

hello

so let me begin this lecture by a summary of what we did in the last lecture
so number one is we elaborated on the temperature coefficient of resistance we had seen that though there are electrons available in the circuit by there being very much there the free electrons in the conductors in order to make the current flow i need a mechanism by which you push this electrons in the same way as the water is pushed in a pipe and that is job done by the battery

so battery is the one which is pushing the electrons in the circuit and as we had said battery works like a pump

so which according to our convention pushes the positive charge actually what it does is exactly the opposite but on the other hand that has been our discussion

so what the battery actually does is to take the positive charge carriers and it pushes them from a lower potential to a higher potential i repeat once again that i always talk about positive charge carriers though the natural charge carriers are electrons

so all that means is the direction of the electron flow is opposite to the direction of conventional current

so uh these positive charge carriers when they are raised to a higher potential and that is the job of the battery in the external circuit they can just flow down the potential

so that is what it does after that we defined something known as electromotive force which is a characteristic of our battery and we said that electromotive force and i repeat that electromotive force is not a force it's an unfortunate nomenclature but but that's the way it is because it was thought to be a force because apparently something was pushing these charges but the name has stuck

so basically the electromotive force was defined as work done on that positive charge work done on a unit positive charge in taking it from a lower potential to the higher potential

so our definition is electromotive force which is usually represented by a script \mathcal{E} is dW by dq and you can see since numerator has the dimension of work

so which is in joules and denominator is in charge which is coulomb and that is the definition of a volt now if you look at this definition there is another thing that becomes clear that since i know that the work in taking a charge by a vector distance $d\mathbf{l}$ is given like $\mathbf{f} \cdot d\mathbf{l}$ this is just the standard definition of work in terms of the force $\mathbf{f} \cdot d\mathbf{l}$ is the force and and remember that my electric field \mathbf{e}

so so this is my force and

so therefore i can write my emf as equal to if you like integral of $\mathbf{f} \cdot d\mathbf{l}$ by q because we said that it is per unit charge $\int \mathbf{e} \cdot d\mathbf{l}$ that's the definition of this thing now let us look at this definition a little more carefully now this is from the lower potential to the high potential

so let me draw the standard battery

so that's the way it is the battery

so the electric charges are being taken positive charges are being pushed from here to there and after that of course in the external circuit they can flow but if you look up this expression very frequently we write the electromotive force in a slightly different way we write this as integral of $\mathbf{e} \cdot d\mathbf{l}$ because we are talking about electric field which is nothing but the force per unit charge and what you will find is that your definitions will also have a circle around that interval meaning thereby this is called a contour integral thereby that you ah take the line integral of the electric field this is the line integral as you were around a closed loop now how does it work how do i show that these two things are equivalent now look at it this way that when i am if you like the

word pushing the positive charge from here to there this is happening by the chemical reactions driving them

so this force if you like is a non-conservative force

so inside the battery the force is non conservative now outside everything is nothing changes really you have to of course say that once the transient currents are gone i mean everything is time independent

so outside the field is electrostatic field

so field outside by definition electrostatic field as you have learnt is a conservative field

so therefore my force has two components one is that there is a conservative part or electrostatic part which is outside and a non-conservative part which is inside now i also know for the conservative part $\int \mathbf{f} \cdot d\mathbf{l}$ is equal to 0 and that is because by definition of a conservative force the work done is independent of the path between any two points

so if you are going back from one point to another point the you can go by any path but if you return back to the same point then the work done has to be zero

so if i look at conservative $\int \mathbf{f} \cdot d\mathbf{l}$ it is equal to zero that's not true of course of non-conservative part but you remember that my non-conservative force outside the battery is zero

so therefore i if i add up these that is outside the battery i add a non-conservative inside the battery i add a conservative part which was zero but i add it anyway outside i add the non-conservative part and non-conservative path is 0

