Engineering Physics - II

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Module No. # 04

Lecture No. # 02

So, in last lecture we started discussing conduction of currents in wires, and then we introduced the concept of ohm's law, but this was largely qualitative. We did not make it very quantitative, we did not get deep into the physics. I was trying to explain to you how although there is a constant electric field which is applied the charges do not accelerate, but rather move with a drift velocity, because of friction, and I also told you how one can model such a situation by appealing to your experience in mechanics.

Today what I will do is to combine ohm's law with the basic Maxwell's equations, and we will see what are the conclusions that we can draw, and what is the rich physics that emerges out of it, mean the physics is very interesting. The technological aspects are also equally interesting, except that the technological aspects involve a lot more. Then the simple principles that we are going to state therefore, I will also look at a few examples which tells you how we should be very careful in this matters. Now, what we have is a steady current let us not forget that, and all fields are time independent. Now, irrespective of whether we have a medium or not the minute we are given this piece of information. We know how to write down the relevant basic loss of electrodynamics.

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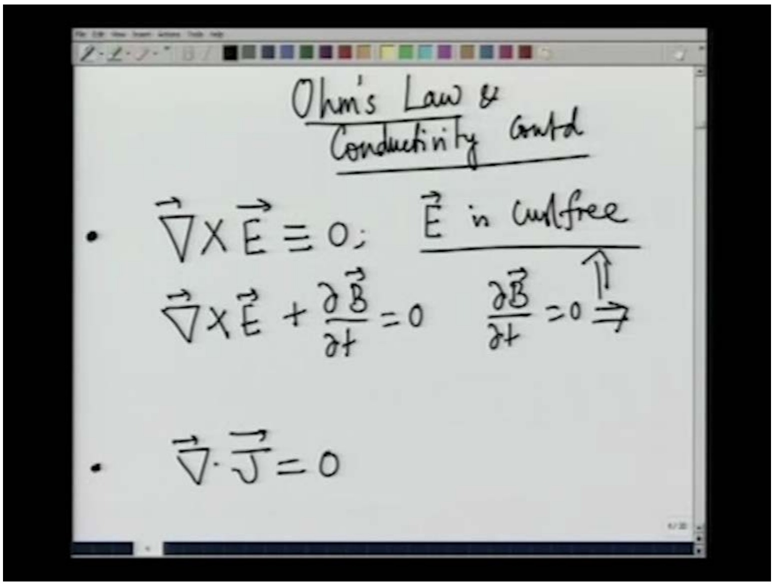

So, what are the relevant things? So, the first equation that we have to remember is that curl of E is identically equal to 0. Let me argues why it is. So, if curl of E were not equal to 0 then by faraday's laws induction which you are all familiar with from your twelfth standard tells you that there is a change in the flux, but if there is a change in the flux; that means, there is a time dependent magnetic field.

If there is a time dependent magnetic field; that means, there is a time dependent current, but as I told you I am interested only in time independent currents D C currents if you feel like; therefore, curl of E identically, equal to 0 therefore, E is curl free everywhere. So, what I mean is the basic equation is curl of E plus delta B by delta t equal to 0. This is the famous induction law. If you integrate both of them with respect to some surface open surface of course, that will give you the standard law. The induced D M is proportional to change in the flux so on and so forth. is that.

But then delta B by delta t equal to 0 implies that E is curl free. That is the statement that we are making. This is a very very important principle that we have to use in other words we are looking at an electrostatic situation in spite of the fact that they are currents. What is the second law that we have to use? That is the incompressibility, of the current. That is there is no charge accumulation anywhere, and how did we state that we stated that with a lot of emphasis with a lot of effort two lectures earlier, and that states that divergence J equal to 0.

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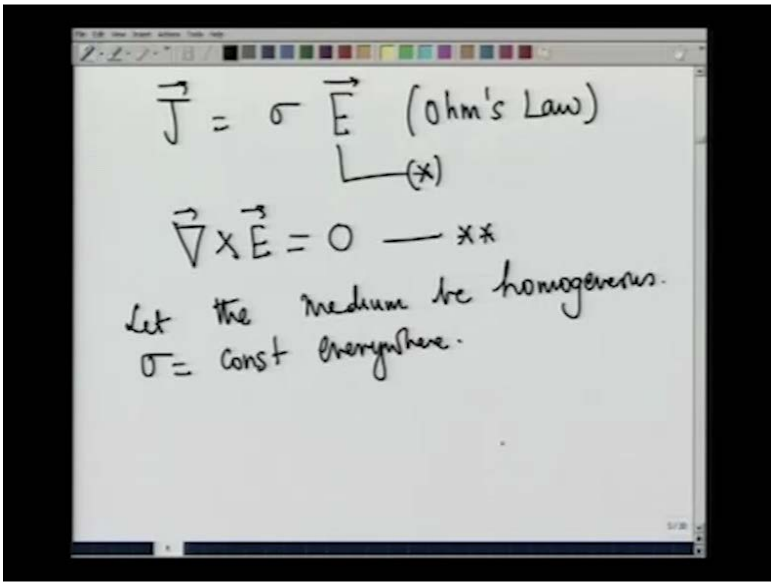

So, we have 2 fundamental statements. Divergence J equal to 0 is the condition that I create, curl of E equal to 0 is given by Maxwell's equations and of course, we have the next law which is phenomenological which ohm has given, and that is given by J is equal to sigma E. So, naturally, the question that we are going to ask is how ohm's law together with the Maxwell's equation namely curl of E equal to 0, and the physical condition divergence J equal to 0 which we have ensured is going to dictate the nature of the current, the nature of the field etcetera. It is a fairly straight forward thing all that have to do is to keep on manipulating this equation together with curl of E equal to 0. Well given an E. I can determine J; therefore, I have to eliminate J or I have to eliminate E, and of course, sigma is a property of the material, at a given temperature, at a given pressure so on and so forth.

To make our life simple let us start with a homogeneous medium. So, let the medium be homogeneous. It is also isotropic, it looks the same in all directions, it is the same in all points, it is a uniform material, it is the same identical material for example, a chunk of copper, a wire of aluminum, a disk of silver so on and so forth. No impurity, no alloy so, it is the same material everywhere. So, we are looking at a homogeneous medium. If the homo medium is homogeneous sigma equal to constant everywhere; it does not change with position; it does not change with time; it does not change with orientation; that is the statement that we are making.

So, the first thing that we do is to set sigma to be some number. Like it is of the order of 10 to the power of 7 in S I units for very good conductors so on and so forth. So, let us keep that.

