hello everybody

so ah i will start my lectures by summarizing what we did yesterday

so the first point was that we defined current and we said current is a flow of electricity or electric charges if you like the ability of a material to conduct electricity depends on the properties of the material

so ability to conduct in particular we are interested in what are known as conductors we observed that conductors have what are known as free electrons the free electrons belong to the material as a whole and are not bound to a particular atom or atoms the point about the current electricity is unlike an electrostatics where the field inside a conductor must be equal to zero the electric field inside a conductor having said this we defined a quantity which is known as charge density we did point out that electric current itself is not a vector but we defined current density denoted by vector j and we said in terms of this the current is given by j dot ds where this is defined in such a way that the product j dot ds is positive for positive current flow primarily in conductors the charge carriers that is those which are responsible for conduction are electrons however ah the there are situations where we saw that ions can also conduct particularly it happens in electrolytes the point regarding the direction of the current is that though electrons are primarily responsible for flow of electricity the direction of the current is primarily defined as the direction in which positive charges would flow if they were free to flow like the electrons

so this is direction of the current towards the end of the last lecture we defined what is known as a drift velocity we said that drift velocity is the average velocity of the charge flow as a result of the presence of an electric field

so we found that what happens in the presence of the electric field as these electrons which are free they are able to or they will accelerate and in doing

so they will go and collide with the static ions or atoms and having done that after collision they would emerge from these ions in arbitrary direction though with similar speed with which they had collided because the collision is nearly elastic but however since the direction is random the average drift average velocity of all the electrons taken together will turn out to be zero but in the presence of an electric field the there is a general direction in which they move and that is the average velocity direction we also defined or obtained the relationship between the current density and the drift velocity by this relationship minus e m v d where this minus sign is because we are talking about the drift velocity of electrons and i have charge of an electron and the number density of the electrons

so this is the relationship between drift velocity and the current density here e is the magnitude of the electronic charge which is 1.

6 into 10 to minus 19 coulomb now i will illustrate these with a numerical example

so let me look at a particular problem suppose i have a sample of copper having having a cross sectional area of 10 to the power minus 7 meter square and suppose this carries a current of 1.

5 amperes we assume that each copper atom provides one electron to the free electron gas and the density of copper atoms is rho

so not to confuse with n is 9 into 10 to the power 3 kilogram per meter cube atomic mass of copper is 63.

5 units

so our problem is to find out what is the drift velocity and the current the current density is fairly straightforward the current density is simply the current i divided by the area current is given to be 1.

5 amperes and area is 10 to the power minus 7
 so therefore this is 1.
5 into 10 to the power 7 ampere meter square i had already obtained this relationship j is equal to minus n e v
 so in order to calculate the drift velocity i need to obtain the electron density the number density of electrons in the sample remember that what is given here is the mass density of the sample which is 9 into 10 power 3 kg per meter cube now in doing
 so i need to recollect a little bit of chemistry for you
 so we know that one mole of copper has a mass of 63.
5 grams which is 63.
5 into 10 to the power minus 3 kg in addition i know and it has number which is known as the avogadro's number namely 6 into 10 to the power 23 number of atoms in one mole with this data i can immediately find out how many moles are there in one meter cube
 so number of moles in 1 meter cube is 9 into 10 to the power 3 kg divided by 63.
5 into 10 to the power minus 3 well i will calculate everything towards the end
 so therefore the number of atoms there which will be the same as the number of electrons is simply this number 9 into 10 to the power 3 by 63.
5 into 10 to the power minus 3 multiplied by the avogadro's number 6.
2 into 10 to the power minus 10 to the power 23 and this if you calculate this works out to 8.
5 into 10 to the power 28 per meter cube and since i have said each atom has one electron contributing to the free electron gas
 so therefore this is also the number of electrons n
 so this is also identical to the n that we have talked about
 so therefore my drift velocity magnitude is given by j divided by n e and j was found to be equal to 1.
5 10 to the power 7 and we have just now found out eight point five into ten to the power twenty eight into electron charge which is known to be one point six introduce power minus nineteen all these are in si units and if you calculate all this this works out to a rather small number 1.
1 into 10 to the power minus 3 meter per second that is equal to 1.
1 millimeter per second now i would like to compare this number with other types of typical velocities that we have
 so one of the things that you must know is that this is drift speed not to be confused with the speed which the electrons have inside a conductor when it is able to move free the drift please speed is an average effect of all the electrons taken together
 so let us look at what else we can compare this with
 so average speed of electrons inside the material is fairly large it's about 10 to the power 6 meter per second that is the speed with which the electrons are moving inside the conductor and before they collide but remember the average of this over because of their directions being random is essentially equal to zero there is another quantity which i would like to compare this with is the thermal speed of copper atoms now this time i am talking about atoms from kinetic theory you know that the average kinetic energy let me call it v thermal square is my equipotential partition principle is three by two kt
 so thermal velocity of the atoms is of the order of ignoring the factor of 3 and things like that kt over m where k occasionally written as kb is boltzmann constant which is 1.
38 into 10 to the power minus 23 in si unit which has a little complicated dimensions meter square kg per semen square degree now if you substitute this