so i can do that

so therefore if you add them together you get a definition like emf is given by because per unit charge like contour integral closed integral of $\mathbf{p} \cdot d\mathbf{l}$ and that's the reason why emf is frequently defined like this and we will have more to say about it when we discuss uh the definition of uh the electromagnetic force in connection with faraday's law of induction but this is this is the way it works having done this what we did is to summarize what happens for ohmic conductors we had seen that the current density is related to the electric field by $\mathbf{j} = \sigma \mathbf{E}$ where σ is the conductivity the current itself which is $\mathbf{j} \cdot \mathbf{a}$ is the area vector this is the current density

so this is given by $\mathbf{E} = \rho \mathbf{a}$ and that's equal to your $\mathbf{v} = \mathbf{l} \cdot \mathbf{E}$ is the electric field i have a row there and an a there

so therefore i get an alternative relationship which says $\mathbf{v} = \mathbf{l} \cdot \mathbf{r}$ because \mathbf{r} is nothing but $\mathbf{l} \cdot \rho / \mathbf{a}$

so any of these relations you have for the ohmic conductors $\mathbf{j} = \sigma \mathbf{E}$ $\mathbf{E} = \rho \mathbf{a}$ then or $\mathbf{E} = \mathbf{v} / \mathbf{l}$ etcetera a constant electromotive force namely a battery which has no internal resistance normal batteries have some internal resistance because you cannot eliminate material elements and they always offer resistance

so firstly an ideal emf source an ideal battery if you like provides a constant voltage across its two terminals

so let me let me draw a very simple circuit and later on maybe i will do a little more complicated circuit

so this is my source of emf and i put a little resistance there i will explain why and there is a resistance in the outer circuit

so what happens is this that this is my seat of emf what is frequently done in electric circuits is to do this type of a mark with a little circle at the base to indicate i am talking about emf direction that is the direction in which the voltage increases from negative terminal to the positive terminals and there is a little internal resistance there

so this is your representation of the battery the outside circuit R_L this is

what is known as a load resistance because that is the load that the circuit bears

so the rule is something like this that supposing you go in the direction of current

so let me just quickly try to write this somewhere here going in the direction of current as you go through a resistance the potential drops by an amount r air that's rule number one the second rule is if you move from the negative terminal to the positive terminal of a battery then you increase the potential by an amount the given by the emf e

so in going from negative to positive Δv increases by e okay with that idea let us try to see how does the potential vary in this case let us look at the following circuit

so i have a battery here and this represents its internal resistance and a load resistance which i will write as r_l let us look at the current in this circuit supposing i go in the direction of current going from the point a to point b say this is likely to be the direction of the current because the positive terminal is on this side

so when i go from a to b there is no drop

so the potential at the point b is the same as the potential at the point a but since i am going in the direction of current in going from b to this point c let us say potential would drop from b to c by i times r_l where i is the current in the circuit then i get into this part where the source of emf has also an internal resistance smaller

so if from c i come to this point just cross the internal resistance which is a representation from c to d it drops by i times small r and then as i go from the negative terminal of the battery to the positive terminal then through the battery potential rises by a

so what have we got we have said then now when i do that i return back to the point a

so in other words if i go from a to b through c d and back to a this is what happens

so in other words i get $\text{minus } i r_l \text{ minus } i \text{ plus } e \text{ equal to } 0$

so which gives me i is equal to e divided by r plus r_l for definitiveness let me take e to be equal to 10 volts the internal resistance to be 3 ohms and the load resistance to be 17 ohms 3 ohms is rather a large internal resistance the current in that case will be 10 divided by 17 plus 3

so that's equal to 0.

5 amperes now let us look at how does the potential change

so look at this that suppose i am going from a to b since we have already seen how the potential varies

so start at the point a and let me look at the potential at various points d c and b

so i start with the point a which is obviously at a 10 volt potential now when i cross over to the point d now since the point d is connected to the negative terminal of the battery the potential comes to the value of the negative terminal value it has in the negative terminal i don't know exactly how the potential changes inside the battery

so let me just draw it by a dotted line now having done that i go from point d to the point c through the resistance small r now there since the resistances have been assumed to be ohmic the change in potential would be linear as it goes through the resistance

so therefore from d it sort of rises as i go to the point c or rather the end point here and this rise not to scale but this rise is current i is 0.

5 r is 3

so therefore this rise is 1.