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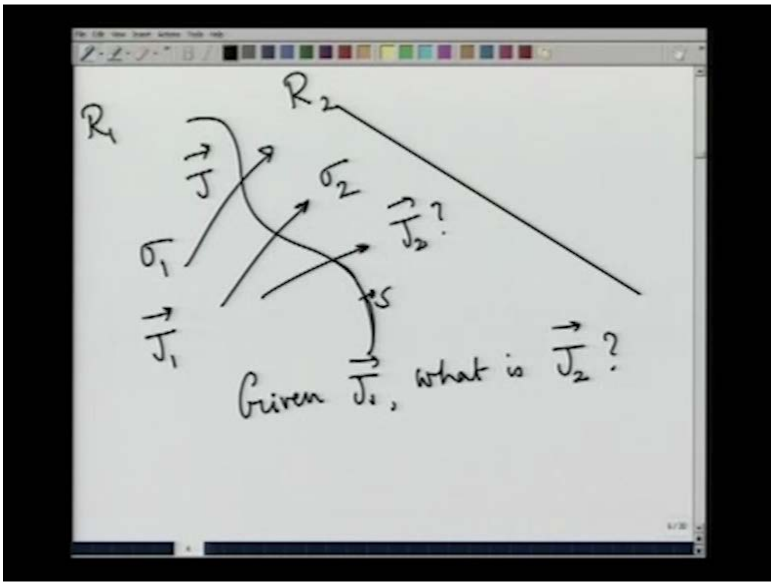

What can we say by combining these 2 equations; star, and double star. What we shall do in order to discuss that is to consider 2 conductors. So, I have rewritten the region into space into 2 regions. This is my region R 1 this is my region R 2, and then this is the interface this surface is the interface. I have my conductor 1 sigma 1 here with a conductivity sigma 1, I have a conductor 2 with a conductivity sigma 2. This is of course, a schematic representation conductor 1 for example, can be embedded in conductor 2 or conductor 1, and conductor 2 can be joined edge to edge.

For example, you take a cylinder of conductor 1, you take an identical cylinder of conductor 2, same radius, same area of cross section, and joined them together so on and so forth. Or you can place 1 conductor on the top of the other whatever it is that is schematically, shown by the surface S. We are envisaging a situation where a current is flowing from conductor 1 to conductor 2 let us say, and this is indicated by J. Obviously the question that we are interested in is given the conductivity let us say in medium 1 sigma 1 given the conductivity in medium 2 sigma 2, and given J 1. The current density in medium 1 what would be the current density in medium 2. That is the question that we are asking. That is given J 1, what is J 2?

Of course, we have to give a little bit of more information sometimes the other way round I mean I might ask given the electric field here what would be the electric field on the other side so on and so forth, and in order to answer these question. We need to make use of the 2 equations that I wrote curl of E equal to 0, and divergence J is equal to 0.

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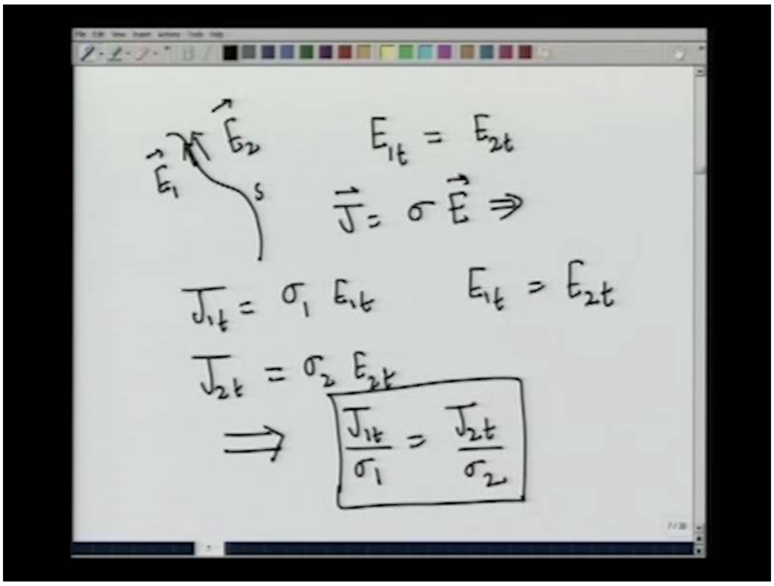

Now, what does curl of E equal to 0 tell me? Remember the discussion that we had in electrostatics. I argued that if there is an interface, and there is an E 1 here, and there is a field E 2 here between 2 dielectric medium, and of course, conductors can be looked upon as dielectric medium in the limit epsilon going to infinity. Let us not forget that given this then we argued that curl of E equal to 0 everywhere implies the tangential component of the electric field is continuous around the surface. So, this is my surface. So, if I look at the point. The tangential component of the electric field is on this side is like this. The tangential component of the electric field on the other side is like this E 1 t must be equal to E 2 t we should not forget that. Now, I have my ohm's law which tells me that J equal to sigma E. So, what do I conclude from that J 1 t equal to sigma 1 E 1 t, J 2 t is equal to sigma 2, E 2 t, but then E 1 t is equal to E 2 t. The tangential components of the electric field are going to be the same on the either side of the surface therefore, what do we conclude? We conclude that J 1 t by sigma 1 is equal to J 2 t by sigma 2.

The continuity of the tangential component of the electric field across the surface, because the tangential component on 1 side was the same as the tangential component on the other side tells you that there is a discontinuity in the tangential component in the current, because the conductivities sigma 1, and sigma 2 are different from each other. This is an important thing for us, but I will return to that at a later time.

What I will now do is to look at the other equation namely divergence J equal to 0, and we will draw a conclusion on the nature of the electric field. So, in this case the continuity of the tangential component of the electric field is giving me information on the current densities on either side namely the tangential components of the current density.

Now, when I use divergence J equal to 0 that will give me information on the perpendicular components or the normal components of the electric field it is a straight forward thing to do.

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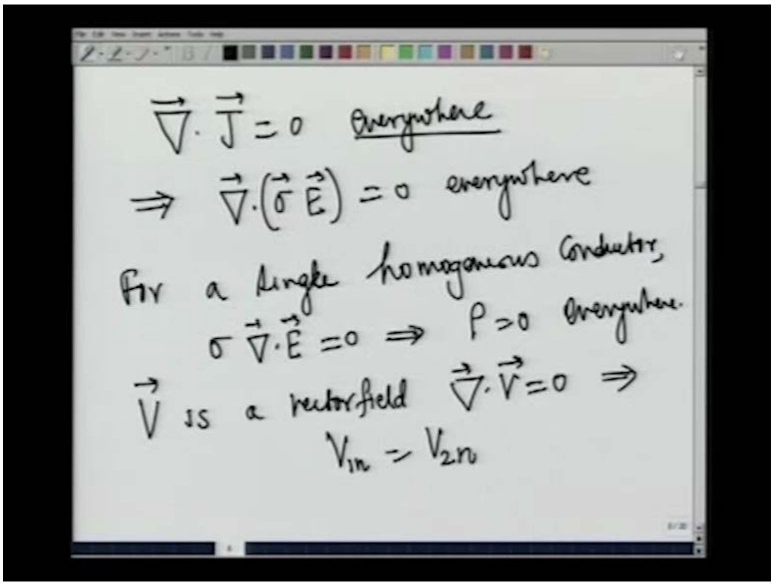

So, let me start writing divergence J equal to 0 everywhere. That is what we said divergence J equal to 0 everywhere. Therefore from this we conclude that divergence sigma E equal to 0 everywhere. Of course, if I had a single homogeneous material then what would have happened sigma would have come out of it. So far a single homogeneous conductor, my sigma will be pulled out, and I would write sigma divergence E equal to 0 this implies rho equal to 0 everywhere, because that is what Maxwell’s equation tells us coulomb law divergence E equal to rho by epsilon whatever rho equal to 0, but of course in this case we are not actually, looking at a homogeneous medium. It is homogeneous in 2 parts, but there is a surface there is a junction between them therefore, what do we conclude from this particular equation from this particular equation we conclude that the normal component of the electric field should change in a particular manner. Why is that? So, because if we have a divergence of a vector field which is vanishing. Suppose V is a vector field. Then divergence V equal to 0 across a surface implies V 1 n is equal to V 2 n. So, you take the surface draw the normal components these 2 must be the same; therefore, we want to employ that in order to get information on the normal components of the electric field child's play.