what you get is you can see it this is 1.
38 10 to the power -23 let's take the room temperature to be 300 kelvin divided by the mass of copper atom which we just now calculated to be 63.
5 into 10 to the power minus 3 divided by the avogadro's number 6.
2 into 10 to the power 23 and if you calculate all this it works out to about 2 into 10 to the power minus 2 meter per second

 so you notice that the drift speed of electrons is even smaller than this thing and you see what happens if i am talking about electron mass here because the mass here appears in the denominator this number that the thermal speed of electron increases substantially and you get this number which is about 10 to the power 26 or

 so so vd is much less than the thermal speed of both electrons and of course even the ions there is another characteristic speed and that is the speed with which electric field gets established inside a conductor whenever you switch it on now that is essentially instantaneous because the electric field speed gets established with a speed of the order of velocity of light

 so therefore drift p speed that we have talked about is an extremely small number i will come back to the way the drift speed arises with a little more detail later but let me now talk about a large class of conductors now what is found is that a large class of conductors satisfy a rather simple relationship between the drift speed and the current density and that law which i will state in a slightly different way is known as ohm's law and a very large amount class of conductor satisfies this now we know that between successive collisions the electrons are accelerated by an electric field now

 so therefore the drift speed is proportional to the electric field itself and the current density which is proportional

 so let me say that the drift speed is proportional to the electric field and i know that the current density by definition or by our derivation is proportional to the drift speed that tells me that the current density j is proportional to the electric field and we can write this as j is equal to a constant sigma times e this is a vector relationship where the value of sigma is usually large for good conductors and its this is the property of the material it's called conductivity now you can see what are the units of conductivity it is the unit of j by e and j is an ampere per meter square divided by volt per meter

 so it has this unit ampere per volt meter this quantity is called a semen

 so now normally this relationship j is equal to sigma e is written by writing the inverse relationship namely e is equal to rho j where clearly rho is nothing but one over sigma and the unit of this is volt sorry ohm meter 1 ohm is same as 1 volt per ampere and is also equal to siemens inverse this row like sigma is independent of electric field and it depends upon the properties of the material conductors are characterized by high values of sigma or low values of rho

 so typical good conductors are for instance silver which has a resistance resistivity of 1.
7 10 to the power minus 8

 so name of row is resistivity

 so this is the no meter unit copper 1.
7 10 to minus 8 aluminum 2.
75 10 to minus 8 etcetera etcetera these are some good conductors on the other end of the spectrum there are good insulators these are conductors insulators are those which do not readily conduct electricity typically water is two point five into twenty per five oh meter glass can have a value between 10 to the power 10 to 10 to the power 14 between these two classes there is a class of material which are known as semiconductors about which you will be learning in detail in one of the review of the later lectures now semiconductors are

generally insulators at low temperatures and as the temperature rises their conductivity increases in addition the conductivity of semiconductors is substantially affected by impurities that might be present or impurities that might be put into and typical resistivity of certain semiconductors for example if you look at resistivity at zero degree of carbon in the form of graphite it's of the order of ten to the power minus five ohmmeter germanium is 0.
46 ohmmeter silicon 2300 per meter

