Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Applied Electromagnetic for Engineers

Module – 01
Introduction to Applied Em

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Hello and welcome to this NPTEL mook on applied electromagnetic for engineers, so most of us are introduced into this world of electrical engineering by a subject called as electric circuits if you remember what a circuit is a circuit is a simple interconnection of components right or circuit elements you are familiar with circuit elements which are passive or active passive circuit elements such as resistors inductors capacitors transformers you know you can take these different elements connect them in a way you want and then create a circuit.

Right you can also take and connect a few of active elements such as diodes field effect transistors or BJT's and so on you can connect active and passive circuits together in order form whatever the functionality when you connect these elements right I mean you study these elements in the form of circuit theory you have almost never encountered anything about the behavior of a wire.

So let us say you have a resistor here and you have a capacitor here and you want to connect this resistor and a capacitor the way that you would connect would be to take some wire and then you just connect the wire and you want to implement these circuits on a breadboard or on a printed circuit board you place these components at appropriate places and then just take a piece of wire and connect it in fact you might be remembering if you remember your lab courses that when you connect to elements by a wire you do not normally concern.

You are not concerned about the wire length or the wire shape most of you would have connected it in the form of a bent wire but you do not worry about what should be the degree of the bend what should be the angle how much should be the length should I twist it should I not twist it because sometimes your wires do get twisted but none of this would have mattered to you in while you are constructing these circuits and making experiments in the lab and performing experiments in the lab.

You would be very surprised to learn that a simple element such as a wire which we take as nothing but a connection between two elements or two chips or two modules on a larger mother board or our daughter board structures can actually generate lot of problems for you can give lot of problems for you because a wire at certain operating conditions is not just a wire but it will have its associated inductance capacitance resistance and conductance.

And that theory is called as transmission line theory and we will begin this course by studying transmission line theory okay, so as I was saying we are introduced to circuits and while we are while we study mathematically these circuits the interconnection of all these elements we almost never worry about the wire okay let us actually look at couple of hypothetical cases you know I will give you some sort of puzzles to you which you would if you think about it will tell you the importance of wire in electric circuits.

And then why electric circuit theory cannot deal with these effects and why electromagnetic should be involved in order to study these effects consider a very simple example okay.

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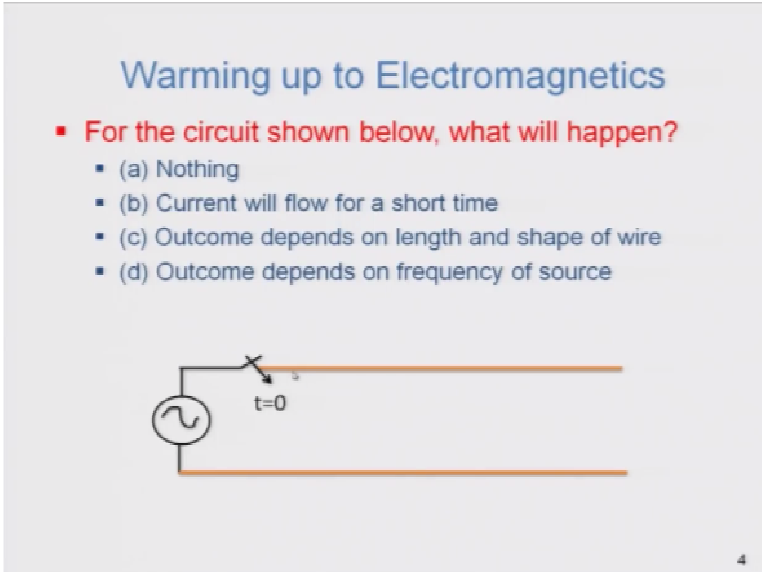

We have a circuit out here which I have shown okay, so you look at this slide here you have an circuit shown here or probably there is not even a circuit here is what you would say but because I have a source here which I have denoted by some you know sinusoidal one it need not be sinusoidal and it could be just a battery that I have connected okay and what I have these orange lines are too long wires, so they are like no ordinary wires but you assume that these wires are about say 10 meters are about 15 meters right.

And this is a switch which I will connect at t = 0 so I will bring down the switch here and once I bring down the switch I ask you this question what will happen now based on what you have studied you might answer differently let us say you will look at the circuit and say well nothing should happen because I have a source and I have a switch once I close the switch there is nothing for the source to deliver the current into therefore nothing should happen but some of you might wonder differently you might remember from you know physics electro electricity and magnetism.