5 volts now having done that i remain the same the potential remains the same up to this point and then again when it crosses the r_1 it rises coming back to the value 10 once more

so this is if you like the point b which is obviously the same as the point a so let us look at it little more clearly

so what i have said is this that there is a method which you can add up now remember towards the end of last lecture i had started talking about how to analyze a circuit having two batteries

so i am going to bring it back and redo the problem with this pictorial representation of the voltage drop that gives you an idea of how one sees the voltage drops

so let me repeat that circuit again

so here i have got two batteries let me say that the first battery is like this and this has an internal resistance of r_1 which is one ohm and this is e_1 which is 2 volts and then i have another battery whose polarities are like this having an internal resistance of r_2 which i take it to be 1.

5 ohms and e_2 which is taken to be 4 volts and then i have the external circuit where i have a load resistance which i take it to be 5.

5 ohms

so let us look at in this situation what actually happens

so let's let's start from some point it doesn't matter matter where you start

so let me start from this point a list now in principle i really don't need to know what is the direction of the current but let us suppose just for convenience i am going like this why why am i going like this very simple by looking at this figure that this is the 4 volt battery this is a 2 volt battery i realize that the net current is likely to be like this

so i am going in the direction of current

so let me let me look at that the if i am going in the direction of current like this and i am going from a this point a and let us suppose there is a point which i mark as h then i will do the following calculation i will say v of h is equal to v at point a minus e_1 because i am going from positive terminal to the negative terminal

so minus two if you like because two volt was that having done that let us go to another point across the internal resistance let us call this this point g now what about v_g now we have said if you are going in the direction of current then potential would drop by an amount i times r

so therefore v_g is equal to v_h minus i times r_1 which is equal to v_h is v_a minus 2 minus i times 1 ohm

so let us light write it as i times r_1 now of course what i could do is to calculate what happens to the current how much is the current exactly the same way what i can do is go from here to there there to there there to there and come back to it

so if i do that all that happens is i drop a potential 2 increase by i times r_1 increase by i times 5.

5 increase by i times 1.

5 and then increase by 4.

so therefore what happens is this that my result is my current i then would be given by i had increased by 4 this was decreased by 2

so this would be equal to 1 plus 5.

5 plus 1.

5 which is simply equal to one by four amperes okay

so how much is this this is v_a minus two r_1 is 1 ohm

so therefore $1 \text{ into } 1 \text{ by } 4$ which is 0 .

25 and that is v_g but then v_g is also equal to i am going by this e because there is nothing in between these are resistances where

so this is identical to v_e now let me come to this point d

so we say that v_d is v_e minus i times 5 .

5 that's equal to v_e i was taken to be one by four shown to be one by four five point five into one by four which is one point three seven five and and if you look at this relationship there

so i have got v equal to v_a minus 1 .

75

so this gives you v_a minus 3 .

62 and that is the same as the point b now what i now need is this from b i come to the point c

so my v_c is v_b minus 1 .

5 times i i is 1 by 4 which is equal to v_b minus 0 .

235 sorry 3 to 5 and that is equal to v_a minus 4 .

so that gives you the difference between these two points that is v_c and v_a v_c and v_a this is the way it is and then of course if you want to come back to a then you increase the potential by 4

so you exactly

so this essentially tells you how the potential drops are to be calculated now here i assumed a priori that current is in that direction you don't really need to know what is the direction of current suppose you did not and you assume opposite

so when you go opposite to the direction of current then of course as you go through a resistance we have seen that the potential is rise

so go exactly like this and come back to the same point if you do that you will essentially have the same calculation accepting that what their what was happening here was when i went from here to there my potential is dropping here increasing there but instead of that this will uh i 'm going from positive to negative here

so therefore the potential will drop there but increase here

so my current would still turn out to be the same in magnitude but it will show up with a negative sign

so therefore i know my original assumption regarding the direction of current was wrong and i should come back and do it correctly

so this is uh the way the you look at the variation of potential as you go through a register

so basically all that i have said is that in go when a current passes through a resistance is very important when a current passes through a resistance in going from higher potential to the lower potential the drop is i times r now having done that let me look at another job that the battery is doing