so we have talked about conductivity and resistivity which are properties of the material but let us now try to talk about a property which depends upon a particular sample for example let's talk about a sample which has a length of l and has a an area a cross sectional area a we have seen that rho is equal to e by j now let's look at now i know that if i have a potential difference between the two ends which is delta v the electric field is delta phi divided by l and current density by definition is the current that is flowing through it divided by the area a

so therefore this quantity is a if you take out the dimensional quantities there

so we will write it as delta v by a delta v by i into area by length okay now we define a quantity called resistance this is quantity is called the resistance and this resistance which is the property of the sample is given by rho times direct proportionality with l and inverse proportionality with the cross sectional area

so this is characteristic of a sample and of course its material

so you notice that resistance of a sample is directly proportional to its length and is inversely proportional to its cross sectional area and this r which we have defined as the applied potential difference divided by the current if you plot this current as a function of delta v you find this is essentially a straight line now it turns out that a very large class of material follow this simple relationship and in fact most of the time unless specifically stated we assume that the conductors with which you work are ohmic material

so let me sort of ah give you an illustration or an example to calculate ah the resistance of a sample let me take a block of copper suppose it has a dimension of one centimeter by one centimeter by 20 centimeter

so let me try to draw it not to scale obviously because length should be 20 times as much

so what i do is this now one of the points that you have to realize is that the response of this to the electric field would depend upon which way you apply the potential difference

so for example supposing i decide to apply the potential difference between the long ends

so this is my l which is 20 centimeter then my resistance between these two ends which we have said is rho l divided by the area rho is i'll take the data for copper that i had given you earlier 1.
3 into 10 to the power minus 8 and the length is 20 into 10 to the power minus 2 divided by the area which is 1 centimeter by 1 centimeter

so it is 10 to the power minus 4 meter square and if you look at these numbers

so here i have got 2.
6 into 10 to the power minus 5 ohms now suppose instead you had applied the potential difference between the rectangular ends now your numbers will change now because what has happened is between rectangular ends

so resistance between rectangular ends now i have the same number 1.
3 10 to the power minus 8 which is property of a material the length this time is just 1 centimeter

so that's 10 power minus 2 and the area is 20 centimeter by 1 centimeter

so it is 20 into 10 to the power -4 and if you calculate this this is 0. 65 into 10 to the power minus 7 ohms the point to notice that the resist while you can talk about resistivity of a sample the resistance depends upon dimensions and not only that it depends upon if you want to measure it then it depends upon where exactly you have applied the potential difference and
 so resistance would vary depending upon which pair of points you have applied potential difference now before i close this let me bring out a similarity between charge flow and heat flow remember that right in the beginning when i introduced the concept of an electric current i had brought out a similarity with the flow of water in a tube now you will realize that the similarity is lot more striking here and let us again talk about a sample and let's suppose that i have a sample of length delta x and suppose across this i apply a potential difference of delta v then by definition of resistance of the sample i know my current i is delta v divided by r which is delta v divided by rho times its length delta x divided by the area and if you write it remembering that 1 over rho is nothing but sigma
 so i get sigma a delta v by delta x
 so notice that the current in this situation depends upon the gradient of the potential
 so how does potential vary with distance now let us recollect the actually speaking if you wanted to write this as a proper relationship
 so i will write d q by d t which is my charge flow current but i will put in a minus sigma a dv by dx and that is because the positive charges move in the direction of decreasing potential
 so since minus sign because positive charges move in the direction of decreasing voltage now let us look at what statement i can make about heat flow if you recall your discussion when you discussed heat conductivity you will realize the equation for heat transport was given by dq by dt is equal to minus kappa a where this q in this case is actually the amount of heat instead of charge as we are discussing now copper is known as thermal conductivity a is of course the cross sectional area and this is a temperature gradient and this temperature gradient is required because heat flows from higher temperature to lower temperature now we immediately recognize there is a similarity in fact the similarity is not just accidental and there is a reason for this similarity and that is because transport of heat takes place by transport of electric charge
 so typically a good conductor of electricity is also a good conductor of heat let me return back to the discussion of the drift velocity little more in detail i would be looking at the microscopic aspect of it but before that let us remember that we said that vd at most is a few millimeter per second now this does not imply that in order to start a current we will have to wait for long because it is not as if the electrons are being literally moved from one end of a sample to the other just like in the case of a water flow the electrons or the free electrons are already there and the if you switch on an electric field the electric field as we have seen gets established with the speed of light which in this scale is essentially instantaneous and it it's because of this that you don't actually have to wait when you press a switch in your home to light up something because the electrons are already there right up to let's suppose you are talking about a bulb it is all there and all that you have done is by switching on provide a pushing mechanism as we did in case of water however there are transients those that is the steadiness doesn't get established immediately
 so there is a bit of a time that it takes for the situation to become steady the second point is that relationship between current density and the drift speed is minus nav and notice that we have said vd is small few millimeters

