Thermodynamics
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Work - Part 4

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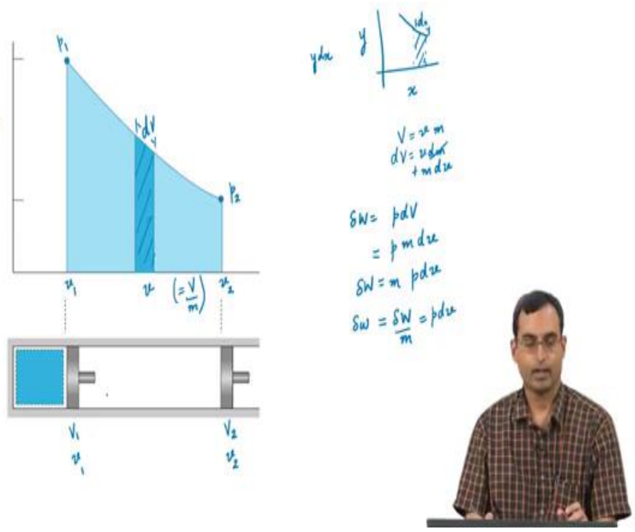

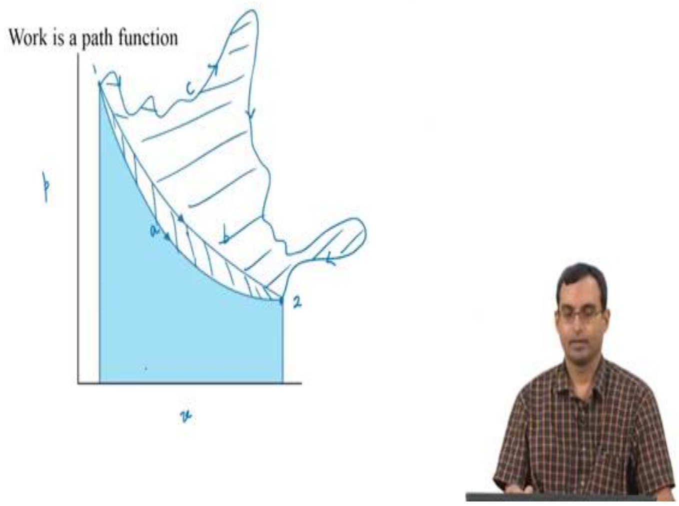

We looked at how to calculate the work when you have displacement work. For example, when you have gas inside a piston-cylinder arrangement, and the gas expands moving piston outwards against some external resistance (for example, atmospheric pressure), then the work is given by $\int pdV$. Work is a path function.

We obtained the mathematical expressions for the work done in various common processes. Please see the notes for the last lecture.

Let’s look at some problems on the concepts covered in the last few lectures.

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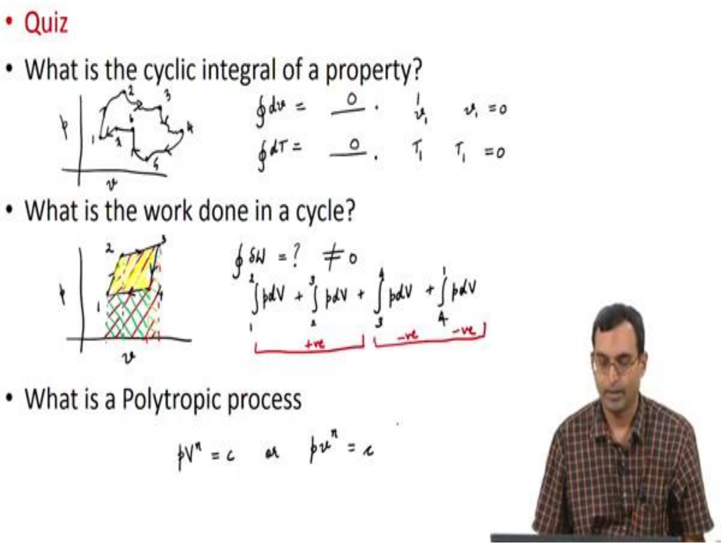

Figure 1

Question 1. What is the cyclic integral of a property?

Answer: The cyclic integral of a property is zero. In a cyclic process, the final state is the same as the initial state. Since properties are state functions, their values do not change after the cyclic process. Hence, the cyclic integral of a property (property value at the final state – property value at the initial state) is zero.

