Electromagnetic Fields

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Lecture – 18

Magnetic Field - 1

Good Morning. The last 16 or 17 lectures we have been discussing electrostatics and today we are going to start with the new topic which is magnitostatics. Let me put down what we already learnt and let us look at, what is going to change.

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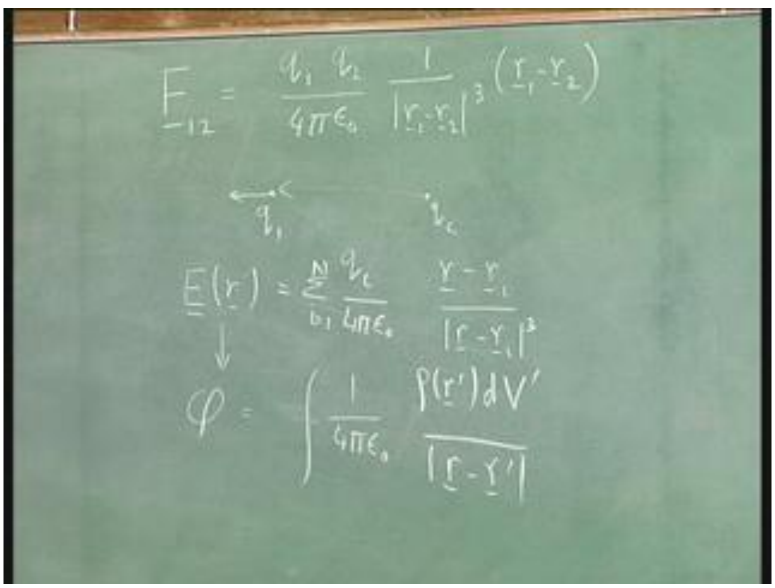

So we learnt that if you put a charge, if you put two charges at a distance that a force is exerted which goes as q 1 q 2 over 4 pi epsilon not one over mod r 1 minus r 2 cubed times r 1 minus r 2. This is the force I call it F 1 2 on a charge q 1 due to a charge q 2. So this is you have to draw the line q r 1 minus r 2. So it is pointing towards r 1 and the force is in this direction. From this force which was experimentally measured this is coulomb's law, we obtain the concept of electric field and we define that as sum on i qi over 4 pi epsilon not r minus ri over mod r minus ri cubed.

There is you have whole lot of charges q 1, q 2, q 3, up to qN. Each of those charges is at a location ri r 1, r 2 up to rN. Then the electric field is any general point r is given by the summation of coulomb's law for a unit charge placed at point r. From this electric field, we came up with potential pie which was we can also write this is an integral. So, I will write this potential form as an integral. Integral 1 over 4 pi epsilon not row of r bran dV bran over r minus r bran. Given these things you also dell derived some relations.

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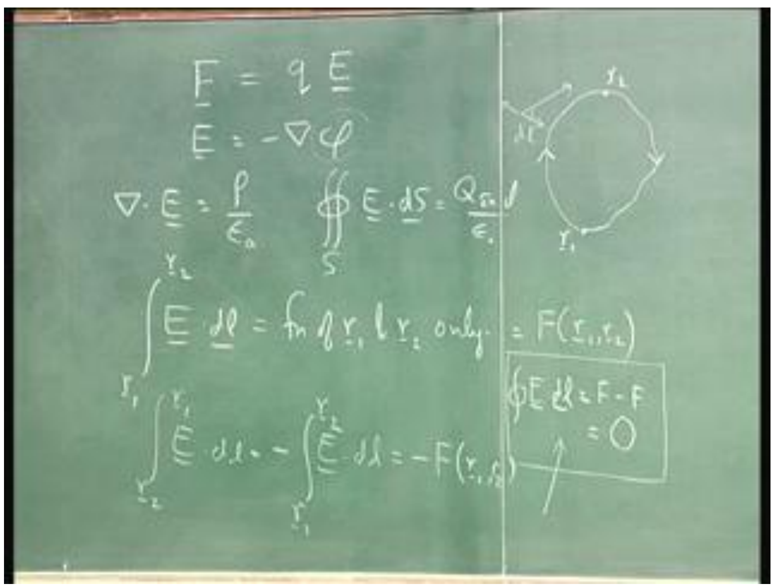

First thing we found was the force on a charge is equal to the value of the charge times the electric field that comes because coulomb's law and the definition of electric field defers by only the value of the charge placed at r. We had that the electric field was equal to minus the gradient of potential. We also derive something else. We derive that the divergence of E was equal to charge density divided by epsilon not and there is another form of this which was you do the surface integral over a closed surface of E dot dS it was equal to Q enclosed over epsilon not.

Now one another things that came out defining a potential was something very important. We proved that if you take any position r 1 and any position r 2 for any r 1 and r 2 if you did integral E dot dl it was equal to a function of r 1 and r 2 only. So it was some function call it some F of r 1 comma r 2. So you could have then do integral r 2 to r 1 E dot dl which was nothing but minus r 1 to r 2 along the same route E dot dl. That is because if you have an electric field, that is in some general direction and this is your dl, E dot dl is magnitude of E magnitude of dl times cosine of this angle. But if dl change sin is pointing that way, now the dot product is the same magnitude but cosine of 180 degrees minus theta is minus cos theta.