so we have said that the job of the battery is to push or lift a charged particle the positively charged particle from lower potential to the higher quotation now

so since it is the amount of work that is done on charge

so this amount of charge in order to push it the eye meaning there by the battery will have to do some work and this work that the battery does is obviously because of my definition of the emf i can calculate it easily because emf was work done per unit charge

so therefore the amount of work done is the amount of charge that you take to a higher potential

so the the work done will then become the emf multiplied by the charge and this

amount of work obviously gets delivered or this amount of work is done by the source which is the battery and once the positive charge comes to the higher potential it can flow in the external circuit in other words in terms of the energy whatever its energy was it now gets it can now be spent this is the amount of energy that is being supplied to the external circuit

so let us look at what is the amount of power delivered by the circuit

so that let us call this p of the battery which i call it as p_{emf}

so that is equal to dW by dt the work done per unit time but dW is nothing but the emf times dq that is the amount of charge that has been lifted through this potential barrier and by dt but if you recall dq by dt is nothing but the current

so it is e times i

so this amount of energy is delivered by the battery to the external circuit and

so therefore this amount of energy has to appear as the internal energy of different parts of the circuit which could be electric field energy mechanical energy in case there is a motor or some such thing in this circuit if there is a bulb in the circuit it can be used to light it up or simply heat up the resistance in the case where the energy is dissipated by the way of resistor getting heated this is known as the joule heat loss this is the amount dissipated by amount of energy which a resistor absorbs and dissipates now in the case i have a very simple circuit supposing we simply have a circuit like this i just have a ideal battery this is plus this minus e and let us say i just have a resistance let's call it just the load resistance r_L there is a point a there is a point b no internal resistance and looking at this direction this is a positive terminal

so therefore v_a is greater than v_b

so if a charge dq comes from this terminal to the point a okay the potential energy of that charge is v_a times dq and at b it is v_b times dq

so what has happened is there has been a change in the potential energy and normally we define change as final value minus the initial value

so therefore that the change in the potential energy let's call it du that's equal to dq times final potential minus the initial potential and let us call this Δv

so therefore du by dt does the rate at which the energy transfer takes place is dq by dt times Δv and that's equal to now dq by dt is i

so the current times Δv now if ohm's law is valid then i is Δv is i times r

so that therefore the power is $i^2 r$ and since i have a simple circuit i is equal to v by r

so therefore this is equal to v^2 by r

so let us look at what is this happening to this energy now when this energy goes through the resistance now we know that it should result in an increase in the kinetic energy of the charges because of the work energy in other words these charges should accelerate but remember what we said we said that that the charges in a conductor actually accelerates but that's a very nominal situation because they keep on colliding and move with an average drift velocity

so what has happened to this increased potential energy that we have given it to charges because of the work done by the battery

so what has increased is this that this increase in the energy is gets used up in collision with atoms

so electrons collect additional kinetic energy collide with the atoms and the as a result they transfer energy to these atoms now this makes the atoms vibrate uh more rapidly because they have now got some kinetic energy now this will

result in an increase in the temperature of the resistor

so so this results in increase in the temperature now i would like to give you an example uh a similarity now in your mechanics course you have always learnt about the when a you drop a mass through a viscous liquid you have heard about that it attains terminal velocity now remember that since it is falling under gravity though there are viscous forces also it is reducing its potential energy now if it is reducing its potential energy but still moving with an uniform kinetic energy uniform velocity then this loss in the potential energy appears as a well in internal energy of supposing you have dropped a stone that stone that liquid or whatever but that would generally result in an increase in the temperature we don't normally measure such increase in temperature because the amount is somewhat low in case of a resistor if a current passes through it because of this reason because of the energy that is being transferred from the battery to the register the resistor will get heated up resistor gets heated up and it radiates heat it would become hotter to touch on and also if there is for instance a bulb in the circuit it can be used to light it up normally these are laboratory situations but you see we also have generating stations which actually generate electricity just as battery is doing in a small scale and supply it to various cities and there are usually large distances between the generating station which are normally not located inside the city and the place where they are being transported over large distances now over large distances when you transport electrical energy that is carrying current you have a power loss