For a cyclic process 1-2-3-4-5-6-7-1 on a p-V diagram shown in Fig. 1, the cyclic integral of volume is given as $\oint dV = \int_1^2 dV + \int_2^3 dV + \int_3^4 dV + \int_4^5 dV + \int_5^6 dV + \int_6^7 dV + \int_7^1 dV = (V_2 - V_1) + (V_3 - V_2) + (V_4 - V_3) + (V_5 - V_4) + (V_6 - V_5) + (V_7 - V_6) + (V_1 - V_7) = 0.$ A similar conclusion can be drawn for other properties.

Question 2. What is the work done in a cycle?

Answer: Work is a path function. Though the states of a system are the same at the end of a cyclic process, the path followed by the system could be different. Hence, the work done in a cycle would be non-zero.

Consider the cyclic process shown in Fig. 1, 1-2-3-4-1. The displacement work for the process is given as,

$$W = \oint \delta W = \oint pdV = \int_1^2 pdV + \int_2^3 pdV + \int_3^4 pdV + \int_4^1 pdV$$

$\int_1^2 pdV$, $\int_2^3 pdV$, $\int_3^4 pdV$, $\int_4^1 pdV$ represent areas under the curves 1-2, 2-3, 3-4 and 4-1 respectively. Since the volume is increasing in the processes 1-2 and 2-3, $\int_1^2 pdV \; and \; \int_2^3 pdV$ would be positive. However, the volume is decreasing in the processes 3-4 and 4-1. Hence, $\int_3^4 pdV \; and \int_4^1 pdV$ would be negative. Adding all the integrals gives a non-zero number which is the area of the region enclosed by the curves on a p-V diagram (colored yellow in Fig. 1). It is the net work done by the system.

What if the system went along 1-2 and 2-3 and retraced the same path to come back to state? Would the work done in that case be zero?

Question 3: What is a polytropic process?

Answer: A process which can be represented using the equation $pV^n = constant$ or $pv^n = constant$ is termed as a polytropic process where p represents pressure, V represents volume and v represents specific volume of a system (the mass is fixed).

$pv^n = constant$ for a system can be obtained by dividing each term in $pV^n = constant$ by m^n. Then, the left hand side becomes $p\left(\frac{V}{m}\right)^n = pv^n$ and the right hand side becomes a new constant $\left(\frac{constant}{m^n}\right)$ as the mass is fixed.

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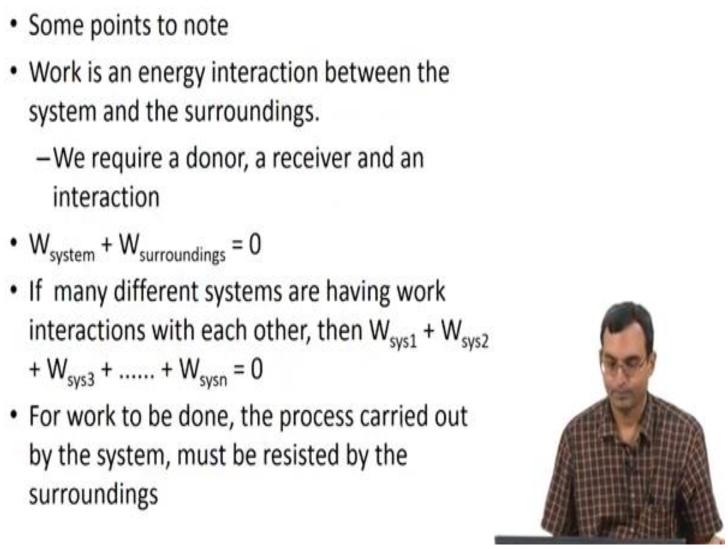

Work is an interaction between two systems or a system and the surroundings. Hence, we require a donor (somebody to do the work) and a receiver (somebody to receive the work or something on which work can be done) and interaction between the donor and the receiver.

The work interaction for the system plus the work interaction for the surroundings equal zero. The work done by the system on the surroundings is positive, while the work done by the surroundings on the system is negative.

If we have n systems having work interactions with each other, then $W_{sys_1} + W_{sys_2} + W_{sys_3} + \ldots + W_{sys_n} = 0$. For a system, all other systems form surroundings. Some of the systems may have positive work output, while others may have negative or zero.

For work to be done by a system, there must be a receiver system which receives work. Otherwise, work done by a system is zero.