So sin alone changes, so that is why it is a minus sign is equal to minus some F of r 1, r 2. So if I take any closed loop this is my r 1 this is my r 2 if I go this route and then I come back on this route that is like doing r 1 to r 2 plus r 2 to r 1. But effectively if I do both of these I am going round a loop and what is it say? It says if I go on any loop E dot dl is equal to F minus F which is 0, this is an extremely important result. Then in electrostatics the electric field can be derived from a potential and equally this fact came from the fact that if you take any closed loop and integrate electric field around the closed loop you will get 0.

These two imply each other. It is clear that, if this is true, then this is true. But equally true is the other way round because if this is not zero then I can find a loop. Well, this is not zero I take two points on it. Then this integral is not equal to this integral which in turn means E dot dl from r 1 to r 2 is dependent on how I went then. How I got then? That means I cannot define E equals minus gradient of potential. So, these two statements are saying the same thing. However his is the very important statement and its important comes most because you are going to break it now. Once we introduce the magnetic field we will start finding the loop integral E dot dl is no longer 0.

It is very important to understand that this was for electrostatics and it is equally important to know why it fails and to find out and what conditions it will hold and what conditions it would not hold okay. So, we have a set of phenomena your charges the charges exerts forces on each other. The charges are calls fields, from the fields we can obtain back the charges and if the charges they put we know that we can derive a potential and that potential is a function only of the n point of my integral E dot dl. So it is a complete theory. Why do we need anything else? This is explain very nicely in Fineman and I recommend all of you to go and read the introductory chapter of Robert Fieman's book lectures on physics second volume. But what the truth is electrostatics is not a complete theory and let us see why it is not a complete theorem. Now, we have all this equations and I am going to now take a thought problems.

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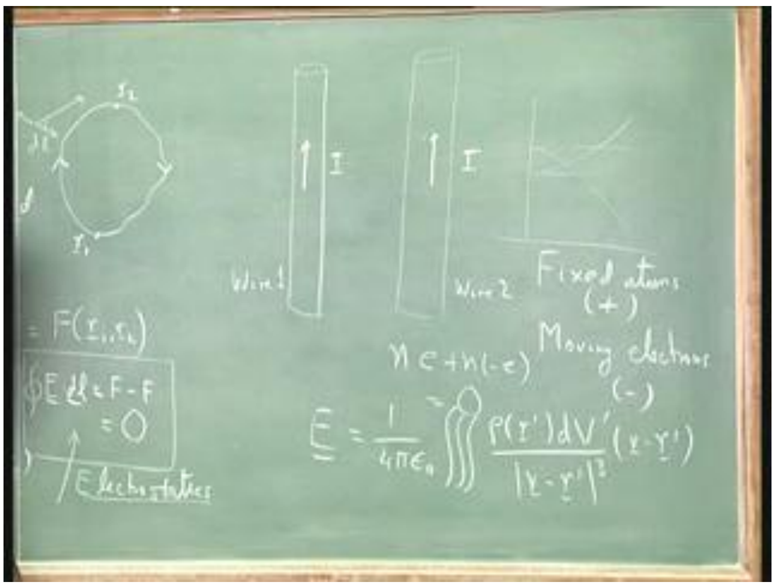

I have got a wire I call it wire 1, I have got an other wire this is wire 2 and then each of this wires I am going to drive a current I alright. Now you know that the wire is a made up of atoms and if there are metals and what is really happening is some of the electrons in the atoms. Let some of the electrons in each atom you have overlap region of the valence band on the conduction band. So there will be electrons here which will be free to move to other locations which are allowed by quantum mechanics. So, the electrons start jumping from atom to atom to atom and that why metals are good conductance.

So, we have fixed atoms which are positive in charge and moving electrons which are negative in charge. But, there are as many electrons as there are atoms will assume one electron per atom is free to move. So, we are as many electrons of atoms so there is no net charge. So there are n atoms with positive charge plus n atoms with negative charge n electrons are negative charge. So, there is no net charge. If there is no net charge, then the electric field which is one over four pi epsilon not volume integral row of r prime dV prime over r minus r prime cubed times r minus r prime.

So, this expression it depends on row if there is no charge anywhere there is no electric field. So these two wires in this picture should not exert any force each other because at every point there is no charge electrons may be moving but that does not cause any force on between these wires. However this picture is not correct, this picture is not correct, because Einstein came along and he introduced the theory of relativity and when he introduced the theory of relativities something went round, this is not how it happen in history, but this is the best way of understanding what is going on here.

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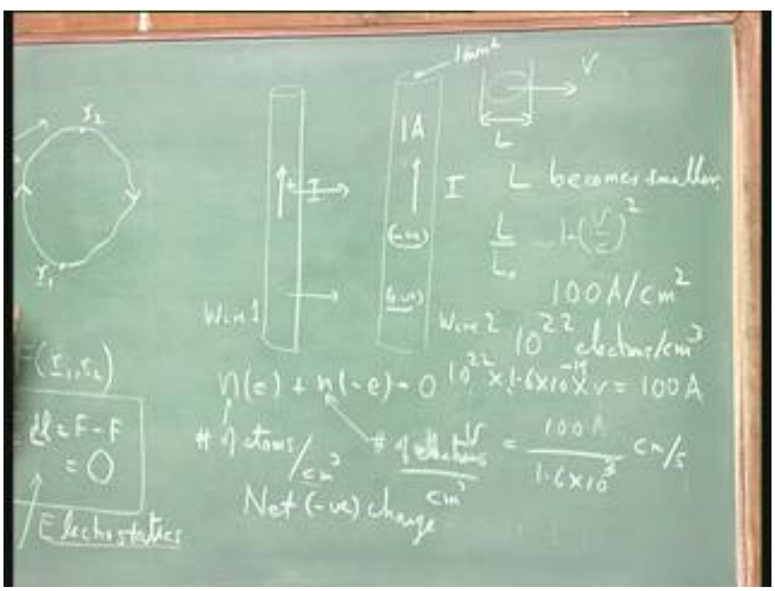

According to Einstein when an object is moving very fast, that the velocity V then the size of that object lets call it L this size reduces. So this size becomes smaller by how much does L become smaller. Well L becomes L over L not the amount by which L becomes smaller goes like is a function of V over c. Actually, it is a function of V squared over c squared one minus. So, V is very small L is equal to L not. But if V starts approaching c then L becomes tiny. Out of that effect is here, if you look at say one ampere of current flowing through a wire, let us say the wire has one centimeter one millimeter squared area, then we are talking about 100 amperes per centimeter squared because 10 milli meters make a centimeter.