That when you have an uncharged piece of wire when you connect a battery to it you are kind of charging the wire right, so you are kind of transferring charges from the source which is battery onto the wire, so you would say that well current flows for a short time but then the current has to die out because there is no complete path for the circuit current to flow therefore current flows only for a short duration of time.

You might argue sometimes that the information is not sufficient because you want to know what is the length and shape of the wire right although that might not be your first answer but some of you might really wonder and say that the problem statement is incomplete unless you specify what is the length and shape of the wire then some of you might also argue if I replace a battery with a sinusoidal source that the outcome actually depends on the frequency of the source so these are some of the know options that you might think over and what I want to do is to discuss these options one by one.

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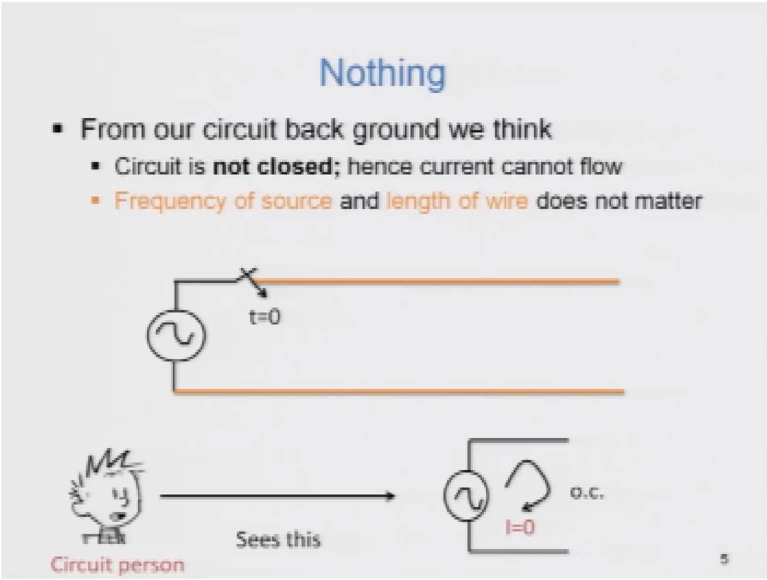

And then look at what is you know the correctness of each option okay first those of you who would think that nothing should happen you might be thinking about a circuit and you might know that for in a circuit for the current to flow you must establish a complete path since in this circuit that I have shown there is no part there is no connection of the top wire to the bottom wire right.

So there is the path is incomplete and circuit is not closed hence current cannot flow and you would also say I do not care what the frequency of the source is I do not care what the length of the wire is I do not care even what he shape of the wire is.

Because the circuit is not closed there would not be any current so if you actually think in terms of a circuit you would see that a circuits person which I am referring to by this cartoon picture over here what this cartoon picture sees the circuit person would see is a battery connected or a sinusoidal signal source that is connected to wires and at the end terminated with the open circuit of course I am not terminated anything it is just that I have left the two ends

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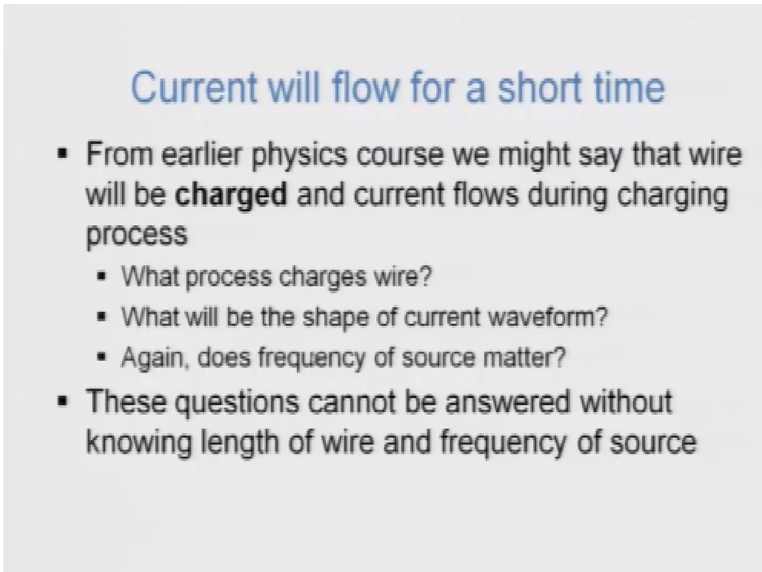

As it is and it is an open circuit well current is zero and those who said that current would flow for a short time you are thinking might have been that from your earlier courses you know that the wires which were uncharged tack type they had to be charged and during that time the charging current must flow but eventually you're right the charging current cannot flow continuously it has to stop at some point it has to stop so what is the charging process what process causes charge of the wire.