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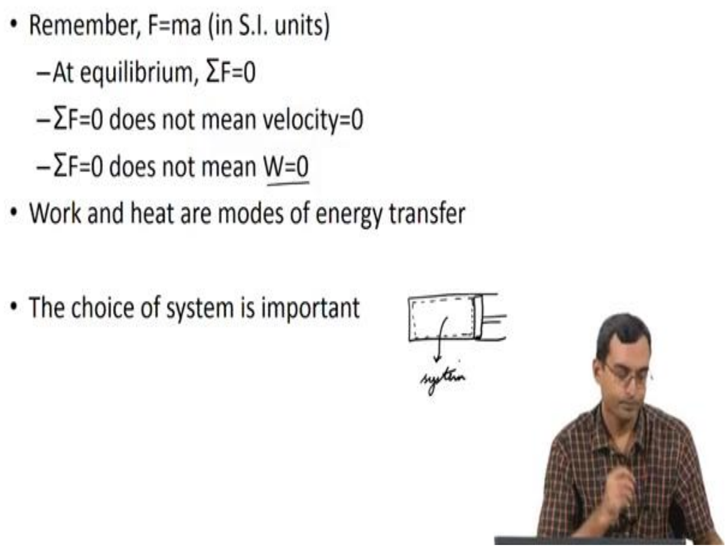

Newton's second law of motion implies F = ma where m is the mass of the object under consideration, F is the force acting the object and a is the acceleration of the object.

At equilibrium condition, summation of all the forces equals zero. The forces are balanced. In thermodynamics, we look at systems which are always in equilibrium or very close to equilibrium. Only at such conditions, we can calculate work interaction for a system.

Just because the forces acting on the object/system are absent or their summation is zero does not mean that the velocities are zero. You can have an object moving at a constant velocity when the forces are absent or their summation is zero. The absence of forces or their summation being zero implies that the acceleration of the object is zero.

Work interaction for a system does not have to be zero if the summation of the forces acting on it is approximately zero.

We are looking at quasi-static processes. The system is always near equilibrium. There is slight imbalance of forces because of which we get work.

Work and heat are modes of energy transfer. We will define heat a little later. Energy transfer can be work transfer or heat transfer or combination of both depending on the choice a system. For example, in a typical piston-cylinder arrangement, a system can consist of only the contents enclosed by the piston and the cylinder or it can consist of those contents as well as the piston. Though energy transfer (sum of heat and work transfer) for the system in both the cases is the same, its components, energy transfer by heat and work interactions, may be different.

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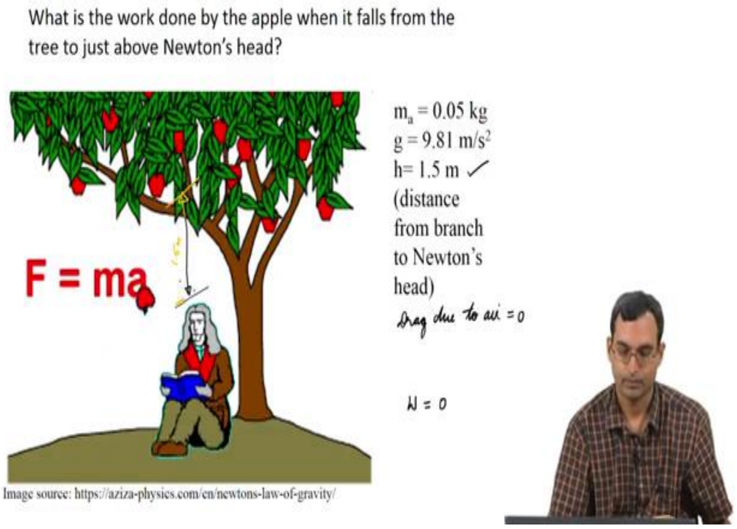

Figure 2

Let's answer the question in Figure 2.

The apple falls under gravity. It covers a distance of 1.5 m before it hits Newton's head. We need to calculate the work done by the apple when it falls from a tree to a location just above Newton's head (it has not touched his head yet). Assume that the resistance due to air is negligible.

During its fall, there is nothing that resists the apple's movement. Hence, the work done by the apple is zero. As pointed out before, there should be a donor system, a receiver system and some interaction between the two. In this case, there is a donor system, the apple. However, there is no receiver system. Hence, the work done is zero. So, as long as we are considering the motion of the apple till the location just above Newton's head, the work interaction is zero. This process, the fall of the apple, is not quasi-static. There are many other processes which are not quasi-static. Let's discuss some of those.