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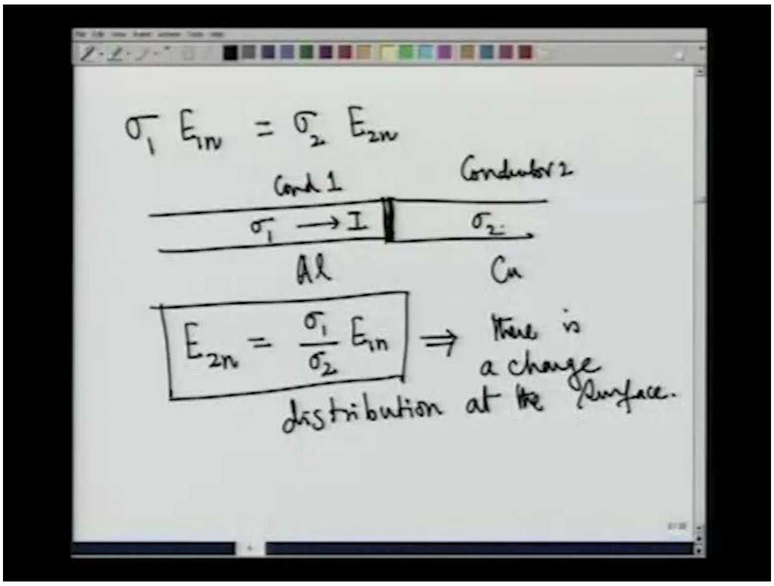

So, what is it that I am going to get; I am going to get sigma 1, E 1 N is equal to sigma 2, E 2 N. So, I have 2 conductors and. So, on you can even imagine that there are 2 conductors same radius of cross section, and this is the junction this has conductivity sigma 1, this has conductivity sigma 2. There is a current I that is flowing, and we are asking for the normal components on the side of conductor 1. So, conductor 1 so, let me call this as aluminum. This is my conductor 2 let me call this as copper. I am asking what is it that happens? This of course, is a very simple configuration, because the way I have shown the current there are no tangential components tangential component is 0 here, the tangential component is 0 there, because the current is flowing perpendicular to this cross section. So, we are only interested in the electric fields and the currents.

Of course, J 1 N equal to J 2 N, because the current keeps on flowing, but the interesting that we find is that E 2 n is simply given by sigma 1 by sigma 2, E 1 n. The magnitudes of the electric field are not the same. Now, if the magnitudes of the electric field are not the same immediately we know from gauss law. What are we going to conclude? They are the normal components let us not forget about that from this we conclude that there is a charge distribution charge distribution at the surface. The surface is indicated by this particular line. We have already worked out several examples of what the nature of the charge distribution is I will leave it as an exercise for you people to work it out you know the normal component on this side, you know the normal component this side, and you know that divergence E equal to rho. So, even N minus E 2 n must be nothing but the surface charge density divided by the appropriate dielectric constant at this interface is that.

That is something I would like to make a statement in a short while, but in any case there is a charge accumulation therefore, we see that if I am going to look at materials which are joint distinct materials which are joint the way to preserve incompressibility. The way to preserve the fact that divergence say must be equal to 0 everywhere which is necessary for steady current is to build up a little bit of charge at this particular point.

Having said that let me go back to the statement that I made earlier. I said that there is a lot of difference between what happens in the real world, and actually the ideal situation that we look at in our examples. It is a very easy thing for me to say oh this is aluminum, this is copper join them together, and make a junction, and probably if I am not trained probably if I am not told. Then I might be fool hard enough to go home, and try to actually make a junction. Take an insulation tape, and put them put them together or try to weld them together or whatever, But the real life is not that simple, because if you go, and ask your electrical engineering teachers or people who practice wiring they tell you that aluminum, and copper should never are joined.

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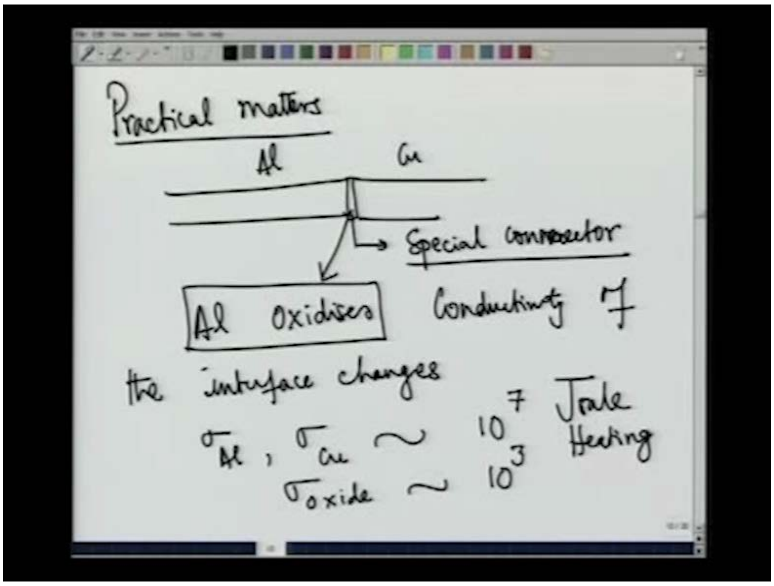

So, what are the practical difficulties? It is a good thing to spend some time on those practical matters. So, in the electrical wiring business, what we are told is that if there is an aluminum wire, and if there is a copper wire, and if we want to join them. This should be a special connector. Now, why should this be a special connector, why should I not simply join them, because I have already worked out the boundary condition there will be some charge sitting. So, what do I care about it. Now, the answer to that is that at this interface aluminum oxidizes. So, it is not aluminum anymore it is one of the aluminum oxides may be A L O 2 then the minute it oxidizes what happens it is conductivity of the interface changes, so conductivity, of the interface changes. Aluminum is a very good conductor of the order of some three into 10 to the power of 7 Siemens per whatever whatever your S I units.

Copper of course, is a very good conductor again maybe it is a factor of 2 or 3 greater than that of aluminum it is conductivity, but this surface has a conductivity of the order of ten cubed. So, sigma aluminum and sigma copper are both of the order of 10 to the power of 7, whereas sigma oxide is of the order of 10 to the power of 3. It is 10000 times less than the conductivity of the parent materials. If the conductivity, decreases the resistivity, increases the resistance increases. If the resistance increases there is a corresponding joule heating is that.

So, what is the thickness? The thickness of the interface may be a few microns, but that is enough to havoc. What happens, because of joule heating let me write it here. Joule heating the interface can melt, and once it starts melting your connectivity is lost it can cause. Lot of problems it can be quite dangerous, and that is the reason why special connectors are actually, advised they are devised in order to join aluminum, and copper. This is something that you have to remember.