So, 100 mili meters squared will be one centimeter squared. You have around say 10 to the 22 electrons per centimeter cubed because that is like an Avogadro's number. If you had them all pack very closely but atoms are heavy there further apart, so around 10 to the 22 electrons per centimeter cubed, what you have? So you need 10 to the 22 electrons multiplied by the charge of an electron which is "1.6" into 10 to the minus 19 columns. This is the charge per cc into the velocity. We do not know what that velocity is equal to hundred amperes. You put in their numbers you will get that V is equal to hundred amperes divided by 10 to the 22. So, "1.6" into 10 to the minus into 10 to the 3 centimeters per second, so V is somewhat less than milli meter per second.

So very small number and it will probably an over estimate of that number as well. So V is very, very tiny, infact V over c is of the order of 10 to the minus, so this is 10 to the minus 310 to the 8. So 10 to the minus 11, 10 to the minus 12 is the range of what V over c is, V squared over c squared is of the order of 10 to the minus 24. So, it is a very tiny change in length. So this is one meter this length became one meter less 10 to the minus 24 meters. So, it is such a tiny change you would not expect it to have any effect. However, it does, what happens is that, if you look at the electrons that are moving, they have got squeezed slightly by this factor 10 to the minus 24. But the ions atoms are not moving fixed atoms.

Because, the fixed atoms they do not compress. So, the result is what I had written earlier n times, e plus n times minus e which is equal to 0. This n is number of atoms per centimeter cubed. Well, this number is not equal to this number because a centimeter has changed, centimeter become less by 10 to the minus 24. So, this number is slightly larger number of electrons because it 1.1 centimeter plus 10 to the minus 24 centimeters has now got contracted to 1 centimeter. So, few more electrons are inside this centimeter. The result, there is net negative charge. So as soon as this current starts flowing electrons are moving. So, because of the theory relativity electrons are squeezed a little bit. There are more electrons per unit length then there are atoms.

So, there is negative charge is very tiny, you can imagine how tiny it is we are talking about one part in 10 to the 24. Now the same thing is happening here alright. So, you have electrons and um atoms and the electrons are moving. So, they also get contracted. So, what happens if you look ahead from the point of view of atoms that I here the atoms are positive. Atoms are not affected by the electrons that are moving in the around wire because there are as many electrons this side and there are this side. So, there is no net force an atom on this wire due to electrons in the same wire. But these atoms see more electrons here then atoms here.

So, there is a net attractive force look at that from the point of view the electrons, the electrons do not get affected by the atoms here because as far as the electrons are concerned atoms are moving in the opposite direction. But, as many of them there thus there are here for the electrons these electrons are still a stationary. But, the atoms are moving backwards, imagine you should think of it as electrons are claimed in to a car and moving. So, both these cars are moving with the equal speed. So, if you are inside this car the other car is stationary but the road is moving backwards. So, the electrons do not see standard number of electrons here. But see the atoms compressed. There are exes of atoms compare to electrons, this is positive and so there is attractive force result due to coulomb’s law these two wires start at pulling each other.

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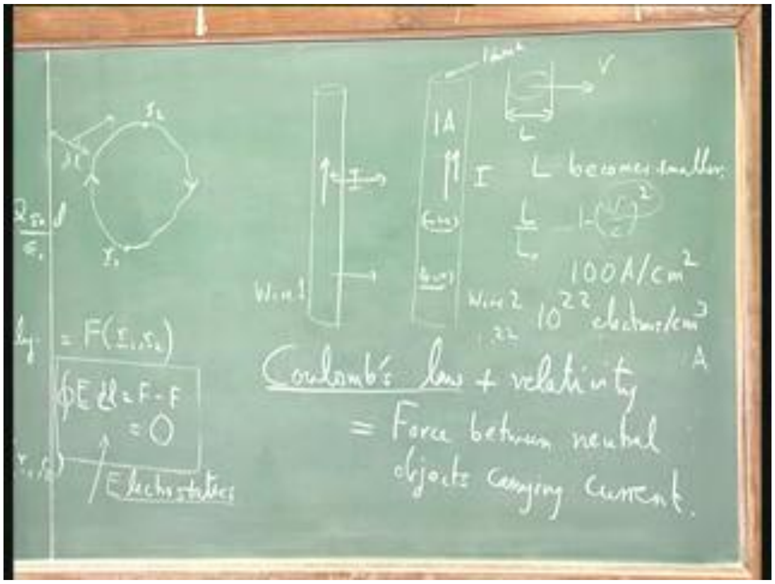

So the conclusion which you can prove regressly is coulomb's law plus relativity equals force between neutral objects carrying current, it is very important we have only used coulomb's law. You we have not used any further law of electromagnetics. But, if you take coulomb's law and you simply add the fact that the moving things according to Einstein get shorter, you just take that piece of information you immediately conclude that current carrying objects attract each other. Now, once you have this idea question is why cannot we just use coulomb's law and go ahead with it and answer is you can.

