m is small and the osmotic pressure is such that my piston is forced from its original position to move rightwards with the same idea of incompressibility in mind. Because water has flowed in to compensate for the high concentration of sugar that was in this part.

When this piston moves right my right piston must also move because water is incompressible I cannot either reduce the pressure nor increase the pressure. The volume change must be accompanied by a positional change molecular flow must be accompanied by a volume change you must say. So this volume decreases so here we represent this by a new length L2 if that was L1 and what is lost here is gained here identical.

Now remember this was connected to a pulley system with a mass if this moves right this means that our mass moves up. It moves through let us say some distance d and remember what we said about work this is pure simple mechanical work, work is equal to force into distance what is our force? Force is nothing but mg mother earth that is Indian, Asia, China work is always calling. but we can always feel force. Suddenly now this is the opposing force it moved it through this so what moved the piston well we say fluid flow but what caused the fluid flow.

Well, we say it was concentration of sucrose which is nothing but osmotic effect which is nothing but osmotic pressure. But what caused the osmotic pressure? Why? Well the bottom line is that the energy for osmotic flow because it has to come from somewhere remember our first law of thermodynamics. The energy for osmotic pressure comes from the outside world and this is in terms of spontaneous movement which is only possible when the free energy is lower. And here we state the free energy is the internal energy minus Ts where T is the temperature, and s is the entropy.

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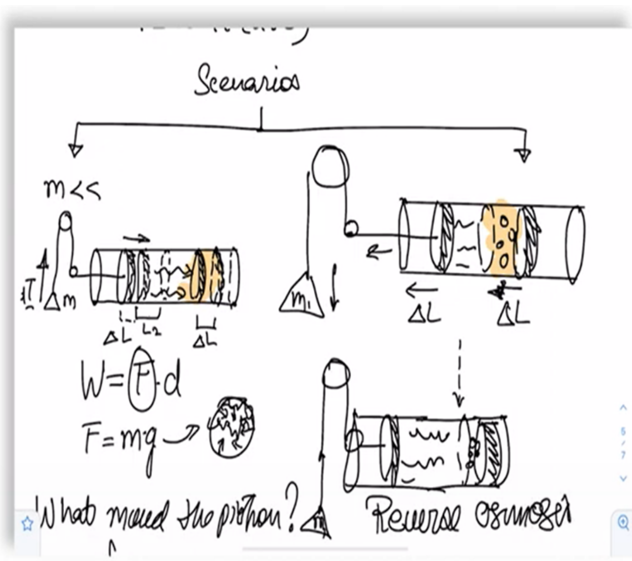