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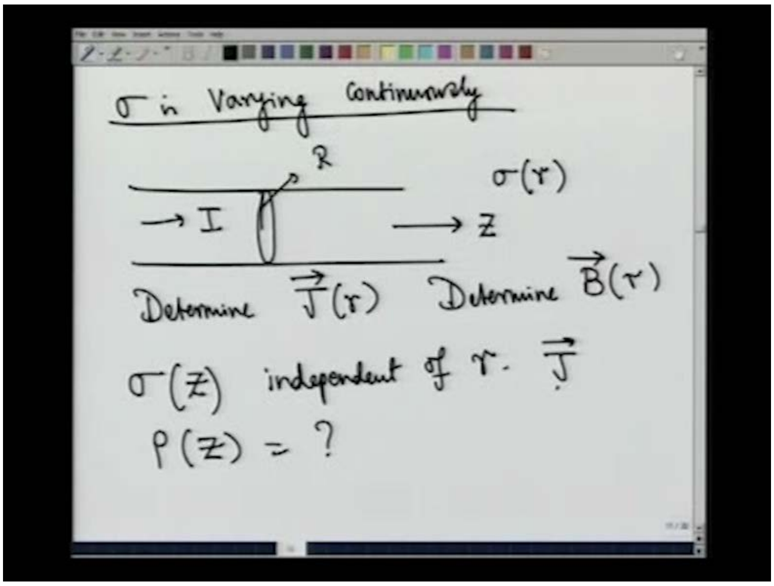

Now, in order to sort of gain familiarity with the principles that we have stated, this is 1 of the practical examples that I gave you. We can actually look at a situation where sigma is varying continuously sigma is varying continuously. So, suppose I gave you a situation where sigma varies continuously along the cross section. So, what do I mean by that. So, let me enlarge my wire whatever is carrying the current, and this is my radius R of the cross section I make sigma a function of r. Sigma is independent of Z. This is my Z axis, but sigma is a function of r. So, what I ask you is that if there is a current I that is flowing in this particular direction determine J as a function of r. Very straight forward example, and there is something that I am going to come to in the next lecture. If you know J of r, determine B also as a function of r. So, I put a vector sign over this I put a vector sign over this, and this will give you some kind of an experience on what happens if there is a variation.

The second possibility is that you can imagine that how were the material where sigma is actually a function of Z independent of r. r corresponds to the cylindrical co ordination root of X square, plus y square this is my Z axis. So, we can imagine for example, as we keep on moving the composition of the alloy keeps on changing. Then again you can find out what your J is, and you can find out what rho as a function of Z is. So, please take these two problems as very simple assignment problems, and work out the solution.

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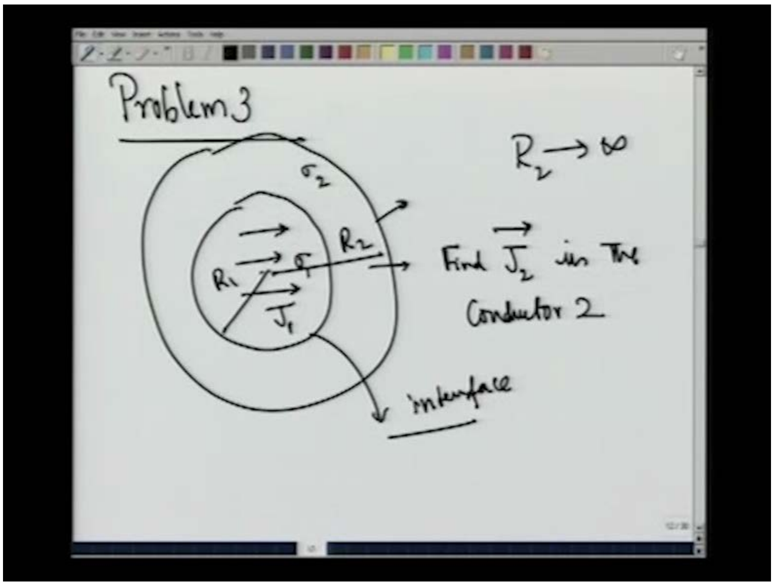

In order to become even more familiar with the boundary conditions that I have stated. Let me look at yet another problem. So, let me call it as problem 3. What is my problem 3? Let me consider a spherical conductor surrounded by another spherical conductor this has conductivity sigma 1 this has conductivity sigma 2, and let me imagine that there is a uniform J which is flowing within the conductor.

I am not going to show you all the connections how the currents are being supplied. Let us not worry about that. The purpose here is rather to understand the fields of the boundary condition. So, I have given you the conductivity sigma 1, I have given you the conductivity sigma 2, and I am telling you that there is a uniform current density J 1 which is flowing inside conductor sigma 1. Please find J 2 in the conductor 2, and this is an interface. This is an interface, and this outer radius. So, the inner radius is R 1, and the outer radius R 2 you can take to infinity. So, you can imagine it is in very, very large conductors.

So, you do not have to worry about what happens when the current reaches this particular point. So, this is as quite some interest to solve, because now you can see that there is both a tangential component and the normal component therefore, given J 1 which is along the Z axis, the way I have chosen you should be able to find out what J 2. These are not unrealistic examples, because we keep encountering them often in our experience fine. Now, actually this is the right time to take a small dig ration, because I told you that whenever there is a variable conductivity, there is going to be a charge distribution, and the way I argued was to look at divergence J equal to 0.

Now, what happens if I have an interface between 2 conductors, and there is no current at all no voltage source, no current. So, what do I do? I simply take a piece of iron or copper, I simply take a piece of aluminum, and put them together. Now, a good question to ask is is there a voltage difference is there a jump in the electric field between them please notice copper is not charged completely neutral, the silver chunk is not charged it is completely neutral. I am not applying any force at all.

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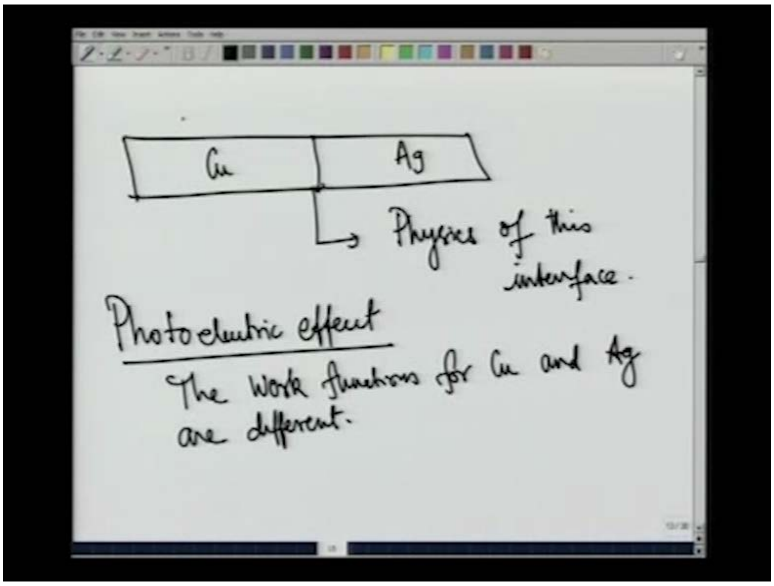

So, now, what we are going to do is to look at again there is a block of copper, and there is a block of silver. So, let me call it as copper; let me call it as silver, and I ask what is the physics of this interface is there an electric field, is there no electric field. Our earlier argument was actually, based on ohm's law which related the electric fields on both the sides, because there was a current that was flowing.

