Engineering Physics – II

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Module No. # 04

Lecture No. # 01

Today's lecture will be mostly devoted to a very interesting, and an important topic. It is a phenomenological law that we are going to describe. I will tell you what a phenomenological law means, and that is ohm's law. We are all familiar with ohm's law. We have solved a large numbers of problems given finding the resistance given the potential, and the current, etcetera etcetera, but my purpose here will be to actually elaborate on the very interesting physics associated with ohm's law, and to highlight to you how involved, and how rich it can be. Of course, there is a large number of applications, because of ohm's law and a equally, large number of problem, because of ohm's law, because of the associated joule heating. We shall also discuss that, and beyond that I will also give you a few examples where ohm's law does not hold, and there is even richer physics.

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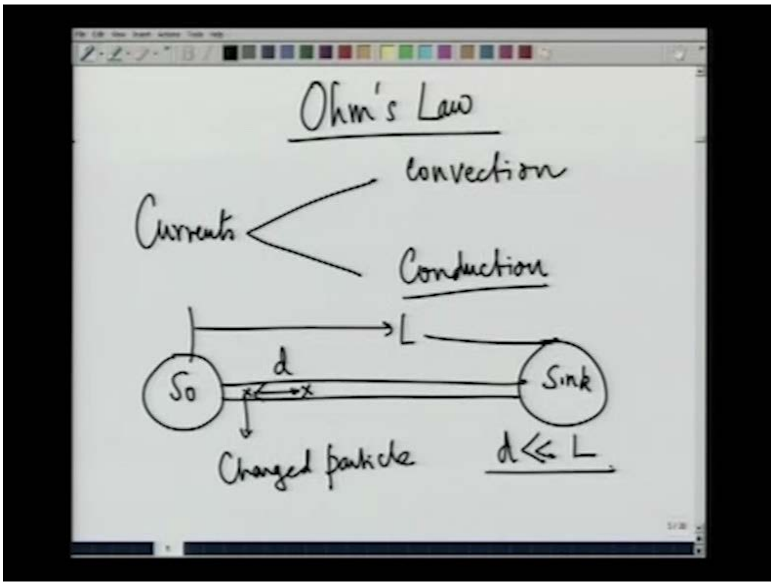

The topic of the next lecture will be to look at the steady currents again, and find the magnetic field produced, but now let us first concentrate on ohm’s law. Before I begin that I should ask you to remember that in my previous lecture. I introduced 2 kinds of currents. Both of them are relevant to electricity the electric current that we are looking at. Of course they appear elsewhere also in fluid dynamics etcetera, etcetera. The first 1 was due to convection. I gave examples of raindrops, and there is a certain amount of charge sitting on each water droplet. The other example is flow of a dust, and on each dust particle there some picocoulomb of charge.

The third example is imagine a fluid moving in a pipe; for example, oil, and it starts shedding charge to the surface of the pipe, and therefore, there is again a convective flow. They have their own interesting applications we will not get into them the other current which we are interested here is conduction when you look at the current produce, because of conduction no individual charge particle traverse such a large distance. So, what do I mean by that.

So, imagine that I have a source here, and there is a sink here. This is a pictorial way of showing that there is a potential difference, and let me imagine that there is a conductor. So, the source is the source for the charged particle, and here is the sink, and of course, I will have to complete the circuit let me not worry about that, and when I say that there is a conduction current there is a current, because of conduction, if I look at a representative charge particle. The total distance made by the charged particle. So, let us say it can come here. This d and the total distance traverse by the current let me call it as L.

If I compare these to d is always much much less than L. Nevertheless there is a current, because this charge particle will now look at another charged particle, collide with another charged particle, transfer its momentum, transfer its energy, and this continues to move then it will transform transfer its energy, and momentum to the neighboring charged particle therefore, this continuous transfer of energy to the neighboring charge particles. Such that there is always a steady net current is what constitutes a conduction current? So, we should be in a position to appreciate the fact that when I say that there is a steady conduction current it is only in the mean it is only in the average, and we obtained that by averaging it over reasonable periods of time the coalition times, and over reasonable volumes several atomic volumes, and several coalition times.

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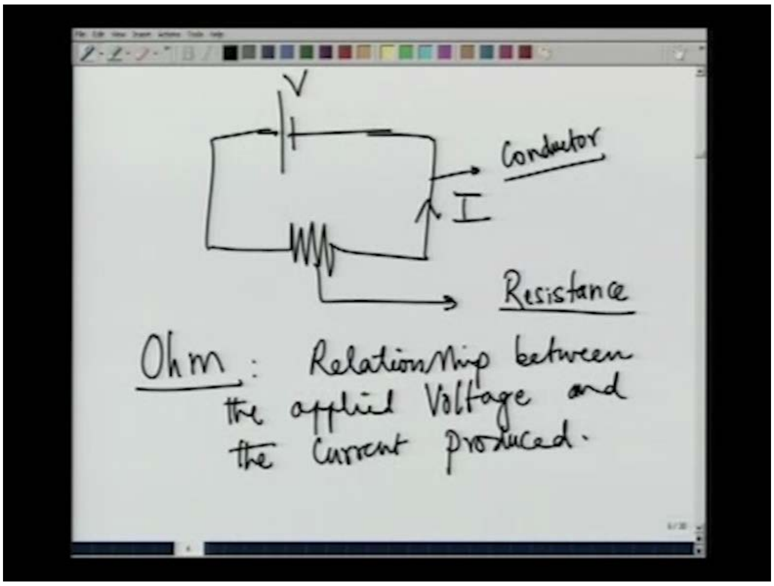

Now, what is the source? And what is the sink? And what is the phenomenon of ohm's law that we are interested in let us ask ourselves that question. The best way to depict that is to actually look at a standard circuit whatever you are familiar with. So, let me put a battery, and let me put a. So, called resistance, and let me close the circuit. So, this applies a certain potential V the battery say 5 volt, 12 volt whatever whatever I am symbolically denoting the response of the conductor.