In fact there is an exactly what the theory of relativity does. The theory of relativity does not have electric and magnetic fields if does have only electric fields. But the electric field representing it in a way that relativity it finds that useful. It is a very complicated business the mathematics of relativity is not simple. But if you actually work with Einstein theory of relativity you do not have an electric field and a magnetic field we have only electric fields and the theory is at a conceptual level very simple. However the mathematics is difficult. The result is that when you come down to using it in simple cases we tend to break up coulomb's law into two pieces.

Coulomb's law when things are stationary and there is net charge that is a normal coulomb's law and coulomb's law and there is no charge but there is moving particles. And for that second case relativity, relativity tells us there is a force we introduce a new concept. But you can see directly that if you have currents there will be a force between wires and this was measured. Now the way we do force calculation becomes complicated because there is no charge here.

So, I cannot put q divided by distance I cannot do any of those kinds of um actions. Furthermore it is fairly clear that it is the velocity that is going to create of force and even more it is clear that is going to be V squared. So it is a square of the velocity that is going to give me a force. So there we need to do some additional work to pull out such a fakes from what we have. So, what we do? Well, historically what people have done came from another theory all together.

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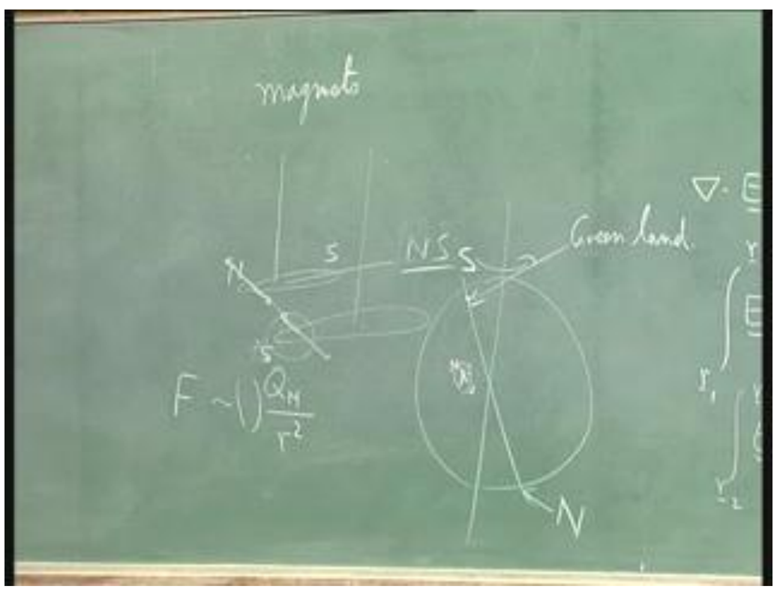

From way back they knew that there was, certain objects magnets that tended to point in certain direction only. If you took a string and you took a magnetized object and you weighted for it settle down it could always point in the north south direction. After fair amount of time, people realize this is because the earth itself is a gigantic magnet. This is the direction on which the earth spins and this is the magnetic axes coming out somewhere in green land and down here I suppose south of Australia. The strange thing you should always be aware of is that at Greenland is the south-pole of the earth and near Antarctica is the north pole of the earth.

If you put s anywhere say, in India, the south pole of the compass wants to point towards the north-pole. So it will turn around till it points towards the north pole of earth. So, north-pole of the compass will try to point towards the south-pole of the earth. This experiment people have done. They brought two magnets and they could identify which was the north and which was the south pole of each magnet. They found that they brought two north poles closed to each other then there was the force between them which was repelling.

Whereas, we have brought on north-pole and a south pole near then the force was attracting and it was also known that this force was inverse square law. It was just like coulomb’s law. In fact if you wrote if you took only the force on a pole of a magnet and you ask what is the force on that pole, you found that the force went exactly like this strength of that pole. Let us say I call it Q magnetic times normalization number divided by r squared. And the direction of the force was infact having to do with the direction of the magnetic field. This was seen this is known.

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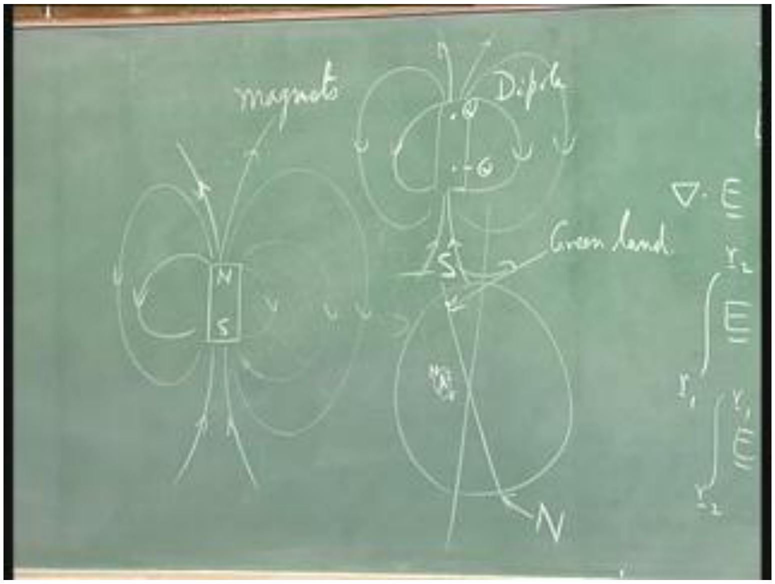

And once the thought about it, is it supposing you take a magnet a bar magnet call it north south and you take lots and lots of ion filings you have done this experiment in school. They found that ion filings tended to tended to arrange themselves in a pattern. So, all this was known. But now having done coulomb's law we know something else, we know that if you take a positive charge Q and then a negative charge Q and you work out the electric field due to this electric field looks like this. In fact it looks exactly like the ways of ion filings arranged themselves cue to the permanent magnet. The electric dipoles this is a dipole because you have a charge and a negative charge.