Now, no current no field therefore, is there going to be a potential or is there going to be a charge accumulation at this interface that is the question that we are asking. Now, the answer to this question comes from yet another phenomenon. After all ohm's law cannot be easily, derived from Maxwell's equation you need the properties of matter that is what I told you, so in order to answer this question. I will bring back to your mind, I will remind you of a very, very interesting effect which you people studied in your twelfth standard, and that is photoelectric effect. Mulligan studied this experiment mulligan studied this experiment for more than fifteen years, because he did not believe in Einstein's explanation of photoelectric effect, because Einstein said that electromagnetic radiation does not come as waves as far as photoelectric is effect is concerned it actually, comes in pockets of energy which we called as photons.

In other words what Einstein did was something very very revolutionary. Planck had introduced the concept of a photon to understand blackbody radiation. That is something that you will study in the second part of the lecture of this course given by Dr. Roy Chowdhury. That was introduced as an ad hoc hypothesis by Planck. Whereas, Einstein raised it to reality he treated them as real entities the photons, and he was explaining them. In terms of the effect in terms of this photons never mind about that. The important thing for about for us about the photoelectric effect is that the work functions. The work functions for copper, and silver are different. And what is the work function that we are interested in the minimum voltage that you have to apply in order to actually, pull out an electron is that. And of course, what you actually studies in terms of the wavelength, radiation frequency, etcetera etcetera.

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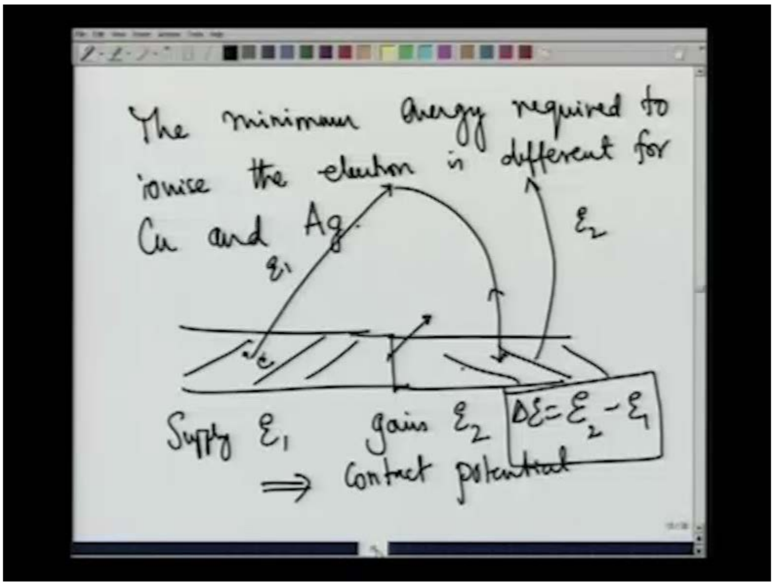

But since you people are already familiar with the physics of what the photoelectric effect. The statement that we want to make is the following, and that is the minimum energy required to ionize the electron is different for copper, and silver. Let us say copper, and silver are simply few example you could take anything that you want. Now, let me draw the figure again. So, imagine that there is a charge here there is a charge here, and what is the energy required to ionize I have to move the charge to infinity. So, very well I do the following interesting thing.

I take these electron move to infinity. I supplied a certain energy for you, and then I bring it back here. Now, if I wanted to move the electron here to infinity. I would have sent an energy E 1. If I wanted to move a electron from here to infinity. I would have supplied an energy E 2. E 1 is not equal to E 2 that depends on the work function. Therefore, now please understand if I were to take an electron from medium 1 take it to infinity, and bring it back, and place then. The net work done if I had taken it, and brought back here then the net work done would have been equal to 0, because I supply that much energy I lose that much energy, but here what is going to gain that much energy. Here what I am going to do is something very different I supply E 1 energy E 1 is that right, and when I bring it back, and put here gain E 2 therefore, the 2 materials are in contact with each other, but because the work functions are different there is a potential difference which is given by E 2 minus E 1. My potential energy difference is given by delta E is given by E 2 minus E 1 that indeed is the potential difference.

Of course any given conductor is an equipotential surface. So, all of it is an equipotential surface all of it is an equipotential surface that is what we studied in electrostatics, but then this is at a different potential from this, and the energy is simply given by E 2 minus E 1. So, in order to measure the potential difference between the 2 conductors which are in contact with each other. All that I need to do is to look up the table, and find out the ionization energy for the electron here, and ionization energy for the electron here. Therefore, whenever they are in contact this delta E implies a contact potential. So, even if there is no current that is flowing between the 2 conductors. Alls, and therefore, there is apparently no electric field, because there is no ohm's law simply, because of the requirement that each metal should be an equipotential surface, and, because of the known fact. That the ionization energies are different that is the contact the work function there is a contact potential, and this contact potential tells you that there is a jump in the electric field from here to here there is an electric field at this particular point.

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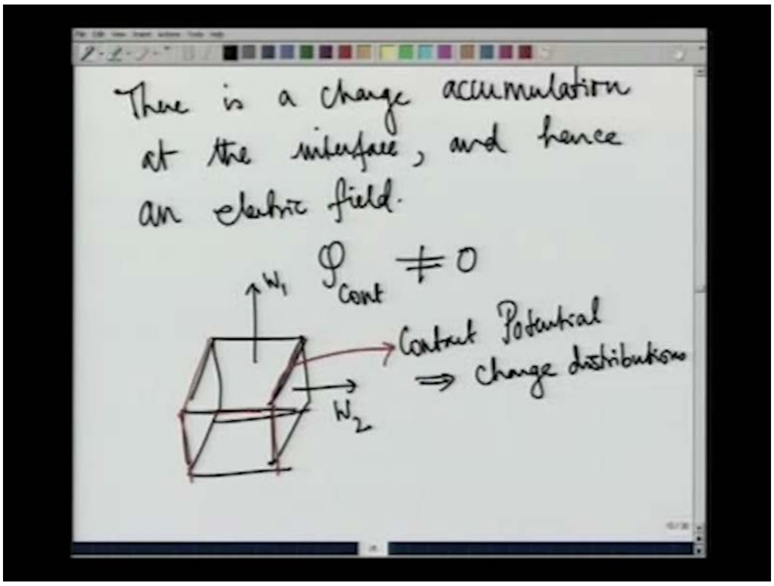

So, let me indicate that in the next line. There is a charge accumulation at the interface, and hence an electric field. Very interesting both of them are electrically neutral, but because of the contact potential let me denote it by phi, because phi contact naught equal to 0 there is a redistribution of charge, and there is a electric field.

In fact, the physics of contact potentials is very rich. It is very interesting you know you people study about crystals face centered cubic lattice B C C, F C C, so on and so forth. So, if I were to draw for example, a crystal let us say a cubic crystal. So, let me imagine we have a crystal here, because of the nature of the crystal it can as I told you an F C C or B C C different phases can be a different contact potentials. The different work may have different work functions therefore, all these edges. So, let me indicate it here. So, all these edges are that they can have a contact potential. So, they will give you a contact potential. Why is it? So, because the work function along this region is W 1, the work function along this phase will be W 2 therefore, this edge will be carrying a contact potential, and therefore, there will be charge distribution.

So, crystals produce nontrivial electric field configurations. Of course, it is not very easy to measure them do not try to go to the lab, and measure them, because what happens there is a lot of free charge floating with the dust, and all that. So, the dust comes, and settles here is that. So, to put it the other way round if you want to keep your crystals very, very clean without any contamination, you have to put it in good vacuum, because otherwise, because of the charge distribution along the edges there will be invariably dust that settles on it. So, this is another very interesting thing about the contact potential.