So, let me make it clear this is the conductor. At this stage you should not imagine that there is a conductor, and there is some other thing associated with it no. There is a conductor connected to the 2 terminals of my battery. The response is denoted by this jagged line, and this is what I call as the resistance. As I told you resistance is not a fundamental quantity. In fact, we are going to now, enunciate a law which allows you to define resistance. So, I have a conductor, and what are the typical examples of conductors copper, aluminum, silver, etcetera etcetera. I connect the 2 end of the conductor conducting wire to a battery source, and I measure what the current is which I will denote by I. For all reasonable voltages that is the voltage should not be too high, and reasonable thickness of the conductor. I should not make the conductor too thick or I should not make the conductor too long I will come to that in a short while.

So, in any case imagine that you are sitting in your laboratory, and you are doing this experiment which you actually perform ohm discovered a fundamental law. What is it that ohm discovered? Ohm found that there is a very simple relation between the applied voltage, and the current that flows. So, ohm discovered a law which relates relationship between the applied voltage, and the current produced.

So, please understand that your V is the input. That is what you are applying it will you could connect the conductor to a 3 volt battery, 5 volt battery, 10 volt battery, batteries in series, batteries in parallel whatever, and you measure the current as the response by putting an ammeter. Of course, you could do the experiment the other way you can actually force a current through a wire, and then measure the potential difference across the 2 edges they are completely equivalent. So, let us stick to the canonical choice the simplest choice that we made. So, in a series of experiments with a series of materials, with a large number of materials ohm discovered a relation, and what is that relation? That relation tells us that the voltage, and the current are related to each other linearly. So, I have my applied voltage, and I have my current the relation between them is a linear relation where R is a characteristic of the material.

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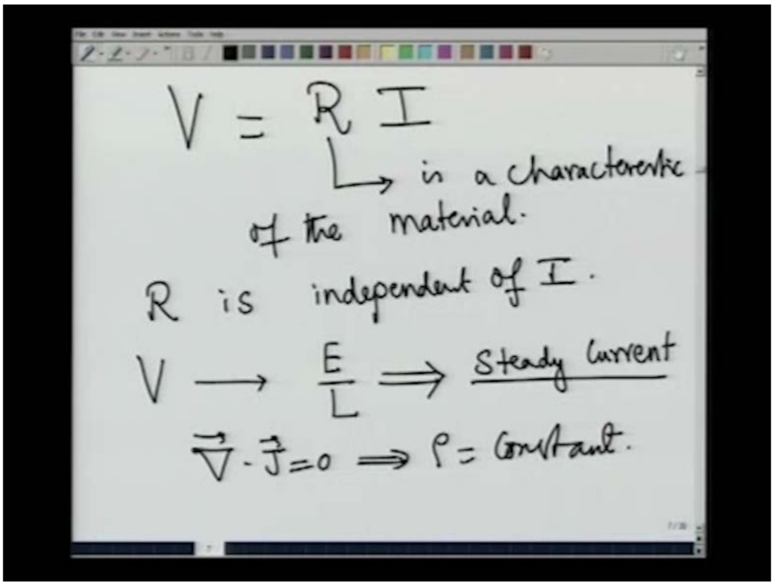

Let us not forget that when I say that it is linear by that I mean that R is independent of I. Am expressing V as a function of I therefore, R is independent of I. It is a constant of proportionality, and this is something which ohm, and many other experimentalist observed through a series of experiments. Now, what does ohm’s law tell you? It tells you that there is a given voltage, and all of you know from your 12 standards that when I connect to the battery there is a corresponding electric field. So, you give me a V this implies an electric field which is given by L. Where L is the total length traverse by the conductor so there is a constant electric field, and we have reached a peculiar situation where this implies this gives raise to a steady current this gives rise to a steady current.

What do I mean by steady current? Divergence J is equal to 0 let us not forget that this implies rho is a constant. In fact, in the case of conduction in a wire the total density is 0, because the electrons might be moving, but then there is a background positive charge, and they completely cancel each other in any case rho is going to be a constant. Suppose I look at the charge density of the electrons which is responsible for the conduction current, because my current is steady this also tells me that V is equal to constant V is a constant. So, I hope that all of you appreciate what I am trying to tell you? I apply a constant force field, and I have ended up producing a constant velocity. It almost looks like the pre-Galilean Aristotelian time.

Let us remember the model for dynamics the picture of dynamics that Aristotle gave us. Aristotle believed that all objects are in a state of rest when no force acts on them. All free bodies like to be quiet in a state of quiescence, in a stat e of static, they will be at rest, and you will have to apply a force in order to move them. It actually required the genius of Galileo to see the truth behind the simple statement namely that actually, the natural state of a free body on which no force acts is actually, uniform motion, uniform velocity whereas, under the application of a force what happens is an acceleration what is produce is an acceleration? And that is what was discovered by Newton in his famous second law. The acceleration suffered by the particle or the rate of change of momentum undergone by the particle is actually proportional to the applied force, but here as I told you it is as if we have moved to pre-Galilean time. Well the answer to that is this kind of a simplistic picture is not going to work. We need a slightly more sophisticated picture, and you people are already familiar with that in your examples in dynamics.

So, let me state that, and then go on to discuss the physics, and the consequence of the simple law, and let us proceed slowly. So, we have been using indiscriminately words like velocity density so on and so forth, but if you people remember our earlier lectures. I said that whenever we are looking at electrodynamics in medium in a medium. That is electricity, magnetism, and also the other dynamical part motion of the charge particle, charge density so on and so forth. We should not confuse them with the microscopic fields. That we should remember that we are always dealing with the macroscopic field. So, please go back, and remember that I carefully, defined for you how to get a macroscopic field given a microscopic field by a suitable average over the volume, and a suitable average over the time scales. Let me repeat that for your benefit.