The electric dipole and the magnet are identical. The effect of the electric field created by an electric dipole and the pattern created by a magnet are the same. So, there is a clear parallel between whatever happens in coulomb's law and whatever is being seen with magnets. This was the state of things may be around the beginning of the 19 century. So, they knew lot about magnets. Magnets are used in practice because shifts required magnets to navigate when you quite a bit about electricity because that had become a very practical subjects. But they could not combine the two. That was where it was until people start at studying current in wires.

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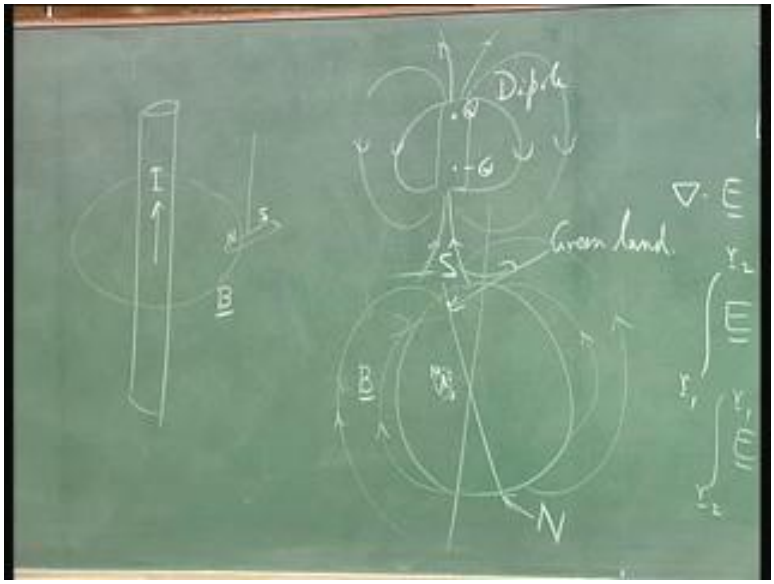

And they did it something interest. What they did? First they took a wire. They do a current thorough it and then took a permanent magnet with a north and a south and they brought it near this wire. Now they already knew that there was something called magnetic field defined by the magnetic field of the earth. Because they knew that earth is probably at dipole magnet, so they can draw magnetic field lines of coarse earth north pole is in the south. So, you have magnetic field lines and it was believed that the compass that we have was aligning with magnetic fields.

What they found was when you brought the magnet closed to wire carrying current, the magnet tint align itself with the earth anymore, it started aligning itself with the wire or other it started aligning itself along circular lines around the wire. So, if you look at these two pictures you can see that the same thing seems to be happening. You bring the magnitude different points, it is pointing in different direction, you take it faraway from this wire, its start pointing to the north again, so the conclusion was there is something called a magnetic field. We gave it a name B and the same magnetic field that the earth produces a current carrying wire also produces because a magnet responded to both.

Magnet responded to the earth by pointing towards the south pole of the earth. The magnet is also responding to a wire. So there is magnetic field being produced by the wire as well. Then they did many more experiments. Because they wanted to understand exactly what is the nature of this magnetic field that is produced by current because currents they knew by them they knew how to produce currents. And if you could produce magnetic field using currents suddenly the kinds of machine you could create we cane very interesting. So, they did a large number of experiments in that was a period when a lot of data was collected and when they did all this experiments, they came up with the summary conclusion.

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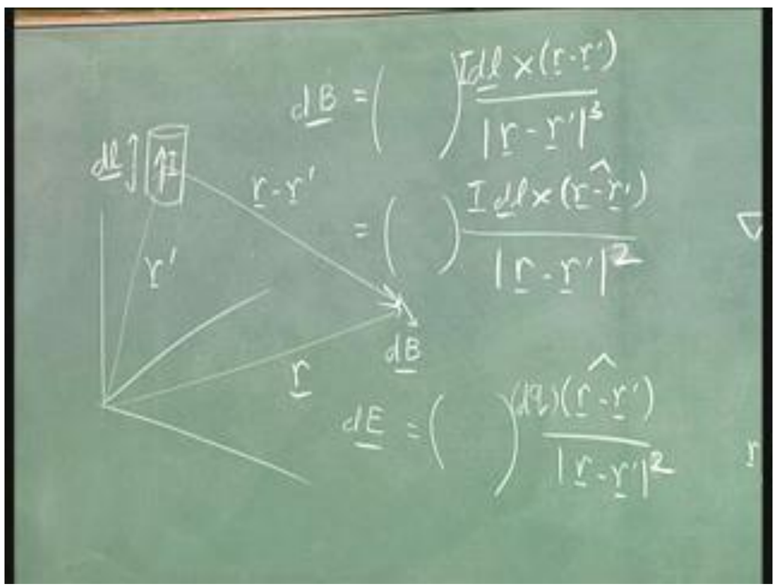

They said that if you had a very tiny piece of wire carrying a current it is not possible. This is like they did all this experiments and say that this is the mathematical essence of what we have found. Take a small piece of wire whose length is dl which is carrying a current now this dl has a direction alright and its carrying a current I and let us say you are standing here with the compass. This is r, this in the notation that will be using is r prime. I always use r for where the scientist is standing or scientist instrument is standing and r prime is where the source either the charge or the current is placed.