electronic charge is also small electronic charge is 10 to the power minus 19.

 so the reason why the current density is not that bad is because this is a large number and we had calculated it some time back and we found n is of the order of 10 to the power 28 per meter cube
 so this number it more than compensate for the product of these two numbers which is small
 so let me now look at why is ohm's law reasonably good and in order to do that i will try to give you a microscopic picture of the situation that is happening there
 so let me get back to the beginning and we said metals have free electrons and these ones they move like a gas inside a the material they do not belong to a particular atom or atoms what we also said is that these electrons would collide with ions in the material
 so electrons i have said already the typical speed of electrons is of the order of 10 to the power 6 meter per second
 so electrons collide with ions and emerge with velocity in random direction emerge from collision now because the direction in which they emerge from collision is random if i define an average velocity of electrons inside a material supposing there is a capital n number of electrons in it and ith electron has a velocity v i
 so this quantity is 0 on an average that's because different electrons are moving in different directions and the randomly they are moving there
 so let us look at what happens if i now put in an electric field in it
 so we said in the presence of an electric field the electrons would get accelerated
 so the way the thing works is this
 so in the presence of electric field
 so electrons which i will write for shorthand by e minus get accelerated but because the sample is full of atoms which are static they collide after collision they emerge with velocity direction change once again they would collide
 so therefore this chain acceleration collision acceleration collision
 so this goes on now what happens is this
 so let me try to draw a typical picture i will show the life of an electron over sometime supposing my electron was at this point a i will not show the location of an atom because it will clutter up the figure but let us suppose i the electron went there
 so let me also show the direction of the electric field to be given by this supposing the electron was directed like that and it goes there
 so this is i will just call it atom number one it collides there and would emerge from there with a velocity direction change though there is not much change in its magnitude of the velocity and then of course it has a second collision and let's suppose it now this time is directed like this undergoes a third collision let's suppose this time it is i am trying to draw essentially a random figure
 so this is 3 this is 4 then it lets say comes like this this is 5 and let us say that once again this is actually an arbitrary direction figure
 so do not worry about any pattern in this this is six and then finally it comes like this
 so this is typical i mean you could draw any way you like in this particular picture i have shown you the electron goes through six collisions now what happens if there is an electric field now if there is an electric field let's suppose my electron starts from a now remember that the electric field right is

in this direction and i have a negatively charged electron

so therefore the electrons velocity because it has a velocity in the absence of electric field in this direction but there is an electric field in this direction providing it an acceleration that other direction

so therefore what will happen is that this electron would not quite follow this path but what will happen is it will take a path which is fairly close to it and maybe go like this now this path though i have shown it as a straight line is actually slightly curved though over this length scale it would appear to be a straight line the reason is that my direction of the acceleration due to the electric field and the direction of the velocity they are not the same

so it is very similar to what happens to a projectile when you throw in an arbitrary direction with the gravity in a particular direction

so you know that that trajectory is a parabola but only problem is that in this case my electron velocities are very large and the electric field that i apply is not that that bad but what is going to happen as a result is that this path is slightly towards the negative e direction because of the acceleration all right then it undergoes a collision there comes here second atoms and then it will go like that