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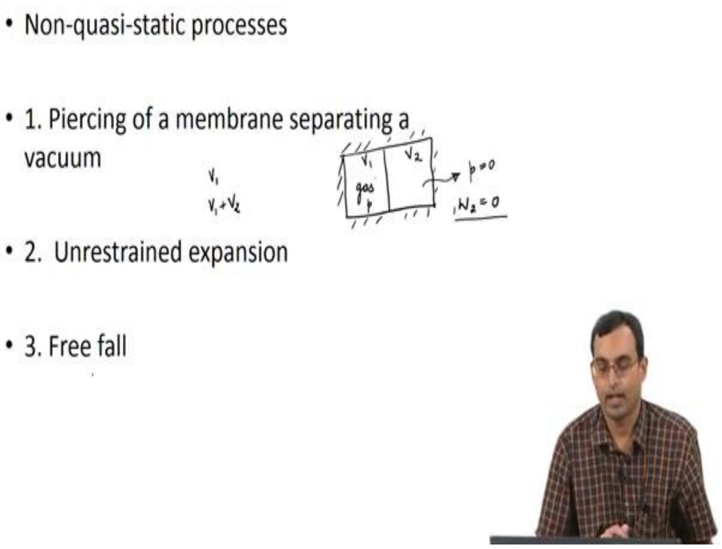

Consider a membrane separating a box into two chambers. On one side of the membrane, there is vacuum, while on the other side, there is gas (at some pressure p_g). Initially, the membrane separates them. If the membrane is punctured, the gas expands into the other chamber (the volume of the gas increases) against no resistance as the other chamber initially had vacuum. In this case, as there is no receiver system to receive work, the work done by the gas is zero. This is known as unrestrained expansion. The example we just considered is a case of completely unrestrained expansion. We can also have partially restrained expansion where there is some resistance to the expansion.

In the above example, instead of vacuum in one of the chambers, let’s have some gas at a pressure less than that of the gas in the other chamber. If the membrane is punctured now, the gas at higher pressure will expand against some resistance. This is the case of partially restrained expansion. In this case, the work is not completely zero. However, the work done is not equal to $\int p_g dV$ where dV is the change in volume of gas at higher pressure.

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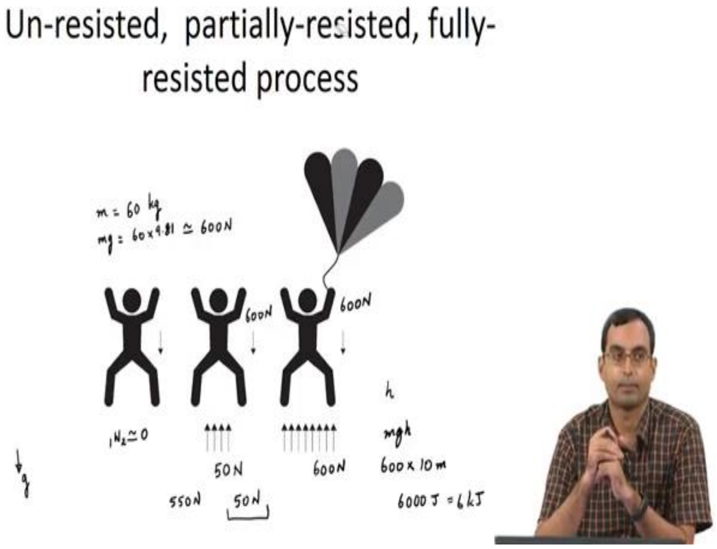

Figure 3

Let's look at an example of un-resisted, partially-resisted and fully-resisted processes (Fig. 3).

A man jumps from a plane and falls under gravity. Initially, he doesn't deploy a parachute. Assume that the air resistance is negligible. In this case, the work interaction for the person is zero.

Assume that for the later part of the person's fall, the air is dense. It offers some resistance to the fall. Let's say the person's mass is 60 kg. Hence, his/her weight is around 600 N (taking g =10 m/s^2). Assume that the resistance offered by air is 50 N. Hence, the resultant downward force pulling the person down is 550 N. The balanced force is 50 N. If the person falls by 10 m, then the work interaction would be $50\,N \times 10\,m = 500\,J$. The work interaction happens because of the balanced force only. Un-resisted force does not do any work.

Now, the person deploys parachute and drifts slowly. The person is not accelerating now. Hence, the person's fall is fully resisted. Fully-resisted force is 600 N (the weight of the person). At this condition, if the person covers 10 m, the work interaction would be $600\,N \times 10\,m = 6000\,J$.

In un-resisted processes, there is no work interaction because nothing is accepting the work. In partially-resisted processes, we have some amount of resistance. Hence, the surroundings is accepting some amount of work. The work is done by the force which is resisted. In fully-resisted processes, there is resistance to the complete force and therefore, all of that force is taking part in doing some work interaction.