So this arrow going from the current element to where my measurement my magnet is standing is r minus r prime. That is because r prime plus this distance is equal to r. So, if I just shift things around this distance is r minus r prime. The magnetic field produced here because the small piece of wire its small amount of magnetic field. The formula was small amount of magnetic field produced is equal to a normalization. Constant times I dl the current times the length cross r minus r prime divided by mod r minus r prime cubed. So it is this length this direction cross this direction. So in this case going in to the board divided by cubed.

Now if I keep only the direction and dropped them magnitude I can write this as normalization constant I dl cross r minus r prime unit vector divided by r minus r prime squared. So this should be seen as very similar to coulomb's law. Because of I wrote dE it would be normalization constant q times r minus r prime divided by mod r minus r prime cubed and again if I took the unit vector this cube will become square and dE it should be dq. So it is the same kind of object and we know it should be the same kind of object because we already look at it. This magnetic force and this magnetic field is nothing more then coulomb's law and relativity. That is all.

It is the fact that moving particles get squeezed and therefore a slight amount of charges produce. So, slight that you cannot measure the charge itself. It such a tiny change one part in 10 to the minus minus 10 to the 24 no instrument can measure that but one part in tem to the four as in effect. That effect is what we are calling the magnetic force the magnetic field. Now, if you been alert you will have a question at this point, the question is we cannot create machines that are so accurate in shape in size that we can measure 10 to the minus 24. So, in that case how is, that a factor of 10 to the minus 24 is observable. In other words why does not get washed out? Sometime is plus 10 to the minus 24, sometime is minus 10 to the minus 24 we will never see it. Well, I have to take you back to the beginning of our courses.

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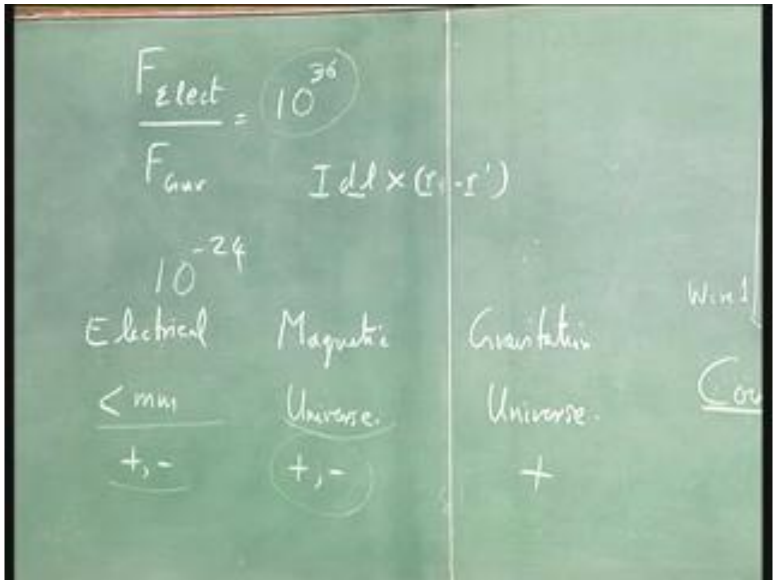

If you remember I compare these, strength of the electric force on the gravitational force, I told you that the force due to electricity divided by the force due to the gravitation was 10 to the power of 36. That is, if you take a proton, two protons and look at the force due to the electrical forces between them and take the force due to gravitation between them, there is a factor of 10 to the 36, the electrical forces 36 orders on a magnitude stronger. It took electrons something like 10 to the 43. So these are huge numbers and I asked the question why is it that ever see gravitational force.

The truth is we only see gravitational force we rarely see electrical force and the answer was that these electrical forces come in two signs positive and negative and they adjust themselves, so that they cancel perfectly. This cancellation is so good that 36 orders magnitude a cancelled out within a few centimeters or within a centimeter and anything beyond a centimeter or two it is gravitation that dominates and not electrical forces. See if this could a cancellation that gravitation starts dominating then clearly a force that is merely 10 to the minus 24 of electrical force is a very strong force.

It is 12 time 12 orders of magnitude stronger than gravitation and that is why even though the magnetic field cannot be measured as a fluctuation in charge its effect is extremely strong. And that is also why if you look at the scale at which you observed phenomena you see electrical effects. They are usually seen at very short scales atomic scales molecular scales, maximum you will start seeing them for a few millimeters okay very small less than milli meters. But if you start asking magnetic effects the earth magnetic field is planetary dimension. The sun magnetic field is even larger and the galaxy as a magnetic field. The magnetic field has this scale which is of the order universe itself.

There is a cosmic magnetic field gravitation is again this size of the universe. So, the difference is electrical forces are extraordinarily strong. But the cancel extraordinarily well magnetic fields do not cancel that well, but they very weak. So on very short skills the magnetic field does not really show up. But longer scale the magnetic field dominates over the electric field, but the magnetic field still has one problem. You go to the equation it says I dl cross r minus r prime. See, if dl changes sign or I changes sign here positive and negative currents then the net effect of the magnetic field is zero. So just like you have positive and negative charges you have positive and negative currents.

