

AP Physics - Thermodynamics

Thermodynamics is the study of heat in motion – that’s if you just want to look at the translation of the grand old word itself.

Whatever it is, it don’t sound good, do it?

Let us now start with a couple of definitions.

A *thermodynamic process* is one in which heat is added to or taken away from a system.

Any system has some *internal energy* state. The energy state is defined by the systems temperature, volume, and pressure.

The symbol for internal energy is U .

$$U \equiv \textit{internal energy}$$

Other important symbols we will make use of are:

$$\textit{Heat} \equiv Q$$

$$\textit{work} \equiv W$$

The purpose behind having a thermodynamic process take place is to convert heat into work. Although sometimes we want to convert work into heat. The system begins at some initial internal energy, we add heat to it, extract some work (let’s say), and, when all is said and done, the system will have some new internal energy.

We know from the law of conservation of energy that the heat, work, thermal energy, &tc. we’re playing with has to be conserved. This brings us to the *first law of thermodynamics*. The first law (as it is usually referred to) is really a restating of the law of conservation of energy in terms of internal energy, work, and heat. It is written as a simple equation.

$$\textit{First Law of Thermodynamics:} \quad \Delta U = Q + W$$

ΔU is the change in internal energy of the system, Q is the heat added to the system, and W is the work added to the system (or done on the system).

Q is positive when it is added to the system and negative if it is taken out of the system.

W is positive if it is added to the system and negative if it is done by the system. This means that the work done by an engine that uses heat is negative. Think of it as being negative because it is leaving the system.

output work is negative

input work is positive

Fair warning: there is disagreement amongst physics experts on the sign of work in thermodynamics. Many authorities view the work thing in a completely opposite way.

The first law basically says that the change in the internal energy of the system is equal to the sum of the heat added and the work done on the system.

A system that undergoes a thermodynamic process system can:

- gain heat or
- gain heat and do work on something or
- lose heat or
- gain heat and have work done on it or
- and so on.

Anyway, the thing goes from some initial internal energy state to some final state.

Joule's experiment that showed that mechanical energy and thermal energy were equivalent was a thermodynamic process. Work was done on a system which increased the internal energy of the system. The internal energy state changed as well – the temperature went up.

$$\Delta U = Q + W$$

Another simple thermodynamic process is boiling water. The system is a pan of water. You add heat to it and its internal energy state changes – the temperature goes up. No work is done, however. So all the added heat goes to increase the temperature of the water.

$$\Delta U = Q + W \quad \text{But work is zero so:} \quad \Delta U = Q$$

Heat engines operate by adding heat to system, which then does work. This is what the engine in your car does.

Another type of device that uses a thermodynamic process is a refrigerator. Here mechanical work is done on the system in order to extract heat from it. The heat is removed from inside the system and deposited into the room the thing sits in.

Using the first law is very simple. Let's look at a typical problem.

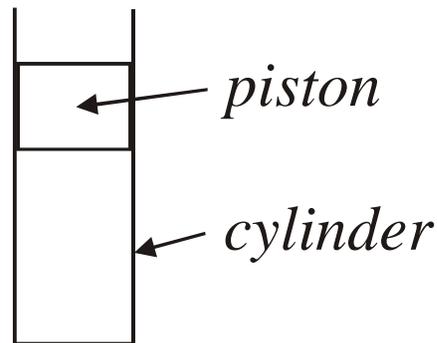
- In a thermodynamic process, a system absorbs 450 kJ of heat and does 87 kJ of work on its surroundings. By what amount did the system's internal energy change?

$$\Delta U = Q + W$$

$$\Delta U = 450 \text{ kJ} - 87 \text{ kJ} = \boxed{360 \text{ kJ}}$$

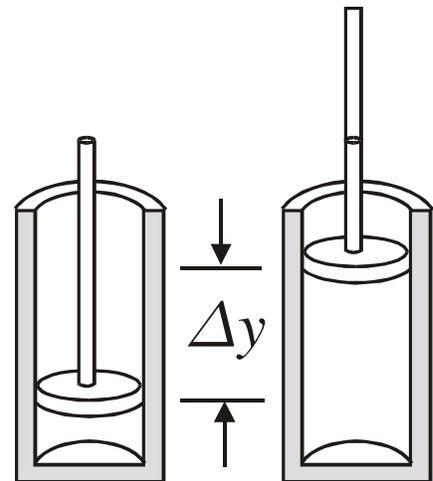
Note that the work done by the system is negative.

Pressure/Volume Work: Many engines that do work involve pistons and cylinders. Everybody knows what they are? A cylinder is a tube and a piston is a solid cylindrical device that exactly fits into the cylinder so that there is very little gap between the piston and the side of the cylinder.