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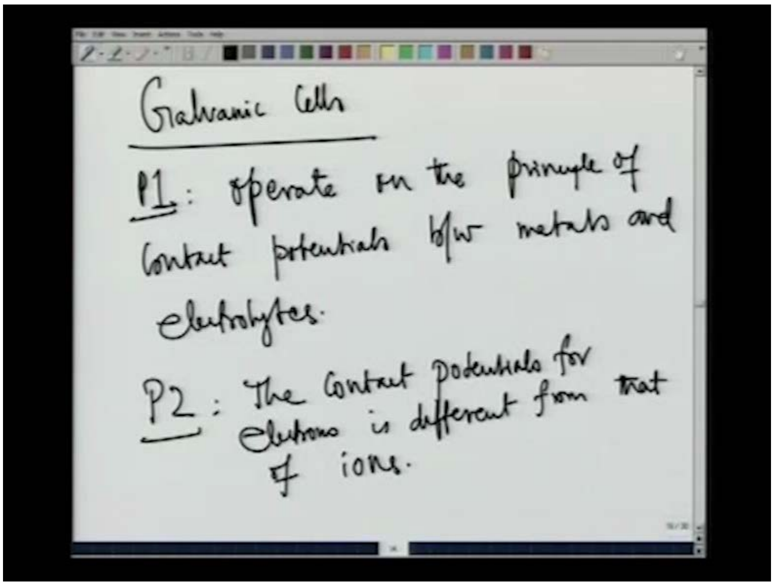

The last thing that I have to say about the contact potential is about the work of the galvanic or the voltaic cells, and we know that this is a very, very rich branch of what electrochemistry. I am not going to get into the details of that we do not have that kind of a luxury of time in this particular set of lectures. All that I will tell you is that galvanic cells operate on the principle of contact potentials. Contact potentials between metals, and electrolytes. From the examples that I have given I am sure that all of you understand that. They also operate on the. So, this is principle number 1 let me call it P 1 the second principle is also interesting. The contact potentials for electrons is different from that of the ions. Remember electrolytes have ions, free ions, and free electrons the 2 contact potentials are different. So, what you are going to actually, do is to exploit that and set up a steady current. In this particular case of course, the energy is supplied by the chemical reactions that are taking place. So, if you go back take this as a reading exercise, and understand that then

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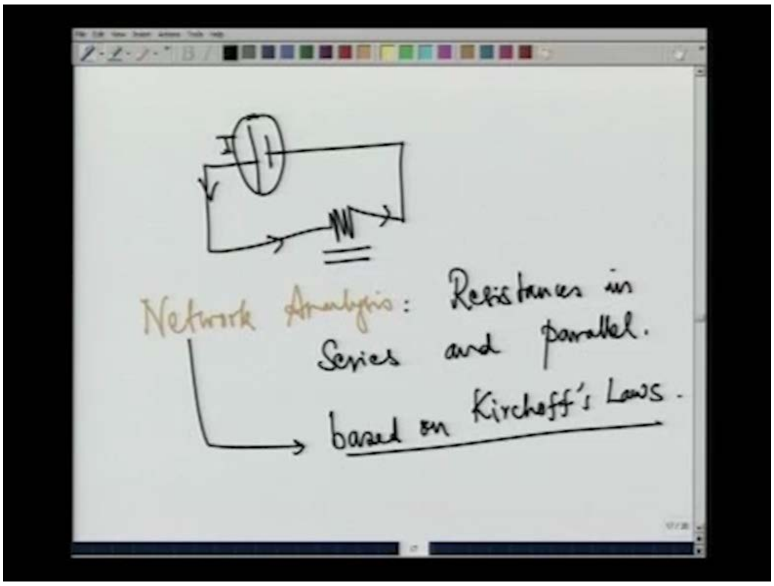

I can tell you with confidence you have indeed understood the meaning of the symbolic circuit which we write here right. We say that there is a current flowing, and there is a resistance. We spent a fairly long time describing the concept of resistance, and of course, we also studied the boundary condition. Then I looked at the interface of 2 conductors, and I told you how the charge accumulates. Then I look introduced the concept of a contact potential.

Now, what I am telling you is that if there is a wet battery for example, here is that then you can use the concept of this contact potential the difference between different contact potentials where you pertain into metals, and electrolytes ions, and charges then you would have understood the meaning of the circuit. Now, you are off to study network analysis. Kirchhoff's entire etcetera etcetera; so what remains for you is to now, extend your studies to So, called network analysis consisting of resistances in series, and parallel, and if you people remember all of network analysis is based on what based on Kirchhoff's laws. You have already studied that in your twelve standard you will study that in even greater detail, and greater sophistication in your course. We are not going to spend any time on that instead what I will do is to look at another very, very interesting example involving the conduction of particles in a conductor. Except that now, we are going to like the situation slightly more complicated in the sense that apart from an electric field there will also be a magnetic field.

So, what I am trying to tell you is that all this time we looked at a situation where there was a conductor connected to your voltage source, and there was only an electric field, and the relation between the conductivity, and the electric field was given by ohm's law. Now, what we shall do is to switch on in addition to the electric field. That is in addition to the voltage source we are going to subject that material to a magnetic field, and we are going to ask what the physics is.

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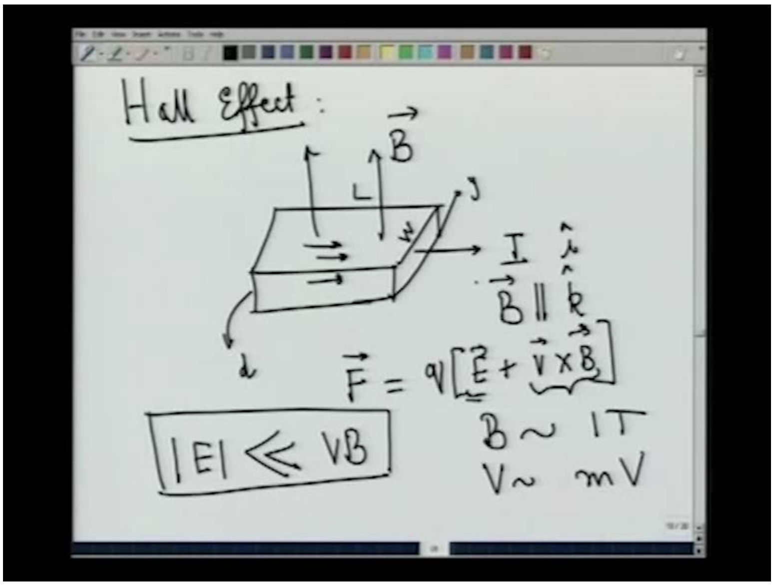

This is a very, very important effect, and goes by the name Hall Effect, and it is quite a fascinating subject. In fact, the Hall Effect is sort of reinvented in this particular sanctuary in a very very unexpected form called the quantum Hall Effect which I will mention very briefly in a short while. So, let us spend some time understanding Hall Effect, because Hall Effect actually allows us to find out what the charge of the carrier is see suppose I tell you that there is a current that is flowing in a wire. Now, it does not tell me whether it carries a positive or negative for example, ions may be moving along the positive Z direction, the electrons may be moving along the negative Z direction they will both produce the same current.