And how would the charging current look like even if it flows only for a short duration of time what would be the charging current waveform the shape of the current waveform again does it depend on the frequency or does it depend on the waveform of the voltage source that you are connecting these are the questions which unfortunately cannot be answered by circuit theory and certainly these questions require us to know the length of the wire and the frequency of the source much more than what I have specified here.

So this is slightly better answer than the earlier answer because physically it is correct once you connect an uncharged wire the charging current flows but then eventually the charging current has to die out okay we still are looking at the length and the shape of the wire.

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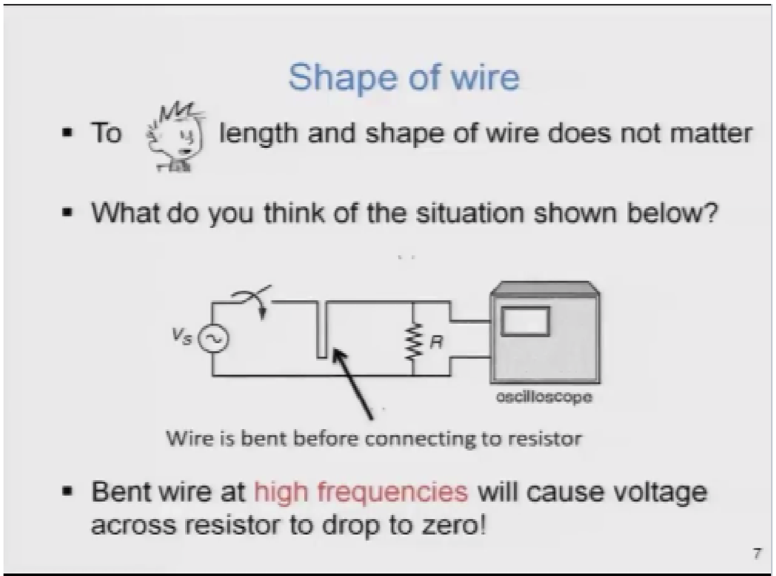

So we this time change the no experimental hypothetical experiment which you are of course also can perform in the laboratory two slightly different things now we know from circuit theory that length and shape should not matter but what I do is I take the same sinusoidal signal source okay and then I have a switch here I close it at T = 0 but then instead of sending one wire you know without any change I bend this wire before connecting to the resistor okay.

You can see that I have bent the wire in this way and what I see on the oscilloscope is that at very high frequency that is as I start increasing the frequency of the source here you will see that the output voltage across the resistor will actually drop to zero now that is something that is very unusual to happen right why should the resistor I mean voltage across the resistor go to zero that resistor can go to zero only when the impedance of this part of the wire would start to look like a inductance right.

The impedance of an inductance will be very high which would absorb all of the voltage across it and therefore drop the voltage across R to be 0 an ideal infinite frequency the impedance of the inductor would be infinite and no current would actually flow again so this is something that you can appreciate but the question is how can I piece of wire which I have bent in a particular way can induce inductance or inductive effect I mean how can a wire act like an inductance that you have not studied in the circuit theory it is something that is quite puzzling if you think about it okay.