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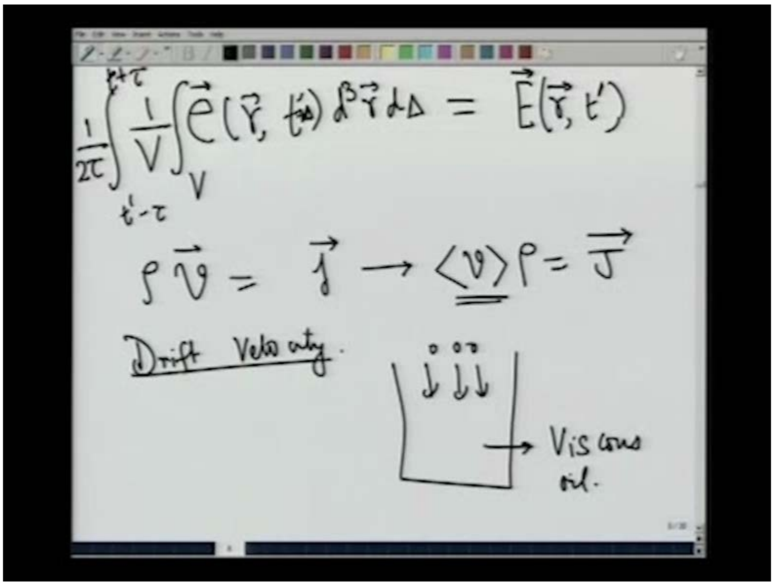

So, suppose I gave you a microscopic field e of r t which is the complete field which is produced by all the sources let me imagine that there are charge particles some of them are moving some of them are at rest, and suppose I am not interested in this, because either I am not able to measure that or I do not want to measure that. What do I do? What I do is to integrate this over a certain volume. I find the net electric field. So, I will integrate it over a certain volume, and then take the average over this particular volume.

This gives me a mean averaged macroscopic electric field which smoothens all kinds of singular behaviors highly, oscillatory behaviors of the of the field, and produces a smooth behavior. In a similar manner what I can do is to again average over the time. So, for example, I can do a dt prime. So, let me put a t prime minus tau, to t prime plus tau t prime plus tau and divided by 1 over t tau. This will give me the average field between t prime minus tau, and t prime plus tau. This is going to be my E of r comma t. I am sorry, I employ a rather bad notation what I should actually, do is to write t prime plus delta, and then let me erase this I will put a d delta, and that delta will go from t prime minus tau to t prime plus tau, and therefore, this will be a function of t prime.

So, the value of the electric field at any given time is the mean between t minus tau to t plus tau. The value of the macroscopic electric field at any point R is the mean integrated over a certain volume imagine that to be a sphere. So, it is this kind of a macroscopic field that we are interested when I wish to state the ohm's law. So, now, it is a trivial generalization for you to write what the velocity, the acceleration, etcetera etcetera, and now, if you remember that when I say that my current is constituted by the flow of the charges.

So, let me recall the steps that I had written. Give me a density of the let us say the charges that are moving. Give me their velocity this will give me the microscopic current J this can be having a very complicated behavior. What do I do? I replace this by the averaged macroscopic velocity. So, let me imagine that rho is already averaged. So, what do I do? I replace it by the averaged macroscopic V, and this will give me the macroscopic current density J. It is still a current density, but it is averaged. The volume that I consider is large compared to the microscopic volume, the atomic volume, but it is small compared to the total volume of the system.

Therefore, it is still small compared to the total volume, but large compared to the elementary volume, and it is this velocity that we are interested in, and when we state ohm's law this macroscopic velocity has a name, and that is called the drift velocity. So, ohm's law refers to bulk currents of this particular kind. Now, how do I get a uniform drift velocity given a uniform field. Nobody was going to violate Newton's law what really happens is that when we apply a force that is not the force acting on the system. Please recall from your dynamics what is it? That you studied. So, imagine that there is a block resting on a table you apply a constant force, but then the block does not accelerate with the law given by A is equal to f by M, because there is a frictional force which is acting on the block.

There is a contact between the block, and the table there is a reaction force there is a coefficient of friction, and therefore, there is a frictional force mu 1 which acts that is 1 simplistic picture. The other example is you take for example, a small sheet of paper a small piece of paper which you let it drop. There is a uniform gravitational force acting on it, but unlike a tennis ball or a marble which will fall down with uniform acceleration. My sheet of paper will not fall with uniform acceleration, but it will actually, move down with what a uniform terminal velocity. Yet another example

Take for example, a highly viscous fluid. Let us say oil, and then imagine I take small steel plates, and let them drop. The viscous fluid offers resistance the gravitational force pulls it down, and these move with what uniform drift. That is the 2 forces conspire in such a way that the net affect will be a uniform velocity, and not a uniform acceleration. So, the correct picture in order to understand the physics behind ohm's law is to imagine that each electron is actually in a medium which is highly viscous. What is the kind of the viscous force? Analog of the viscous force that the medium constituted by the other electrons, and the lattice of the system that exert on each of this conduction electrons that of course, depends on the details of the material.