so this is equal to $i^2 r$ of the wires and remember that these wires are over large distances

so this is equal to $\frac{P^2}{V^2} \times r$

so what happens is this that if you want to reduce the power loss you would like to transport it at very high voltage because if V is large then the loss during transmission will be small but that makes the whole process a unsafe because you are supplying energy at um transporting electricity at high voltages

so it is and it's unsafe

so it is necessary that at the consumer's end they are the voltage is reduced using what are known as step-down transformers

so let me now talk about or by giving some examples of how this power thing works

so let us first start with a simple circuit

so in this simple circuit i have taken supposing i have a resistor of length l cross sectional radius r resistivity ρ etcetera and supposing i have a 18 volts battery and it is given that this resistor this resistor absorbs 80 watts of power the source now my question is this that supposing this resistance wire you take it out and draw it to another resistance uniformly which has four times length now then what statement can i make about how much of power is absorbed from the source this is the question

so what we have given is this let us first write down what is the resistance like

so resistance as you know is $\rho \times \frac{l}{\pi r^2}$ the current as you know is $\frac{V}{R}$

so what you have said is this that this absorbs 81 watts of power now when you draw it to four times its length now remember the volume had to remain the same if the volume remains the same it means the cross sectional area has also reduced by factor of 4 but the resistance which is proportional to length which has increased by a factor of 4 and inversely proportional to the cross sectional radius which in this case has decreased by a factor of 4

so the net resistance in the process has increased by a factor of 16

so my r prime is 16 times r

so how much is v square by r prime this is my power

so v square by r prime is v square by 16 times r but v square by r is given to be 80 watts by 16

so therefore that this situation it will absorb 5 watts of power look at the current in this situation now if you look at the current since the voltage is 18 volts i have v by r prime v is 18 divided by 16 r but 18 by r my was my original current i

so it's i by 16.

so i square r prime if you want to calculate is equal to i square by 16 square which is 256 times r prime which is $16r$ that is equal to i square r by 16 as expected now the question is this that what frequently confuses people is that which formula do i use is the power is power v times i or since i is v by r is it v square by r or is it since v is ir is it i square r now you would say they are all the same now they are all the same provided all that you have is a symbol single source of voltage that's an emf source and a single resistance now look at what difference does it make

so i'll give you a small example

so let us look at this situation this is potential drop is v whatever i have done here is right no problem all the three formulas but suppose i have a slightly different problem i have a 100 volt source there are three resistances there 5 ohms 8 ohms 7 ohms let's see what is happening in this situation let me first calculate how much current i have my current is 100 divided by 5 plus 8 plus 7 which is simply 5 amperes

so the power that is delivered by this source is given by this formula

so power delivered by two circuit this is equal to hundred into five which is equal to five hundred what's of course but let us look at what happens here here it is i square r the reason is if you want to use the other formula you must then find out what is the potential drop across this point not this 100 but if you say what is the current because the current is the same in the whole entire circuit then you can do i square r

so how much is i square r for this this is the current is 5

so it is 5 square which is 25 times 5

so this is giving out 125 watts this one 25 into 8 that's consuming 200 words this is 25 into 7 that's 175 words if you do the arithmetic you find this plus this plus this is 500 as expected

so what we are saying is that when you use this formula be a little careful the v in this formula is the potential drop across the resistor that you are talking about not the potential supplied by the battery i square r is always correct provided that is the current passing through this you have to be careful if it is not a simple circuit like this because there various parts of the circuit may have different amounts of currents

so this explains what actually we need to use

so let me quickly tell you what we have achieved today we have said that the seat of emf lifts positive charges from a lower potential to the higher potential as a result of which the battery does work on these charges this charge that the battery does is equivalent to an amount of energy which is available to the external circuit and this energy that we have got if they are passing through resistances or other components they can be used to do either useful work like for example turning and motor or simply gets dissipated as happens when you use it for example just the register dissipates the heat

so this is we will continue with the power and some more examples we'll give you in the next lecture and after that we will go to a discussion of circuit

principles you

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