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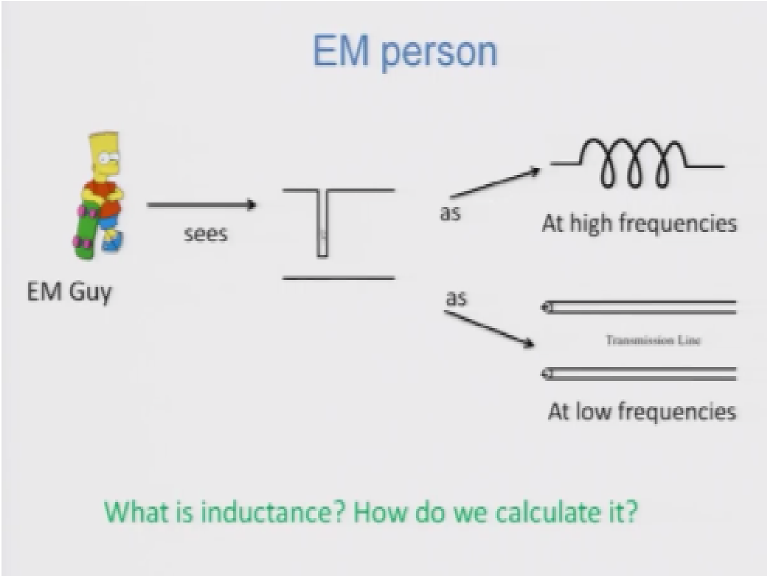

What really is happening is that when you see this kind of a wire that is bent you would see them as an inductor so you have to have feet at a different element and you would actually start seeing this one at a different element called a transmission line at different frequencies right this is say very high frequency this is at mid to high frequencies okay but then the question is what is meant by inductance.

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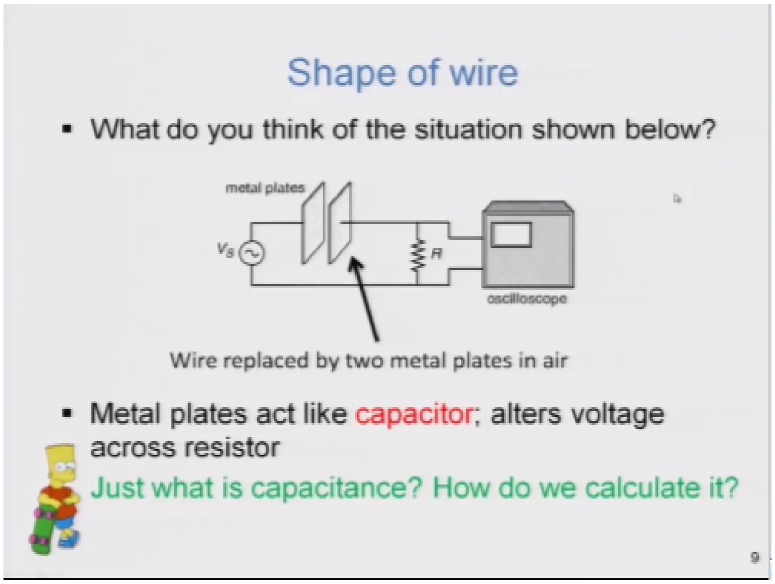

And how do I actually calculate this inductance right so we have never been told in circuit theory how to calculate inductance we are only given an inductor and you want to look at what is the behavior of an inductor now instead of an inductor or wire now what I do is I take two metal plates so these are wires that are coming out but I take two metal plates and then connect this one clearly you would know from your earlier circuits courses the two metal plates will have a certain area.

And if I fill this region between the two metal plates with some dielectric or an insulator this arrangement will be that of a capacitor correct again my question is how do we calculate capacitance what happens if instead of taking a square metal plate if I replace them with circular metal plates would the capacitance change yes the capacitance changes but how do I calculate the capacitance right so how do I calculate all that.

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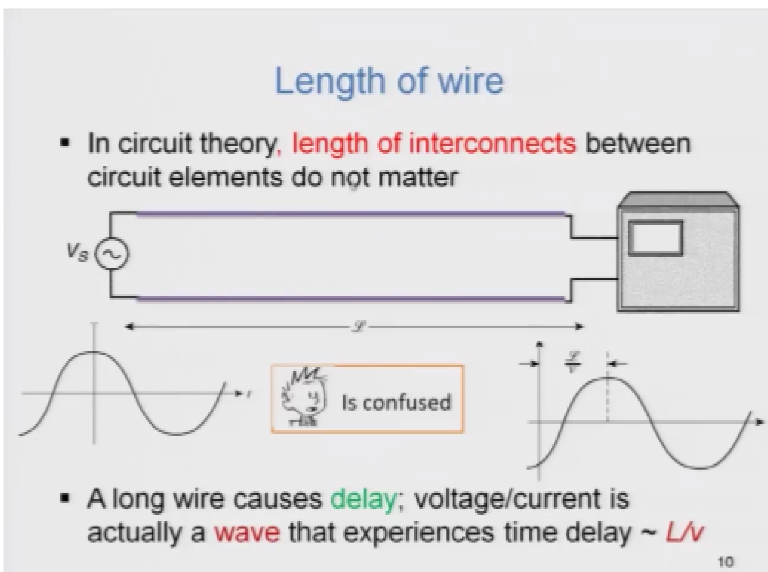