A very interesting question 1 would like to ask is are there measurement that I can perform in order to determine the size of the sign of the charge carrier is it positive or is it negative. For example, if you look at a P N junction semiconductors sorry. Then you know that the charge carriers can be either wholes or electrons, and the wholes are all positively charge. In principle the answer to that can be provided by Hall Effect. So, let me spend a few minutes. Hall Effect is a very important diagnostic in material science, so those of you who do material science, and physics will certainly be using it quite a lot I am not going to spend too much time on that. I would rather just give you the bare outline of the physics of the Hall Effect.

So, let me start with geometry. So, let me imagine that there is a conductor which I will imagine is kind of a bar. So, this is my bar let me also fix the dimension the length is L, my width is W, and let me say that the thickness is given by d. So, it is a cubical chunk that is what I have? Let me also fix my coordinate system. My current is flowing along this direction is a bulk current. So, I am forcing a current, and let me take this to be the Z axis. I can also checks it to be the X axis. So, let me take it to the X axis. So you can imagine that there is a wire which comes, and connects it to the resistance less wires which comes, and connects to the voltage source we are not worried about that. The important thing about this geometry is that we are going to apply a magnetic field perpendicular to this plane.

So, this is my X axis, this is my Y axis along the width, and my Z axis is perpendicular to this rectangular plane that we are seeing here, and now I am going to apply a magnetic field. So, my magnetic field is parallel to the Z axis. In order to drive the current along the length of the wire I have to apply an electric field. Over and above that I have applied a magnetic field, and hall geometry Hall Effect corresponds to the magnetic field being much, much larger than the electric field. What do I mean by saying that the magnetic field is larger than the electric field? Let us understand that remember Lorentz force. In fact, I am going to use it quite extensively now, Lorentz force tells me that F is equal to q into E plus, V cross B. So, I cannot say that I will compare electric field, and magnetic field, because they have different dimensions. How you can compare 2 different objects with 2 different dimensions.

The electric field has the dimensions of V into B. So, what I mean to say is that the modulus of the electric field is much, much less than VB where V is the velocity with which the charge particles are moving. So, this is a very important geometry, in realistic situations in laboratory if you go to your solid state lab. The magnetic field will be typically of the order of a teals, and then voltage will be of that of (( )) may be. The voltage will be something like a (( )) which is will quite small; therefore, this condition is always satisfied.

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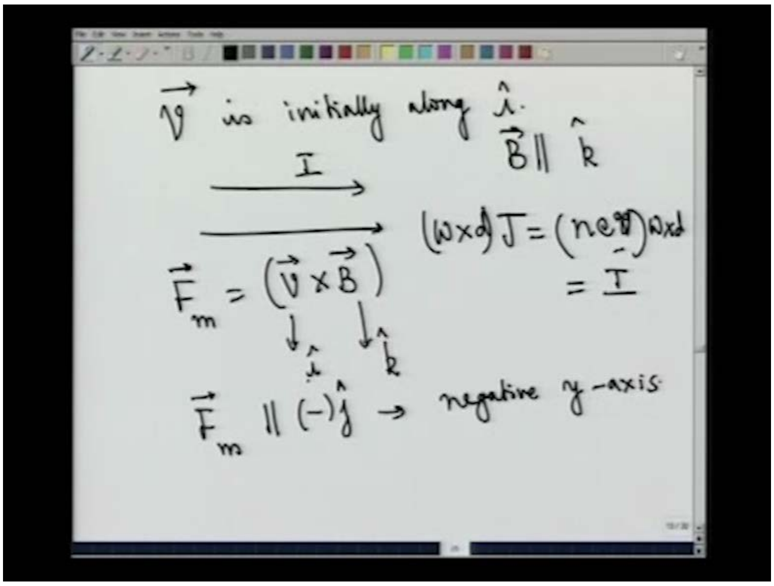

What is the interest in this particular geometry? Now, let us understand the situation, because of the electric field, because of the current that is there my velocity is initially along the X axis along I. The unit vector i, because the current is flowing along this direction, but then there is a magnetic field parallel to the Z axis. There is a magnetic field parallel to the Z axis, and now, mister Lorentz comes, and tells us that the magnetic force is given by V cross B. Let us not forget that the current density, is charge density, multiplied by the charge of the carrier, multiplied by the velocity, so J is equal to n e v, and if I multiplied this by the width into the depth, so width into the depth of the block.

This will be the current. So, given the current you know how to find out. What this velocity is? you know how to find out what the velocity is this is along the X direction Lorentz force expression tells you that there is an additional force, because of the magnetic field. So, this is along the direction I. This is along the direction K. T his is along the X axis, this is along the Z axis therefore, my magnetic field magnetic force is parallel to I cross K which is minus J right the negative Y axis. When we say that there is a magnetic force acting on them.

The magnetic force is; obviously, going to act on the carriers. For the time being let us imagine that they are negatively charged particles is that, because my conductors typically always. In fact, always conduct only through the electrons. The positive charges are all fix to the lattice they are all there in the atoms in the nucleus they are not going to move is that. Therefore, the negative charges are the once that are going to experience this particular force. If the negative charges move from right to left the right, is a current from left to right let us not forget about that therefore, there is a force along the Y per axis.

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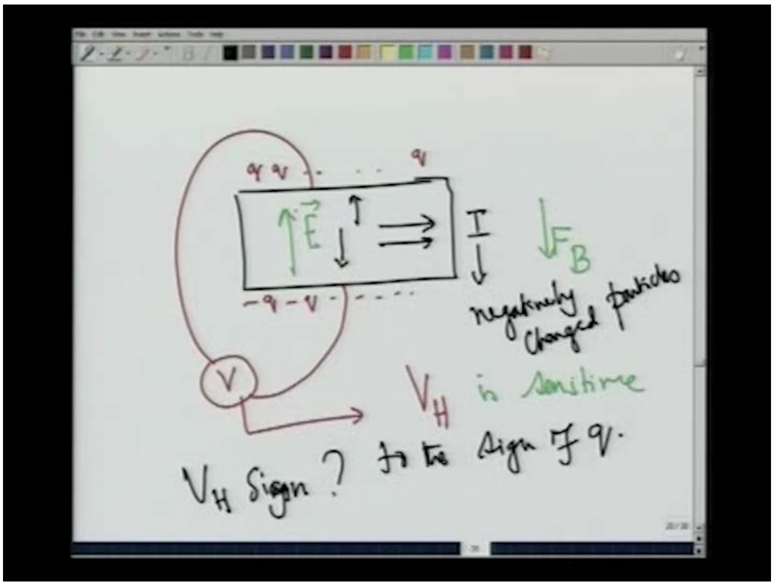

So, what happens is that again if I am going to look at one particular cross section. Here is force acting along a particular direction. The q is taken into care of therefore, the charge particles start drifting like this. So, depending on the size of the sign of the charge carrier corresponding to this I there will be an accumulation of charges here, and there will be the accumulation of negative charges here. What happens is that? Whatever, is conducting that will move in 1 particular direction.

So, that there is an excess of that in one side, and the depletion of that in the other side. We should not imagine that both the positive, and negative charges move, and the minute you do that you see that there is a voltage difference that is developed between them, and this is called Hall Voltage. How long will the charges move? The charges will keep on moving until they produce an electric field. So, I am denoting all this symbolically you should not imagine that the electric field is actually, along this particular direction you should not imagine that. If q is negative then of course, the electric field will be in the opposite direction that is what I mean.