- The piston can move up and down in the cylinder.
- Inside the cylinder, under the piston, is a gas.
- The gas cannot escape around the piston.
- Push down on the piston and the gas is compressed into a smaller volume.
- Pull up on the piston and the gas expands into a larger volume.
- The motion of the piston involves work. If you do work on the piston, you make it move. If the gas expands or is compressed causing the piston to move, then work is done on the piston.

If you add heat to the cylinder, the gas expands and pushes the piston upwards, doing work on it. We make a major assumption – that the pressure stays constant. This is actually reasonable. The area on the top of the piston doesn't change, so the force exerted on it by the atmosphere is constant. When the piston rises to some position, the force pushing down is still the same, so the force inside pushing up must be the same as well. Since this force comes from the pressure, the pressure must still be the same.



Gas expands at constant pressure moving piston a distance of Δy

A process like this where the pressure stays the same is called an **isobaric process**.

The piston has moved a distance of Δy .

- A force pushed the piston upward.
- Work happens when a force causes an object to move.

So can we figure out how much work was done on the piston?

Well, we know that pressure is the force divided by the area it acts on:

$$P = \frac{F}{A}$$

The force exerted by the pressure is equal to:

$$F = PA$$

The definition of work is:

$$W = Fd$$

So, plugging in the value of the force, we get:

$$W = Fd = (PA)d = PAd$$

We know that the area of this cylinder multiplied by its height is its change in volume:

$$\Delta V = Ad$$

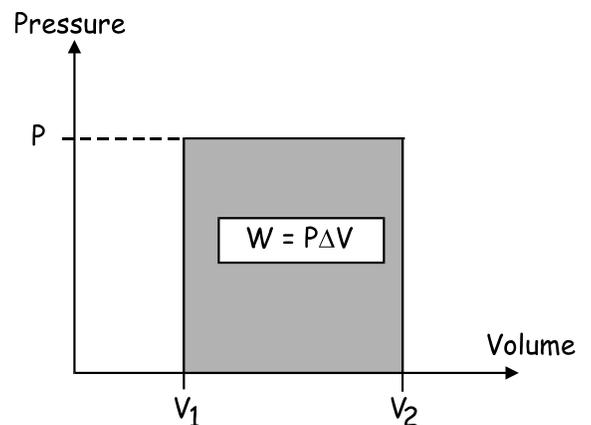
Therefore, plugging this in for Ad we get:

$$W = PAd = P(\Delta V) = P\Delta V \text{ So}$$

$$W = P\Delta V$$

We have now found that for an isobaric process, the work done is equal to the pressure multiplied by the change in volume.

To make this general, we look at a graph of pressure vs volume. For our isobaric process, the graph looks like this (see graph to the right):



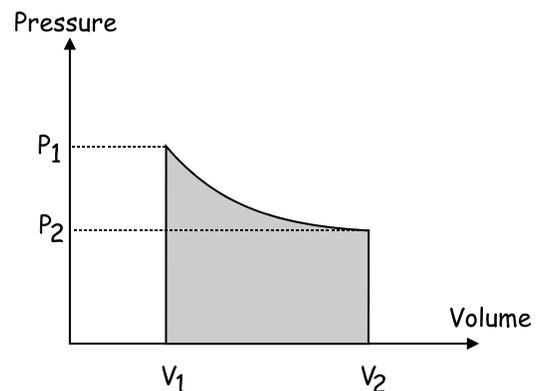
Work done when gas expands at constant pressure.

The area under the curve is equal to the work that is done.

This is also true for any graph of pressure vs volume. The area under the curve is always equal to the work.

Work done on the system is equal to the area under the curve on a P-V graph.

$$\Delta Q = \Delta U + \Delta W$$



Work done when gas expands at varying pressure.

Dear Doctor Science,
Is there a reason for not ending a sentence with a preposition that you can think of?

-- John Mostrom from Seattle, WA

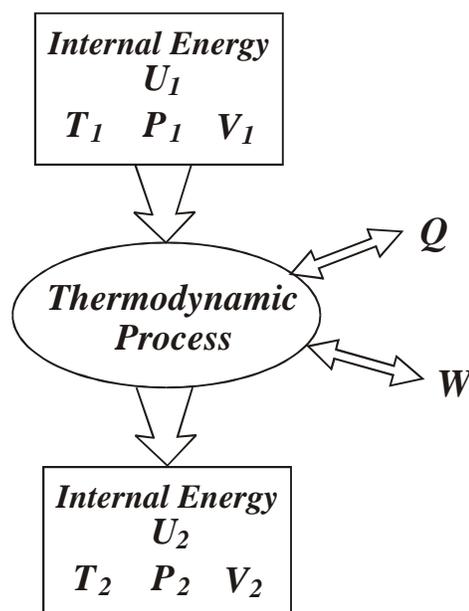
Dr. Science responds:

I must admit I don't know where you're coming from. Correct usage in English and Science is something I've devoted my whole life to. Of course, if I say anything you can't understand, it will just become a new hammer you can try to hit me or another expert over the head with. There are plenty of people like you I can't hope to change the mind of. But then, I've dealt with people like you before. People who don't really want to learn, but just hope to find someone they can publicly disagree with. There's little I can say that your type won't find something to object to. But getting back to your question, no there's really no reason for not ending a sentence with a preposition, at least none I can think of.

Curious, this Dr. Science bit had nothing to do with science, and especially thermodynamics, which we are happily studying, do you wonder why the Physics Kahuna put it in for?

Back to thermo!!!!

Here is a diagram of a generic thermodynamic process. A system has an initial internal energy. Heat is added to the system, or taken away from the system. Work may be done on the system or the system may do work or there may be no work involved at all.



The system ends up at some new internal energy state. This means that any of the following may change: temperature, pressure, or volume.

It can be very complicated to have all these things change at the same time, so the clever physicist is always looking for a way to make things simpler. This can be done by only having two of the three things change.

Adiabatic Processes: In an adiabatic process, heat is neither added or taken away from the system.

$$\Delta Q = 0$$

The word “adiabatic” is of Greek origin and means “impassible”. The idea being that heat does not pass into or out of the system.

An adiabatic process has the following jolly definition:

Adiabatic process ≡ a process in which there is no net heat transfer.

This means that the first law can be simplified:

$$\Delta U = Q + W \quad \rightarrow \quad \Delta U = W$$

What this means is that work is done by the system at the expense of internal energy.

Adiabatic processes are very common. There are two simple ways to have one take place:

1. The system can be insulated so that heat can neither enter nor leave. Joule’s “heat equivalent” experiment was adiabatic. The tub of water was insulated so the water would not absorb heat from its surroundings. Instead the work done on the water by the paddles increased the internal energy of the system - the temperature went up.

Note that the system did no work because $P\Delta V$ was zero.

2. The other way to have an adiabatic process (this is actually called a “near adiabatic process”) is to have it happen very quickly. The process happens so fast that there is no time for heat to be transferred.

The combustion of gasoline in an engine is considered to be adiabatic because each combustion step happens in a very short time – a few hundredths (or less) of a second.

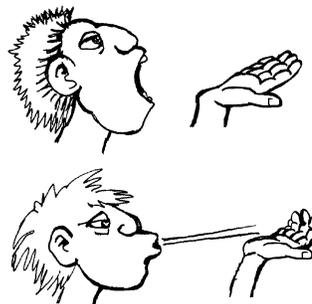
In an adiabatic process the following can happen:

- a gas that is adiabatically expanded will lose internal energy (ΔU) and become cooler.
- a gas that is adiabatically compressed will gain ΔU and become warmer.

We did a little activity in class where you puffed air onto the palm of your hand. The air felt warm.

Then you compressed your lips into a kissy shape and blew air over the palm. This air felt cool.

This was the same air and it was coming from the same place (your lungs). For one event it was warm and for the other it was cool.



The explanation lies in adiabatic expansion. The air puffed out of your lungs felt warm because it was warm – it gained heat from the warm blood in your lungs (you better hope that the blood in your lungs is warm).

Puff air from your open mouth and it warms your hand. Blow air in a thin stream and it cools the hand.

The air coming out of your pursed lips was compressed in your mouth. When it came out of your mouth it expanded – actually, adiabatic expansion – and so it lost internal energy. It cooled.

Dear Pete,

You would not believe how mediocre the students taking AP Physics here at Campb

Isothermal Process: The isothermal process happens at a constant temperature. The pressure and volume change, so work is done, but ΔU is zero.

$$\Delta U = Q + W \quad 0 = Q + W \quad Q = -W$$

Isochoric Process: In this type of process, the volume stays constant. This means that ΔV is zero. If ΔV is zero, then the work must also be zero.

$$W = P\Delta V = P(0) = 0 \quad \text{Thus:}$$

$$\Delta U = Q + W \quad \Delta U = Q + 0 \quad \Delta U = Q$$

Examples of isochoric processes:

Cooking food

Pressure cooker

The key points for this type of process is:

No work is done.

The internal energy is changed by the addition or extraction of heat from the system.

Isobaric Process - pressure stays constant

Work can be done if the volume of the system undergoes a change. Without the change in volume, can't get no work out of the system.