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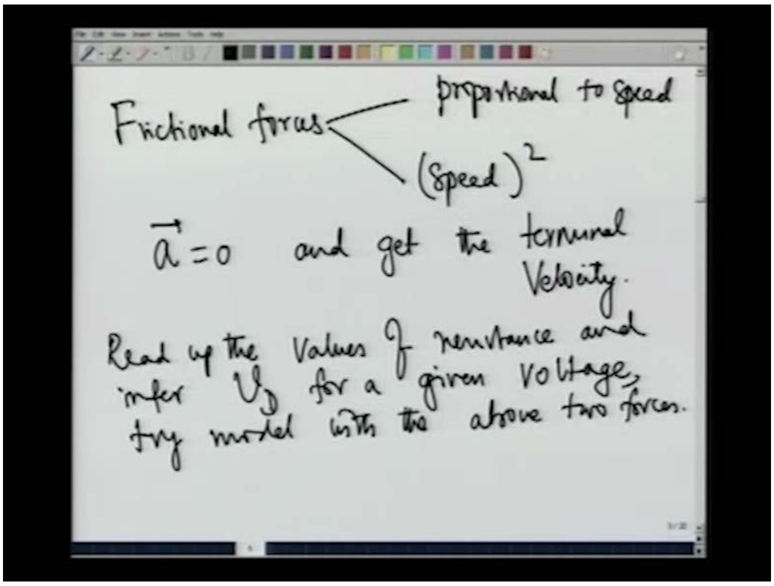

So, I am not going to get in to that, because that is not the subject matter of the course, but there are 2 well known examples that will give you terminal velocities.

So, you can have proportional to the velocity, to speed or speed squared proportional to speed squared what I can do is to write a simple law, where you write the additional friction force together with the applied voltage put the left hand side acceleration is equals to 0, and get the terminal velocity, I should not be spending. So, much time on this particular problem, because this is something that you people are familiar with. So, please take this as a home assignment problem. Those of you who aspire to become electronic engineers, and contribute in a substantial way semi conductor devices today we have nana devices, we have quantum devices you people should not be contented with this kind of a statement these are gross statements.

We should ask ours elves where do the frictional forces come. Under what condition do these frictional forces become proportional to the momentum of the particle that is the speed of the particle. Yet under what conditions will these frictional forces resistance forces be proportional to the energy of the particle. The answer to that lies in the material properties, and this cannot be understood in terms of simple classical picture, but it require a quantum theory. So, you people should certainly do a course in condensed matter physics or material science. There you develop a theory called the free electron theory where given the properties of the material of the medium you can actually, find out what the resistance is so to repeat please work out these problems in a few simple cases, and estimate what it should be. Even better you can take it as some kind of an intellectual challenge.

So, what should you do you look up a table of resistance remember when I introduced dielectric, and conductor I gave you showed you a table of resistance, and conductivities, and resistivity so on and so forth. And I remember making the statement that I would call a material as an insulator if its resistivity is greater than 10 to the power of 16 or so in S I units. So, look up that table make use of ohm’s law invert the relation, and get the drift velocity, and try to see how the drift velocity can be obtained by modeling these frictional forces that is yet another assignment, and probably you can look up a nice book on condensed matter physics, solid state physics, and see whether it can be understood.

So, take it as the next assignment problem. That will actually not be a part of your syllabus, but that will certainly be an enriching experience. So, what is the problem that I am stating now, Read the read up the values of resistance, and infer the drift velocity, for a given voltage, and then what should you do try to model with the above two forces .

I am sure you people can do that you should go ask your instructors to explain a little bit more of the physics, and that would be real fun. This is so much about the underline physics which causes ohm’s law. So, naturally you do not expect ohm’s law to be exact. As I told you first of all it requires average over space, average over time, and there is no fundamental principle which will tell us that all materials should behave in the same way under the application of the voltage even if you call them as conductor or whatever. In fact, you know much more than just a mere classification into a conductor, and a dielectric. As I told you there is something in between them the so called static discharge materials which are of use great use actually, but which can also be troublesome.

I also told you that there are other materials such as semiconductors, there are liquid crystals, there are super conductors you have heard all of them. So, now, the natural question to ask is to all of them obey ohm’s law. Before I answer the question let me state a few more facts about the resistance, and then go on to discuss the violation of ohm’s law. So, what are the properties of the resistance?

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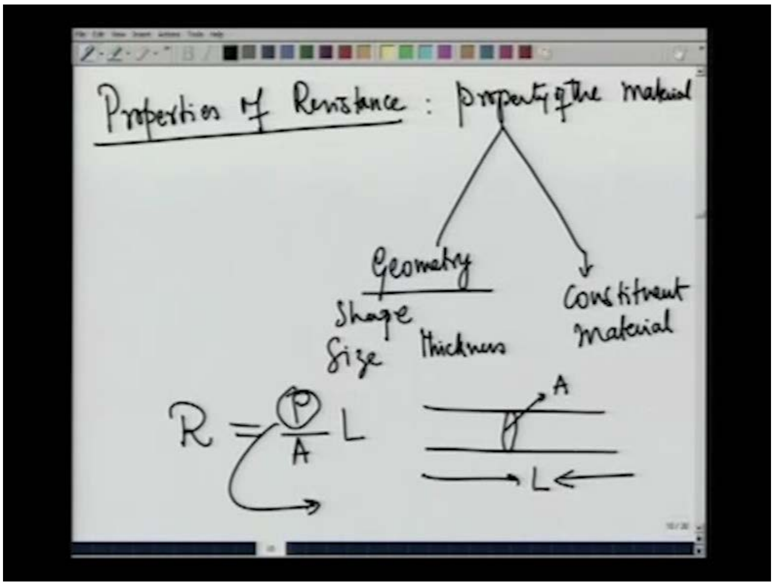

So, I am still looking at the standard conductors after this I will go to the violation of ohm’s law. As I told you it is a property of the material.

It is independent of the voltage or the current that is if you give me R the resistance of the material, and apply a voltage the value of the current is fixed or if you force a current through the conductor the value of the voltage difference is also fixed. So, that is what is going to happen.