so it will be roughly similar but slightly different notice that instead of arriving at this point

so let me call this original point where it arrived in the presence of electric absence of electric field as b and this is going to arrive at b prime

so there is this slight drift in the direction of minus e okay and we have seen that the electron velocity is about 10 to the power 6 meter per second and drift speed is a few millimeter per second

so that is the electron speed is greater than the drift speed by a very large factor now let us look at what exactly is the dynamics a little more uh quantitatively

so you notice that in the presence of an electric field the acceleration of the electron of course direction we know is opposite is given by ee over m mass of the electron easy now let us suppose the time between two successive collisions is down this is also known as relaxation time that's where the electron is relaxing after equalism now suppose v i was the velocity of the ith electron immediately after the last time it collided then in time t which is less than tau because in time tau on an average there would be another collision but before the next collision occurs the velocity after collision let's call it by capital v

so this is given by the usual formula v i minus e over m into t minus sign because the i am talking about an electron which must move in a direction opposite to the velocity of the electric field

so therefore now remember i also mentioned that the average value of v i which is 1 over n times sum over i v i that is equal to 0 but if you look at this now then the velocity close to a relaxation time would be v i minus e tau over m

so therefore my average drift speed is average of this which is of course equal to zero because this is random but notice that this is not quite random because it depends upon the direction of the electric field which is given to be constant

so therefore this is given by minus e tau

so therefore the magnitude of the drift speed is given by e e tau over m now this

so this actually connects the drift speed with parameters which depends upon the characteristic things like electric charge mass the strength of electric field applied and a parameter which depends upon how frequently the collisions are taking place

so this is on dynamics of collision but let us look at the relationship that we have because we wanted to show why ohm's law becomes valid recalling that my relationship between the current density j and the drift velocity was minus any d that tells me that j is given by n e square tau over m times e and this has the same structure as equal to sigma times e thus the expression for conductivity is n e square tau over ohm's law will be valid if sigma remains independent of e

so this means ohm's laws validity is the same as sigma being constant since in my expression here i have got n e square over m which depends upon the characteristic there

so this implies tau is constant by constant i mean independent of the electric field now this is quite reasonable because we have seen that the electron velocity distribution okay this is independent of an electric field and tau which is the time between two successive collision would depend upon the electron velocity distribution and not on the electric field and this is the microscopic reason why the ohms law remains reasonably valid now i will conclude this with a an example let me return back to the same example where i worked out uh the velocity of the drift velocity was shown to be equal to one point one into ten power minus three meter per second and this i we using this i want to calculate this quantity e m by tau

so that my sigma which is n e square tau over m or inverse relationship is resistivity

so resistivity is m by n square tau remember i have given you the data for rho which you have said is one point seven ten to minus eight

so therefore for copper one point seven into ten to minus eight which is my resistivity is m which we this mass of the electron

so 9 into 10 to the power minus 31 kg divided by n which we calculated in that problem to be eight point five into ten to the power twenty eight into e square e is one point six ten to minus nineteen

so it is two point five six into ten to the power minus thirty eight and this time star

so take these numbers up and calculate this and you will find this is of the order of 2.
4 into 10 to the power minus 14 seconds

so this is a fairly small time during which the electron remains free and that is the typical relaxation time between two colleges one occasionally defines a new quantity known as mean free path mean free path is the distance that a typical electron travels before undergoing another column now obviously since time is tau if i multiply this with typical velocity of the electron

so mean free path which is frequently denoted by lambda or even l is 2.
4 10 to the power minus 14 times the velocity of the electron which is 10 to the power 6 well let me take 1.
6 into this power 6 meter per second typical speed of electrons and that happens to be about 40 nanometers

so this is the distance that an electron would move without suffering another collision

so let's quickly summarize what we did today the what we did is to look at little more deeply into how drift speeds arise in conductors the other thing that we talked about is that the drift speed is small but drift speed being independent the the drift speed being proportional to the current density and the fact that relaxation time is independent of the electric field is the reason why ohm's law turns out to be a reasonably good description of the phenomena that happens in case of conductors we will continue with this in the next lecture and look at certain other parameters which are connected with conduction

you