Dear Doctor Science,

Is there any truth to the old bachelor's saw, "The higher the heat, the sooner we'll eat"?

-- Dean F. Cully from Bethel, AK

Dr. Science responds:

Bachelors are an impatient bunch, too antsy to put up with the demands of wife or children. They do most of their cooking on a hot plate, warming up cans of beans or soup and making plenty of coffee, while they pace their furnished rooms, mumbling to themselves about what's wrong with government, and women. The Underwriter's Laboratories makes sure that hot plates can only get so hot, otherwise the number of rooming house fires would be even greater than it is now. Oxy-acetylene would, of course, heat things up even faster and a clean hydrogen flame could char a can of beans in seconds.

Dear Cecil:

Cecil, how can dogs walk around in snow and subzero weather without getting frostbite on their feet? --Lisa Burns, via the Internet

Cecil Adams replies:

Consulting with the veterinary section of the Straight Dope Science Advisory Board, we found a diversity of opinion on this topic, which may be summarized as follows:

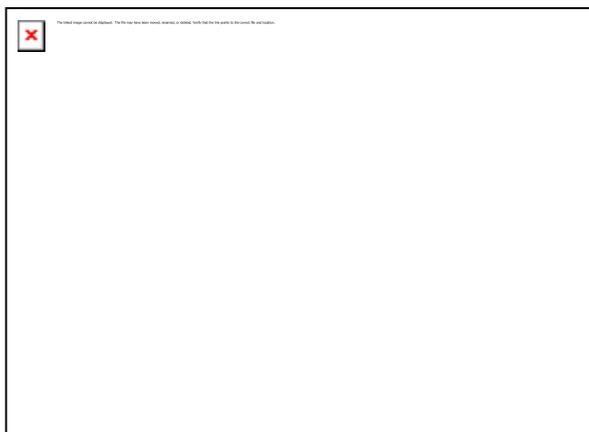
(1) Dogs do so get frostbite on their feet.

(2) They do not either.

Once again, it seems, we've got our work cut out for us.

Heading up the do-not camp was Stuart Nelson Jr., head veterinarian for the famous Iditarod dogsled race currently under way in Alaska. This 1,100-mile event lasts two weeks and features several dozen dog teams and their mushers racing from Anchorage to Nome in some of the most grueling conditions imaginable. The temperature sometimes falls to 40 below (at which point, I might note, Fahrenheit and Celsius thermometers read the same). I figured if ever a vet knew about dogs and frostbite, Dr. Nelson had to be the guy.

The doctor says he's seen lots of frostbitten canine parts, including the nipples, vulva, and prepuce (no wonder the Iditarod has been condemned by animal-rights groups), but he's never seen any



frostbitten feet. He thinks this may result from some peculiarity of the canine circulatory system. When people are exposed to extreme cold, vasoconstriction in the extremities reduces the flow of blood there, helping reduce heat loss and maintain the body's core temperature. Maybe this doesn't happen with dogs. Or maybe they just have more blood vessels down there. Whatever the case, it's not something peculiar to sled dogs. The doc says he's never seen frostbitten dog feet in private practice, either. He sees this as a survival mechanism: if a dog can't move, it dies.

Other vets doubt that dogs enjoy any special protection, though they do concede that frostbitten paws are rare. A 1975 veterinary account of the Iditarod, written before Dr. Nelson's time, mentions a few cases, but these occurred because booties intended to protect dogs with paw blisters were tied too tight. Researchers have induced frostbitten paws in the lab to learn more about human frostbite, suggesting they don't see much difference between us and the pups circulationwise. One vet believes dogs are protected by the thick epithelial pads on the bottoms of their feet, their somewhat higher body temperature (100 to 102.5 degrees Fahrenheit), their thick fur (remember that the frostbitten areas noted by Nelson were hairless), and their practice of curling their paws next to their bodies when sleeping.

I doubt we need to look for an explanation any more exotic than that. Dogs don't wear clothes either, but they withstand conditions that would kill you or me.

--CECIL ADAMS

Trees – Joyce Kilmer

I think that I shall never see
A poem lovely as a tree.

A tree whose hungry mouth is prest
Against the earth's sweet flowing breast;

A tree that looks at God all day,
And lifts her leafy army to pray;

A tree that may in Summer wear
A nest of robins in her hair;

Upon whose bosom snow has lain;
Who intimately lives with rain.

Poems are made by fools like me,
But only God can make a tree.

Sargeant Joyce Kilmer was a member of the 165th Infantry of the 69th New York Regiment of the AEF. He was killed in action near Ourcy, France on 30 July, 1918 in the Great War.