So, it is the property of the material, but when I say that it is a property of the material. What do I mean by that? There are 2 aspects of the property of the material. 1 is what appears that I will call as a geometry. So, you look at the shape, you look at the size, you look at the thickness, etcetera etcetera. Shape, size, thickness, and the other 1 is the constituent material. What is the constituent material? I say aluminum it does not matter whether it is a sheet or there is a thin wire or a big wire. So, what is the substance, and what is its geometry the resistance depends on both of them, and again we know phenomenological. In fact, you have done experiments that my resistance behaves in a particular manner on the geometry given a particular material.

So, take the same substance aluminum 1 wire is of length l, another wire is of length 2 l you know the resistance gets multiplied. The area of the cross section of 1 wire is a, the area of cross section of another wire is 2 a. Then the resistance gets divided therefore, a succinct way of summarizing that is to introduce another property, another quantity, which is exclusively a property of the material, and it has nothing to do with the geometry. That is isolate the geometric quantities, and that we do. So, by writing R equal to rho by A into L. T his is the area of the cross section over which the current is flowing. So, this is my area of the cross section A, and this is the total length L.

So, if somebody is if there is a people are continuously pulling you back. The net resistance that you experience is equal to the number of people who are pulling you back you as you keep on moving more, and more people are pulling you; therefore, it is proportional to L, but then if you have lot of room to go along that is if you increase the cross sectional area then the frictional force becomes small therefore, 1 writes R equal to rho A by L rho by by A, and this rho is what is called as the resistivity. So, rho is the resistivity.

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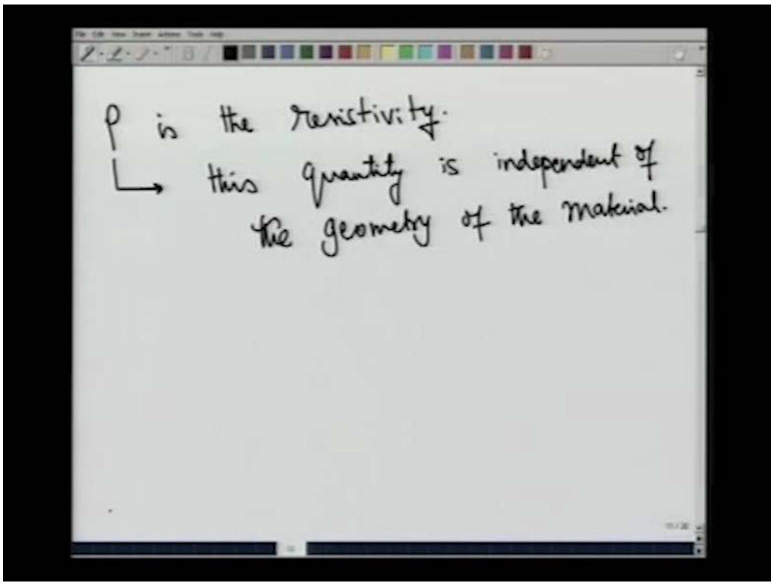

You should remember just as ohm's law is a phenomenological law. The statement that R equal to rho L by A is also a phenomenological law, because we want to assert that this quantity is independent of geometry of the material. Having stated that, I do not want to spend any time giving you examples. This is an exuberant which you did in 12 standard, 11 standard, probably, and you'll certainly repeat your engineering courses. What I shall rather do is to emphasize that this is not the only way that I can write down a relation between the current and the voltage there are actually, even more interesting and intricate systems. So, let me start with an example.

Now, all of you are familiar with transistors. When I was a student we use to study what is called as the current voltage characteristics of a triode of a diode. So, here is an example of a transistor called the field affect transistor, and as you people can see what we have plotted along the X axis is the voltage, and what has been measured along the Y axis is the current. Of course there is a lot of complication in this you can see that for very, very small values of the voltage that is what I was telling you initially, and that is shown in this inset. For very small values of the voltage, so it is 0.2, 0.4 that is a fraction of it may be 0.01 volts.

You will find that there is indeed a linear relation between the current that is produced, and the voltage that is applied, and that is shown in this inset, and the extrapolated line is showing you what it would have been if that linear relation had persisted. If the resistance had remained the same, but what happens is actually, slightly different. Depending on what kind of a gate voltage that you apply the response of the system changes, and the response of the system is summarized by a quantity, called the resistance.

In this case the ratio between what the applied voltage, and the produced current, and you people see that what is happening is not a linear behavior at all it starts linearly, and eventually it gets saturated. It does not keep on increasing linearly after a while it is given up the resistance cannot increase beyond a point is that. In this case it is the current is saturated around 2 at a voltage of 1 therefore, the resistance is something like how much. So, I have V is equal to 1, I is equal to 2, R is something like half half in ohm it is saturating at this particular thing, and it is this rich physics that is responsible for the utility of transistors almost everywhere in all the electronic devices that you see. In fact, the voltage current characteristics can be even more abrupt.

So, let me show you yet another example, and this is another field of a transistor called the super conducting field of a transistor, and here you see that depending on whether you apply a positive voltage or a negative voltage there is an anisotropy there is an asymmetry that you are establishing. The behavior of the current changes abruptly there is a sudden jump it is a highly non-linear relation, highly non-linear relation in the sense that there is a great jump at V equal to 0. There is certain amount of mirror symmetry that is not bothers to us. What bothers is the way it jumps from 1 point to another point is that as you keep on increasing the voltage. So, those of you are imaginative can almost see that this can add a some kind of a switching device. So, do go look up the text books, and verify whether my speculation that this can probably act as a switching device is correct or not or find out what the true application is so this is yet another example.

So, these are the things that you people are going to study in your complete course in further courses on electronics, and electrical circuits, but right now our business is to actually become thoroughly, familiar with basic underline electrodynamics, and simple electric circuits. So, this for given only as illustrations. So, let me return to what whatever I was discussing in my 1. How do we proceed, I gave you a basic picture of how a constant force can actually, produce a constant current.