But you only have positive mass. So this is the reason why as you get a larger and larger scale the magnetic field loose out to gravitation. Because gravitation keep building up it, there is a very slowly it is after all 40 orders are magnitude weaker than everything else. But if you go 40 orders in size, then that is the only thing around because every piece of mass pushes in the same direction. Whereas the currents the drive a magnetic field tend to start canceling and the result that the magnetic field even though it out loss electric fields, you see it larger scales is much much weaker than the gravitation okay. So now we have this formula. Let me look at what this formula is saying.

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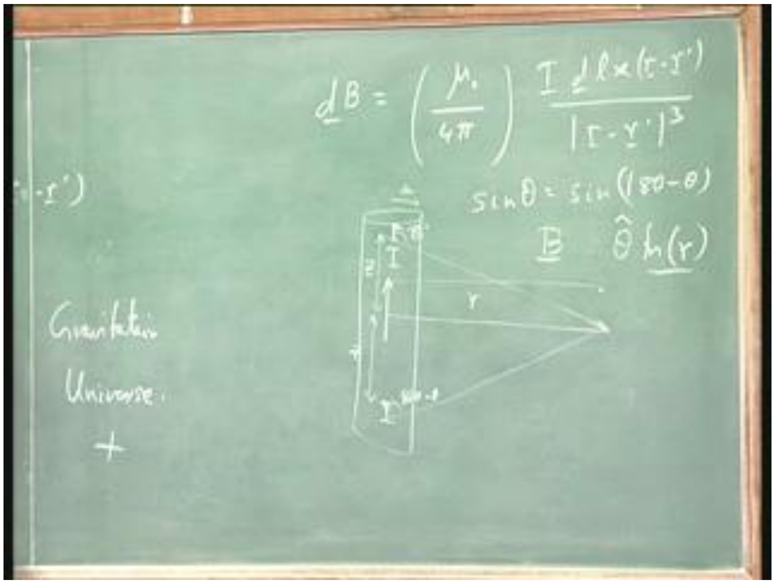

dB equals I am going to put in the mew not over 4 pie this is the normalization constant that comes out of si unit I dl cross r minus r prime divided by r minus r prime cubed, very complicated looking equation. Let us see we can use it and extract what this magnetic field really should be. So, I have a wire the wire is carrying current I am assuming my wire has a very small radius a negligible and I want to know what the magnetic field is at some distance r from the center of the wire. Now this wire is straight long wire. So clearly whatever magnetic field I calculate here it will come from I dl here it will come from I dl here.

Let me take a piece that is a height z above and height z below. If I join this current element to this observes point, then you can see I cross r minus r prime that direction I do the cross product I have to use my right hand rule. That is, I take my right hand pointed into the board and try to screw a right hand screw. Starting from the first vector, going to the second vector, so, it gives me a value here. Now if I do the same thing here it also gives me the same value except that in this case the value is greater than ninety degrees. In this case the value is less than 90 degrees. So some theta this is 180 minus theta.

But both sin sin of theta is equal to sin of 180 minus theta. So both of these give me the same force and the force is into the board. So I just take pairs of point pairs of ideal and keep going to the top and the bottom and I will get some number going into the board. Now if I choose a points slightly above, well this same argument will hold this is, the wire is long enough I will get the same answer for the magnetic field.

So, whatever answer I get for the magnetic field B is along the theta direction and it is a function of r is not a function of z. Because its move slightly up it does not make any change to my calculation and it is not a function of theta that is fairly obvious. So, B is in to the board as a function of r only. If I now try to calculate this number, let us see what I get. I have my wire because it can be any z I am going to choose z equals zero, this is r and I am taking a piece that is z above and z below.

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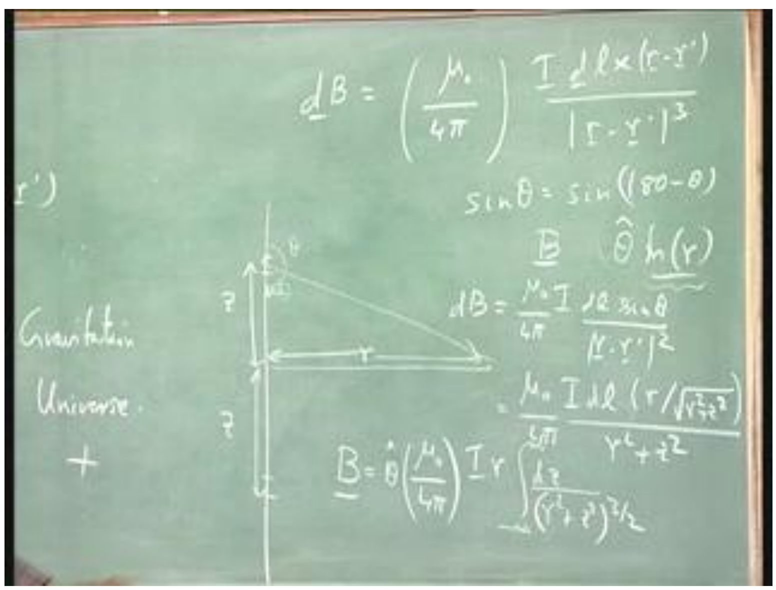

I know that B is in the theta directions so all I need to know is do it is calculate the magnitude. So I get dB is equal to mew not over four pi that current I dl the dl cross r minus r not is just going to give me a sin theta divided by r minus r prime squared where the theta I am talking about is this angle. That is, this dl divided by this I mean the angle between this dl and r minus r prime. This angle I want sin theta so sin of 180 minus theta.