So, there is a magnetic field, and the magnetic force acting along the negative y direction. Therefore, there will be an electric field which has to compensate. My picture is obviously, wrong. So, I can make it more precise now, although I indicated it schematically for you people. So, let me do that by the last compensation I can actually, confidently tell you that my electric field will be in this direction.

The magnitude of the electric field exactly, compensates the magnitude of the magnetic force. That is the most important thing of B. Then they stop moving. When they stop moving there is an accumulation of charges here and there is an accumulation of charges here.

Now, what to do is to measure the Hall Voltage across this and the Hall Voltage of course, is sensitive to. So, it is sensitive let me revert to my usual color to the sign of q. May be I should not spend any more time on this part secular problem. I will leave it as assignment for you people to take this current to be carried by negative charged particles. Negatively charged particles, and give me the sign of V H.V H sign what is the sign of V H? And this is an interesting nice example that I would have discuss the little bit more if I have more time let us let us stop at this particular point. Having discussed Hall Effect now, is the time for us it is right to go back to the problem of resistance. That is something that I introduced at the end of the previous lecture, and what is it? I said that we want to measure all quantities in terms of some units which are provided to us by nature, and I gave you 2 examples.

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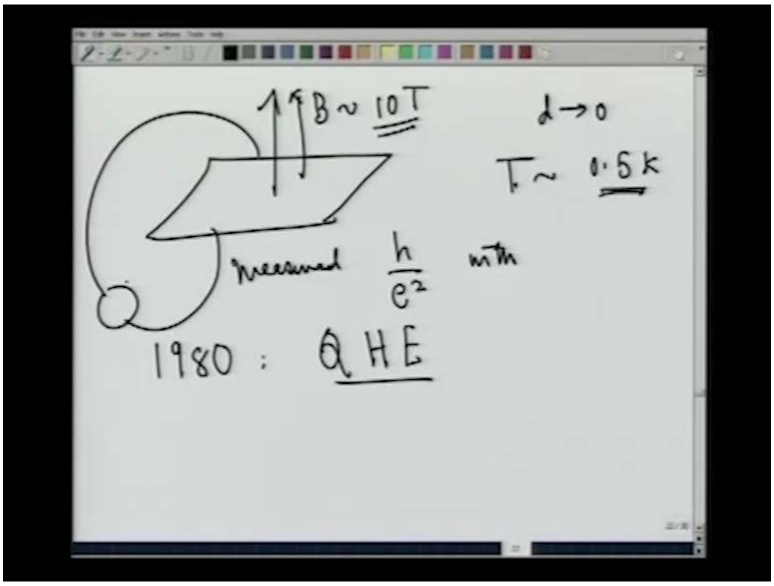

If I want to measure the speed of light If I want to measure the speed of light. We can of course, endlessly debate whether we should use centimeters per second or meters per second the C G S units or the S I units, but if you want to go, and ask a physicist the physicist would say that there is a natural unit of the speed sorry . I am not interested in this and that is given by the speed of light itself, because speed of light is the same for all observers. So, speed of light is a unit for all speeds, so instead of trying to measure the speed of light in terms of some other units. It is better to take a measure all other speeds in the unit of speed of light.

Similarly, angular momentum, suppose I want to measure the angular momentum of a body. Then you can again worry about whether I should use S I units, M K S units, C G S units so on and so forth, but quantum mechanics tells you that it is convenient to measure all angular moment in terms of a fundamental quantity namely the Planck's constant, because the dimension of the Planck's constant is actually, angular momentum. I am sure all of you have heard of what is called as the spin of an electron which an intrinsic angular momentum in the units of h or h bar half of h bar. So, this is a natural unit. That is something that we should understand. What about resistance? Here is a very simple exercise for you people considers the quantity h by e squared. Now, I will leave it as an assignment for you people to find the dimension of this quantity, and this will be having the dimension of resistance.

So, it would be wonderful if actually somebody can measure this, because now you are not measuring resistance in sums of some ad hoc units, but in terms of fundamental constants. Planck's constant is fundamental. It is fundamental to all of quantum mechanics, and charge is fundamental, because all are electrodynamics is, because of this unit of charge. So, this has the dimension of resistance, and therefore, if I could create a device, and what should that device be that device should be a quantum device, because h comes with quantum mechanics. Then I would have had a fundamental unit of resistance. If I could measure this very, very accurately then the resistance standard also improves. Whereas, what is happening today by that I mean until the last seven or eight years was that people had a convenient standard, but not an absolute standard.

So, they had an alloy some conduct metal which was placed at a certain temperature in some standards like our national physics laboratory or bureau of standards international standards, and you calibrate the resistance with respect to that, but then there are always fluctuations the material property changes with time everything you know under decay whatever whatever.

Therefore the good question that we should always ask is if there are absolute standards which are independent of the choice of the material. That appears to be possible there is a hint that perhaps we should look for that by the simple dimensional analysis. Now, such a device was indeed realized by a gentleman whose name I am not going to give you I will leave it as a reading assignment for you people, in 1980 this very famous physicist. What is his name? That is an assignment for you discovered what is called as quantum Hall Effect is that, and the geometry of the quantum Hall Effect is shown in this figure. It is a very, very thin vapor the electrons are not free to move perpendicularly. It is found by an interface of gallium arsenate, and aluminum gallium arsenate or it is in silicon mosfets.

You go, and ask your instructors more about the details of this you apply a very strong magnetic field of the order of ten teals perpendicular to this surface. The temperatures are very very small it can be as small as millikelvin. What our friend that physicist whose name I am not going to give you measured whets the Hall Voltage is that. He forced a current along this particular direction as I told you in the Hall Effect, and he was able to show that this quantity is the unit in which my resistance comes. This is a kind of cultural exposure for you people is that.

Rather than spend too much time with words let me give you a few interesting details. This is the typical ordinary Hall bar geometry which I described to you in great detail is that right. So, let us not spend too much time on that this, whereas this is the famous quantum Hall system. This will be a few millimeters your magnetic field is shown the Hall Voltage is also shown here. This is the example of what is called as a quantum Hall device. What is the dimensions here? For example the distance between these 2 ports is 1000 micrometers. So, these are really small devices there are various great voltages. The current is flowing in this particular direction, and the Hall Voltage is measured here. T he temperature as I told you is very, very low, the magnetic field is very, very large, and what is it that I get.

The result of hall resistance is shown in this particular graph, and what I would like you people to concentrate is on these values plateaus; these are called plateaus. You see that the plateaus are becoming broader, and broader, flatter, and flatter as you keep on increasing your magnetic field. This figure shows the magnetic field all the way up to 12 teals as I told it is a very, very large this one, and these are precisely in multiples of what the Hall resistance that I gave you. The plateau is. So, flat the resistance is. So, flat and the jump are. So, large you can actually measure the resistance with an accuracy of something like 1 part in 10 to the power of 7. This is an accuracy which is not encountered in any classical device. Therefore, you see if I say that I want to be a physicist, and I am not interested in technology I am doomed, because no physics can be tested no principle of physics can be tested without advance in technology, and in a similar manner I cannot say that look here I am an engineer I do not have to know physics, because real advanced instruments precision instruments which are of great practical application in technology comes only through advance in physics.

So, this topic tells you the beautiful interplay between physics, and technology. We will stop this discussion for now, and in the next lecture we will take up another very interesting topic namely the magnetic fields produced by currents.