Through the frictional forces, and all of us know that 1 consequence of the frictional force is an energy loss. So, let me write that consequence of friction is energy loss or to use a more familiar phrase that we are all to energy dissipation. So, how is the energy dissipated? The energy gets dissipated by heating. There are any number of inelastic collisions that are taking place that is friction. It is not an elastic collision the momentum is conserved, but the kinetic energy is not conserved. So, you keep on transferring the energy to the atom, to the lattice, and then what does the atom do it dissipates that energy away by vibration. So, if you pass a current through a wire, and if you touch it it will get heated up, and what is this phenomenon called in the case of conduction this phenomenon is what is called as a joule heating? This phenomenon is what is called as joule heating. So, the system gets heated up.

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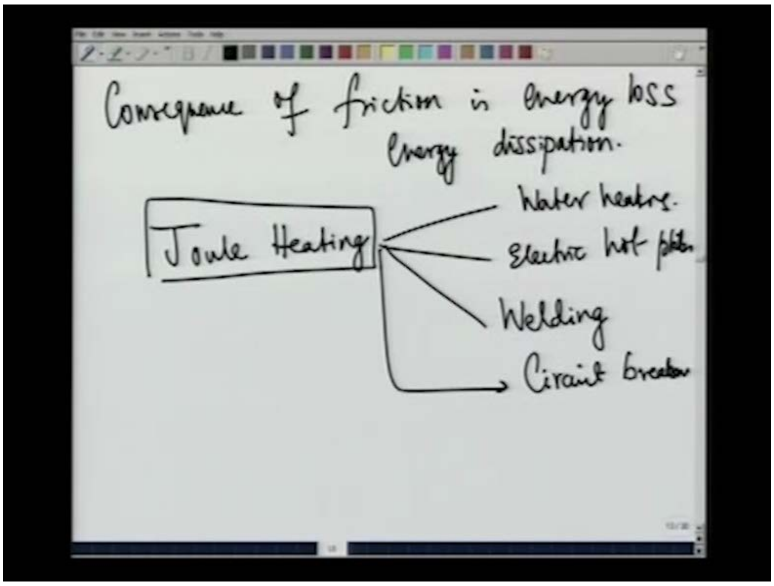

Before, I get into a discussion of what this joule heating is let us remember that it is not a very bad thing always, because there are nice applications all over water heaters geezers run on that. So, a strong current passes through a high resistor is that right that is what is going to happen. Larger resistance, and a large current that produces a larger joule heating or electric heaters, hot plates which we all use that is useful.

It is useful in welding, and a large number of other applications that I can come. So, joule heating can be effectively, employed in order to transfer energy from the electron. Whatever is there in your battery the voltage source to the kinetic energy you heat up the water or you cook your food or you melt the material at that particular point or you can also use it in circuit breakers. Where the heating will become so much, but that part of the wire will melt, and when the wire melts we say that it has fused. So, these are the applications. Now, I do not want to spend time discussing on this 2 elementary. So, let me write down a few relations, and ask you people to work them out. I am sure all of you are familiar with. The first term the relation is very simple all of you know, the second relation requires a little bit of thought, because in your twelve standard you people did not study the concept of a current density, but never mind it is always possible for you to work out it do not require any help either from me or the other instructors.

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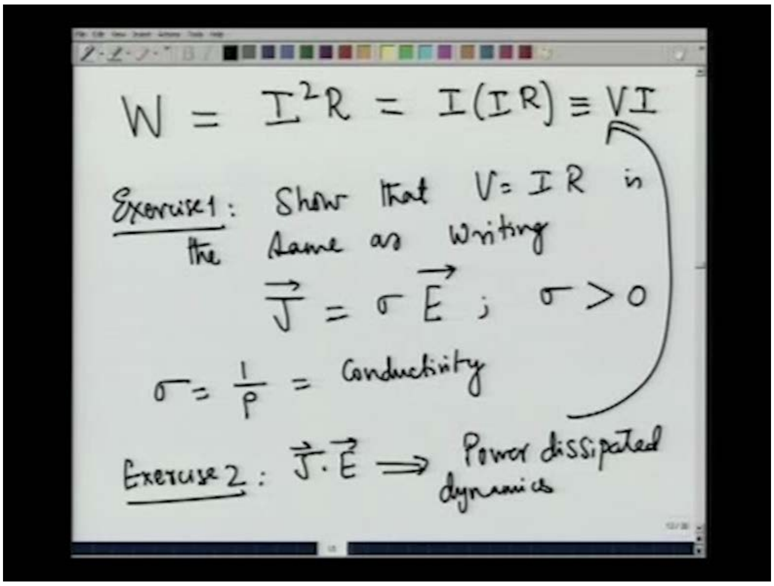

So, what is it that we want to say? We want to say that the power dissipated. The amount of energy lost per unit time. So, I am using the notation W for it is simply, given by I squared R. So, if some of you still think that you need some hint. I will write it as I into IR is identically equal to VI .

There is yet another way of appreciating whatever I am saying, and that is to rewrite ohm's law in terms of the more fundamental quantities namely the current density, and the electric field. So, here is the next exercise for you show that V equal to IR is the same as writing J is equal to sigma E. If there is a constant electric field, there is a current density which is produced in the direction of the electric field of course, sigma is always sigma is greater than 0 for us. What is the relation between sigma, and R? Let us not forget that my sigma is nothing but 1 over rho, and that is nothing but conductivity please take it as an exercise.

The constant of proportionality between the voltage, and the current is called resistance. The constant of proportionality between the resistance, and the length divided by cross sectional area is called the resistivity, and the constant of proportionality between the current density, and the electric field is nothing but conductivity. So, the exercise for you is to start with this primordial expression the more elementary expression J equal to sigma a, and arrive at V equal to IR. If you did that there is a little bit more thing that you can do, and that is you can actually, workout the work done. So, this is exercise 1 I gave already given you other exercises, but let me labels them as exercise 1, and exercise 2.