It is a same. Same sin for both of these is r divided by hypotonics. So its equal to mew not over 4 pi I dl times r over square root of r squared plus z squared divided by this square of this distance which is r squared plus z squared. So the total magnetic field B is in the theta direction and it is equal to mew not over 4 pi.

I can pull this r out times integral minus infinity to infinity dz divided by r squared plus z squared to the power of three halves. I am not very interested in what the answer is. We are going to find a better way of calculating the answer. What is more interesting is to understand that there is something called a magnetic field. We have identified it because if you put a magnet anywhere in this room it will start pointing north. That is same magnet tends to point in other direction the theta direction near a wire. So I can calculate that be using this formula and then I calculate for any kind of wire not just as a straight wire if you give me a loop I can use the same calculation. But what use this is be?

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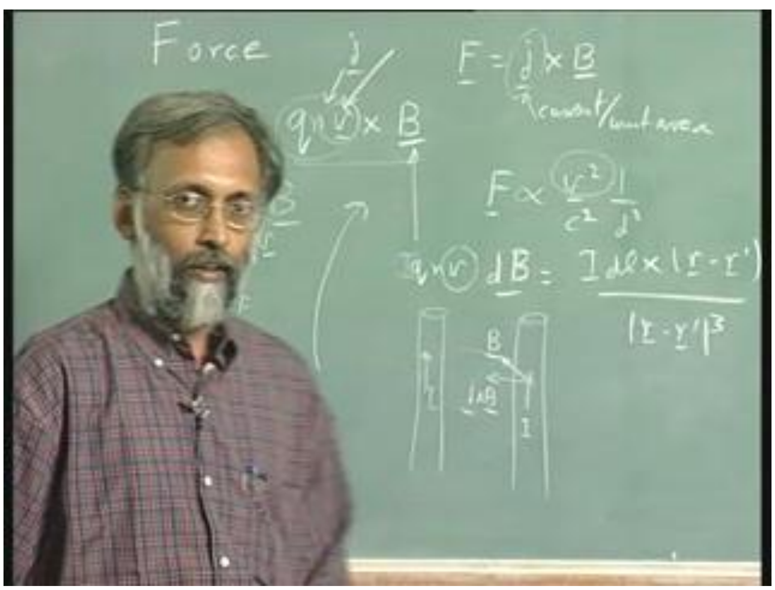

So you need a second equation you need a equation that gives me force given the magnetic field and answer for that was if you calculate B and the force due to that B is equal to q v cross B. That is, if I have a magnetic field it is some general direction and I have a charge q and the charge is moving with the velocity v. Then I take that velocity cross this magnetic fields and I will come out to the force F which is q v cross B. And if you take many charges and have them all moving together then this q v multiplied by n that becomes j.

So the force is some time also written as force is equal to j cross B, that is the current density cross the magnetic field is the force per unit volume. This is current per unit area and this comes just from the fact that q v cross B is the force on one charge. If I have n charges it will be n times q v cross B but n q v is nothing but current density so you get j cross B. Now it is very important to understand how this picture connects back to the original picture I have brought the original picture we had let the force was propositional to v squared over c squared because v squared over c squared was the amount by which the length reduced and therefore that was a measure of the coulomb's force. And it was also propositional to one over d squared that distance squared.

Now where do, this v squared come from? Well, there is one v here qnv. So the v comes here but there is another v here because this magnetic field is due to current, right? Current is nothing but qnv. So there is one v here and there is another v here. So there is a v squared which is the same v squared that we saw in the original picture. So it is after all the same picture magnetic field force is the same picture that earlier we had. Supposing you have two wires carrying current this current this current would cause a magnetic field, magnetic field would be in this direction B and then you would have a second force it should be the force j cross B there will be a j cross B force and the force would cause these two wires to attract each other.

The same argument if you used um the coulomb's law you would say because of the current the electrons are moving electrons are compressed. So there is net negative charge and because of the net negative charge the positive atoms here get attractive. Similarly there is net negative charge here the positive atoms here get attractive and so there is the coulomb attraction which is propositional to v squared which is the same answer we are getting here. The one over d squared came from coulomb's law which is the same answer we are getting here itself.

The picture I have given here is not the picture that is there in your text book. In your text book we go immediately into the bias servo law immediately says dB is equal to I dl cross r minus r prime over r minus r prime cubed and works out the consequence of that. Now that is perfectly alright. I mean calculating thing there is a formula you need. However it is a very unreasonable equation just to accept, it is saying that current is in one direction and the distance to observer is another direction and the force in the magnetic field is in the third direction. Why should that be? And that is why I brought this other ideas in the magnetic field is not an independent field magnetic field is just another aspect to coulomb's law.

However it is convenient for calculation from mathematics to treat as another field. Whenever you have whenever you introduce velocity into coulomb's law you are going to introduce magnetic field because of relativity. And because of relativity you are going to have v squared coming in which is two currents v implies a current and v squared will imply two currents. So interacting currents give you magnetic force and that is what we get here interacting currents giving you a force of attraction. All this ideas we are going to make more precise in a next few lectures and we will go back to following your text book. But I at least do not find it very comfortable.

You just jump into formulas and start using them. So, that is why I have introduced these concepts in this more round, about way so that you will feel there is some reason why the magnetic field exists. Magnetic field is not an independent force at all the moment you set coulomb's law all the remaining equations of electromagnetics are pin down. Just by adding relativity all four equation of Maxwell are fixed. There is nothing new that happen because of magnetic field. It is all implied by the electric field itself and the reverse is true if you wrote down the magnetic field equation and then used relativity you can predict electrostatics okay.