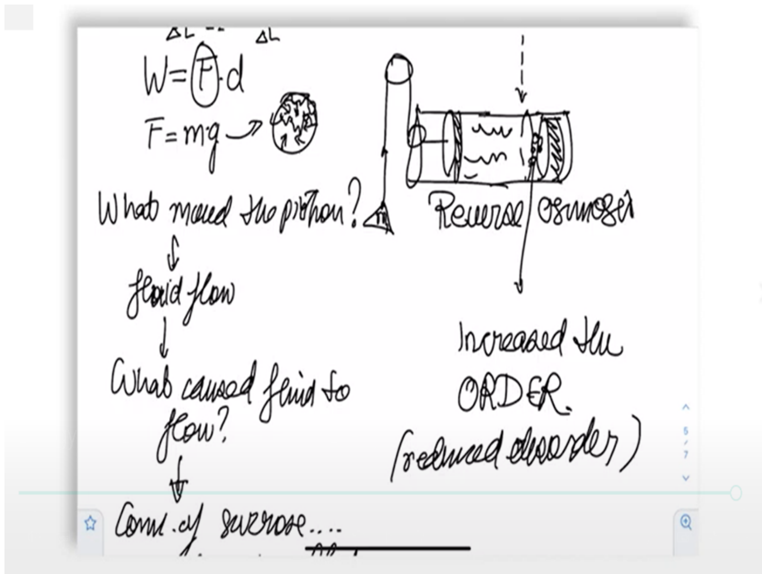

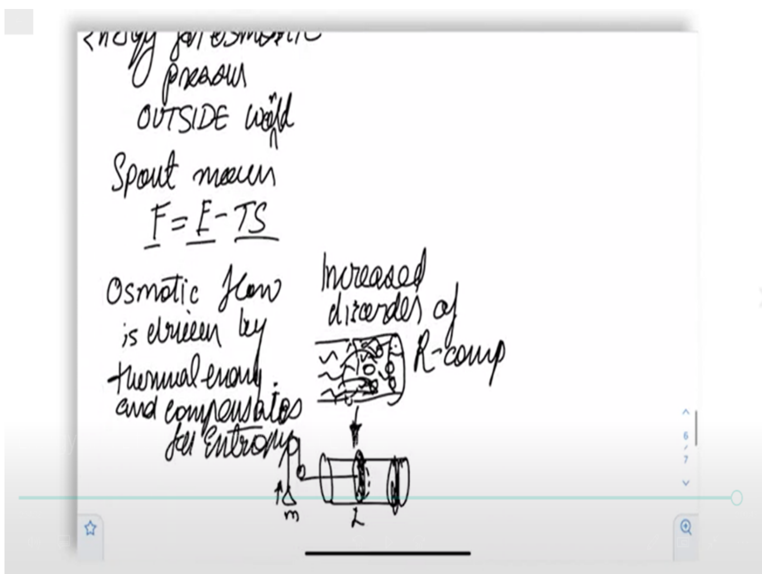

So in some senses osmotic flow is driven by thermal energy and compensates for entropy. In other words, the degree of order in the right-hand side compartment due to the placement of solute molecules inside the water is unfavorable, especially since it is in contact with water on the other side causing water to rush in to space out the water molecule the sugar molecules. And in an ideal case over time what we should see is that our nice cylinder piston system at the semi-permeable membrane should result in the piston over infinite time the left piston moving all the way to the semi-permeable membrane so it cannot move anymore.

This depends on a few different things including the smallness of the mass that is opposing but in theory it is possible that is when it will equilibrium. I said there were two scenarios what is the second scenario second scenario is that instead of the flow pulling the mass up. The mass itself is so large.

Or in other words it is greater than the force exerted by the solute molecules that it opposes the osmotic pressure and pulls the piston to the left causing both pistons to move equally to the left. Resulting in a concentration you may say of the sugar molecules again depending on the size of the mass and equilibrium position either into some minuscule region in the osmotic chamber such that most of it is now water and producing nothing but reverse osmosis.

Now you could argue that while here on the left hand side this has increased the disorder of the right compartment. Here we have increased the order or reduced disorder in the right compartment and this is the fundamental difference between these two systems. In the trivial case you have come across reverse osmosis in some kinds of filtration units, ultra filtration in the kidneys. But more interestingly we said that this corresponds to what is happening in living systems.

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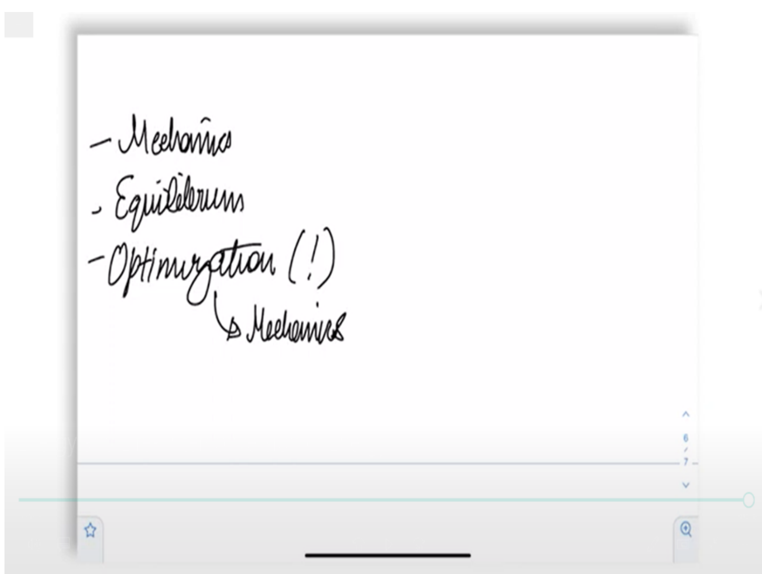

So for the next lecture, which I begin with on Tuesday next week, I am going to start talking to you about a new section on mechanics, equilibrium and optimization because especially this part has both a qualitative meaning and an evolutionary significance. But we are going to try and discuss it in terms of mechanics and how it is either exploited in biology or we can exploit it to learn more about biology.