The next thing that you can do is to argue convince yourself. That J dot E is the actually, the work done per unit time, per unit volume whatever. So, if you compute J dot E is that. There is a current density dot it with E this gives you the power dissipated apart from some multiplying factors. So, couple this with dynamics the work done is integral F dot D L. When you move from a point 1 to the point 2 so couple it with dynamics, and infer this relation. That the power dissipated is given by L squared R. All these are elementary exercise which are worked out in every book of electricity, and magnetism redneck, and holiday Purcell whatever whatever Griffiths.

So, you do not even have to look them up you can yourself work it out. So, please do work them out, and you will find that the power dissipated is given by I squared R. Actually you could do slightly better than that. I already introduce for you non-linear characteristics right transistors show you a non-linear characteristics. So, here is the next exercise for you. So, I will put a star against this exercise, because probably it is not in the main body of your syllabus.

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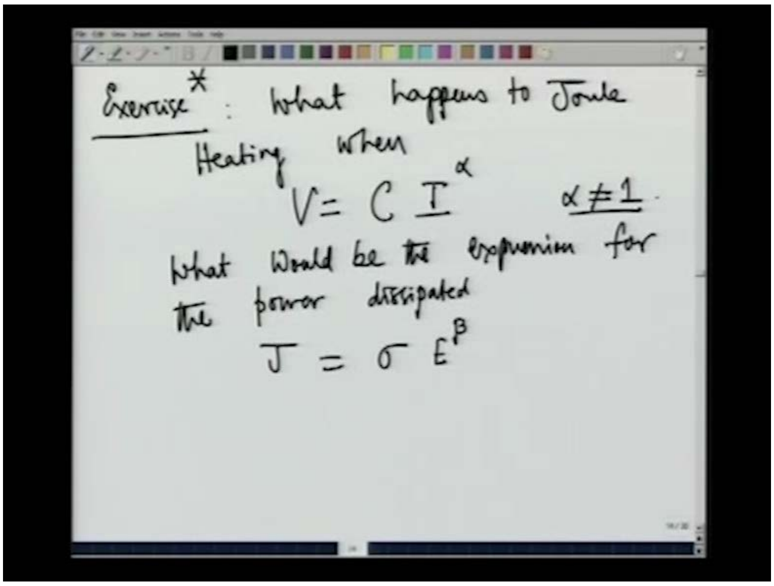

What happens to joule heating when let us say V equal to some constant into I to the power of alpha. Alpha naught equal to 1. In some region it can be I squared in some other point, for some other voltage it can be I to the power of 0.5 etcetera etcetera there could be a complicated relation. So, what happens to joule heating, and what would be the expression expression for the power dissipated.

The (( )) is the expression between J and E, because that is what you would have to use there is simply given by J is equal to sigma E to the power of beta. Alpha is not equal to beta, because I have invited the relation as you people can see E is related to V, J is related to I. So, find out the relation between alpha, and beta, and ask what is the power dissipated, because there is invariably going to be power dissipation otherwise what happens to all the energy that is being impacted by the electric field you please take this as an exercise. Now, we have almost come to the end of whatever I wanted to say. So, for a change this lecture has been largely descriptive not too many mathematical formula, but there is enough thought to think about. We have been able to imagine an underline dynamics for this kind of a joule heating that is what we have been able to do.

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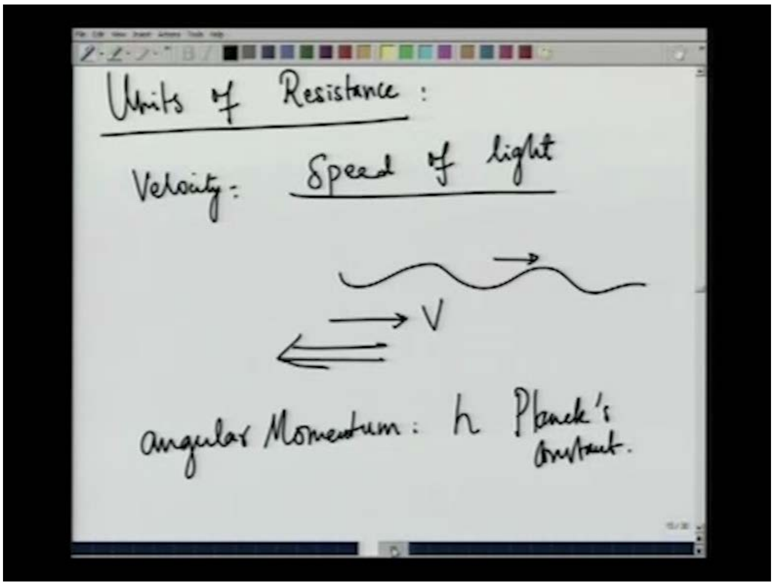

But what I would like to return now is to a very fundamental question which a physicist is always worried about, and that is units units of resistance. We are told that you know choosing unit is a matter of convenience, and this has been exploited to the heat. So, for example, in our own country the unit of distance was measured by a quantity called the crosha, Hindi speaking people crosh. So, what as a crosha? crosha is the distance maximum distance that can be between 2 persons. So, that 1 can hear when the other person is speaking. Crosha means to call. So, how far is the next village? So, the passerby will answer you it is 5 crosha. So, that are a sensible unit. There is other of units sensible units that we employ for other quantities. What is that? For example, the concept of what distance for us the natural concept of distance is what the distance traverse by an adult when you take the next step and that is the foot.

In a similar manner you can try to establish units for weight, units for time so on and so forth. The natural unit for time is nothing but the day night cycle right that is 1 particular way of looking at it, but I am not interested in that I am not interested in the choice of convenient units I all we all know that ohm is a very convenient choice of unit. Whereas, we know that farad which is a unit of capacitance is not very convenient, because all the capacitances that we encounter in your lab are all very, very small fractions of that unit. I am not speaking of that. I am asking if nature provides us with some fundamental choices which is independent of the fact that we are human beings of particular dimension staying on a certain planet called earth.

This is something which is extraordinarily important, and which lies at the heart of the foundations of all physical sciences, and also at the foundation of the theory of measurement the practice and theory of measurement itself. So, although it is a dig ration it is worthwhile spending some time on the unit of resistance. So, what I shall do is to take up an example where there is another fundamental unit which is already provided by nature, and that is the velocity or the speed, and what is that? There is a fundamental unit called speed of light, because the speed of the light is same for all observers. That is something that you would learn at great length in your dynamics course, mechanics course.

So, if there is a light moving with a speed C with respect to me. So, imagine light moving with a speed C with respect to me. I run with a velocity V in the same direction speed V in the same direction, but I still measure the speed to be C. I measure it in the opposite direction I write run it or run away unlike a bullet or a train which will change its speed to C plus V or C minus V it will continue to remain C therefore, nature has provided us with a fundamental unit of speed C therefore, if you were to go and ask a physicist. Look here I want a standard of speed what should I do the physicist tells you should choose a standard which is independent of your taste, and my taste, and that is the speed of light.

Now, we know that it is this speed of light which gave rise to new physics, and what is that new physics? We broke away from Newtonian mechanics, and we have einsteinium mechanics where we have the famous relation the mass energy equivalent C equal to M C squared, and that is a reflection of the fact that there is a deep truth namely speed of light is the same for all inertial observers. The next example is angular momentum you know it is not given to us to choose. What should be a fundamental unit of any quantity it is for the nature to give. So, angular momentum we all know is for orbital motion R cross P. Nature chooses not to provide either a fundamental unit of length actually could be there, but at this point let me not worry about that or a fundamental unit of momentum, but nature provides us with a fundamental unit of angular momentum, and what is that?

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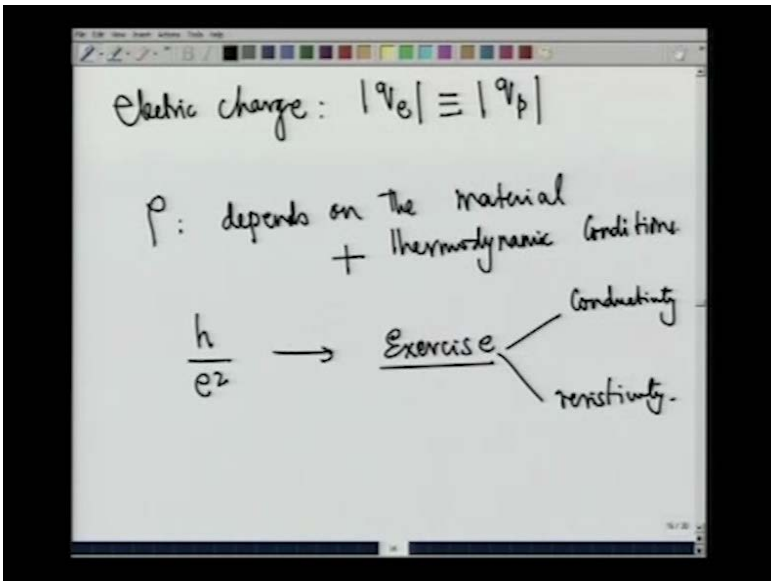

That is your famous Planck's constant, and at the very beginning of this course. I also stated yet another fundamental fact for you a very interesting fact, and that is for reasons not known to us the charge always come in discrete units so the electric charge. It is entirely inerrant whether you want to choose that to be the proton charge or the electron charge it does not matter. Mod q e, modulus of the charge of the electron is identically, equal to the modulus of the charge of the proton of course, they differ from each other by a sign factor is a fundamental unit, and all charges come in the multiples of either the proton charge or the electron charge which essentially tells us that all currents are constituted by that the electrons or the protons or their combinations they of like it happens in conducting materials ions, ionic fluids, super ionic fluids so on and so forth.

So, the natural question that one has to ask is whether there is a combination of these fundamental constants that can actually give me a natural unit of resistance. Why am I spending so much time although I told you that the resistivity is a property of the material it is actually, not entirely a property of the material. Let me come back to that my resistivity, depends on the material plus not the geometry, but the thermo dynamic conditions. You apply pressure the resistivity changes, you heat the system the resistivity, changes for a semi conductor in some normal temperature in when you increase the temperature actually, the (( )) decreases, whereas for an ordinary conductor when you increase the temperature the resistivity increases.

There are materials which show Arrhenius behavior between temperature relation between the temperature, and the resistivity. Therefore, resistivity of all materials depend on not only the material properties, but also on the thermodynamic conditions. Therefore, if I want to measure resistances at different temperatures, at different pressures, of different materials, in different conditions the natural question that I would like to ask is whether there is a fundamental unit which is quite independent of all these external conditions which is independent of the material speed of light has nothing to do with the material properties. Planck’s constant has nothing to do with the material properties.

In fact, dictates the material properties, because it gives rise to quantum mechanics. So, maybe there is a fundamental unit of resistance, and may be if there is such a fundamental unit of resistance there are corresponding devices which I can build, and how do I get them? I get them by combining the charge of the electron, and the Planck’s constant. So, the exercise that I would like to give you is to verify the dimension of the quantity h by e squared so that is the next exercise. It is a very good example in dimensional analysis, and let me assure you if you did that you will get a very interesting dimension I will give the answer there are 2 possibilities either it is conductivity or resistivity 1 of them it cannot be both right.

So, if you work them out, and come back what I will do in the next lecture is to actually, make use of it tell you some very interesting physics associated with it they are what are called quantum devices is that, and then go on to study magnetism let us stop here.