And finally coming down to the length of the wire in circuit theory the length of the wire and a fancy word for wire even in connect the word interconnect is quite popular in the micro electronics and VLSI community where it connects any two modules these modules could be as simple as two elements register and a capacitor for example or it could be a driver card you know driving a or you know or the microprocessor driving a address driver or a decoder or whatever that is.

So it can actually be used to refer to connection between two modules or it could be used to refer to connection between two elements and any such collection is called as an interconnect we call a wire and we specialize only two wires because in our case interconnects are only metallic wire okay at least the ones that we are dealing for quite some time into the course are interconnect means only metallic wires because you can also have optical interconnects you can just take a optical fiber.

And then connect two modules or an optical waveguide and connect two modules or an optical waveguide and connect two modules but that is not what we are considering here .What this experiment is trying to do is that I have a source here I do not have to switch it on at a particular time. Let us say it is there on for quite a sum time and then I am looking at the output.

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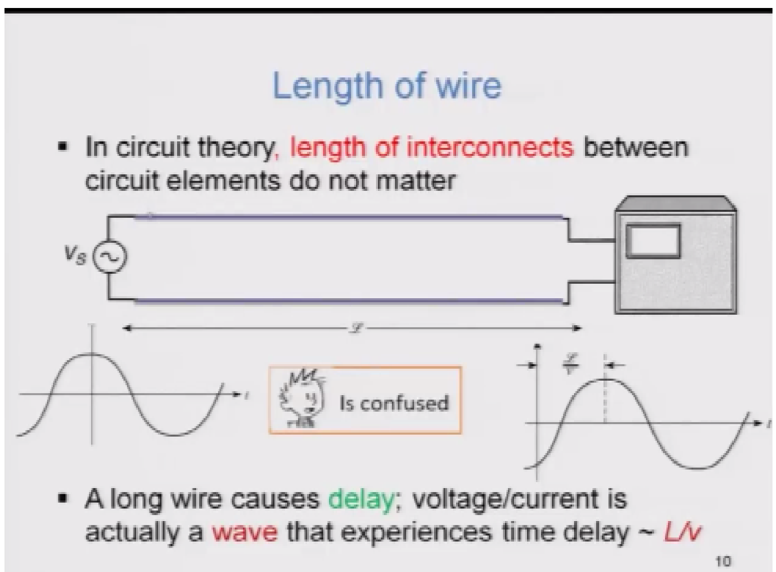

Okay now if I connect the hypothetical oscilloscope here that is right at the input terminals I will see a sinusoidal voltage like this. Right so here your sinusoidal voltage with a peak at some T = 0 please remember this waveform has been switched on quite some time ago therefore it is actually the voltage that is changing.

Right this is with respect to T and I have placed my hypothetical oscilloscope here. I will also place an AI pathetical or a real oscilloscope at this point okay and then look at the voltage waveform as shown by the oscilloscope. Okay both let us say are triggered at the same time I have somehow ensured that they are triggering at the same time.

Okay and what you see here would again be a sinusoidal wave which is what you expect because this is just a wire. But there is one thing that you cannot explain why that is the voltage waveform that is appearing at this oscilloscopes being delayed. A circuit's person would simply be confused why should there be a delay or delay showing up as a phase shift of the voltage waveform.

At this end compared to the voltage at this Android Y the circuit person is confused why is there a delay because the circuits' person has been told that the length of the wire does not matter. The circuit model for this scenario right I am using a word model in the sense that I am capturing the essential features of this experiment.

So if I make a circuit model for this there will be a source and there will be a nozzle of scope the wire would simply not be part of any meaningful entry out there. So the model does not include wire or it includes wires but it reads wires as just an interconnection with zero effect on the circuit it is only job is to connect the source to the oscilloscope or connect one circuit element to the other circuit element. So this person is confused and in fact if you start extending the length of the wire then this delay would be even more.

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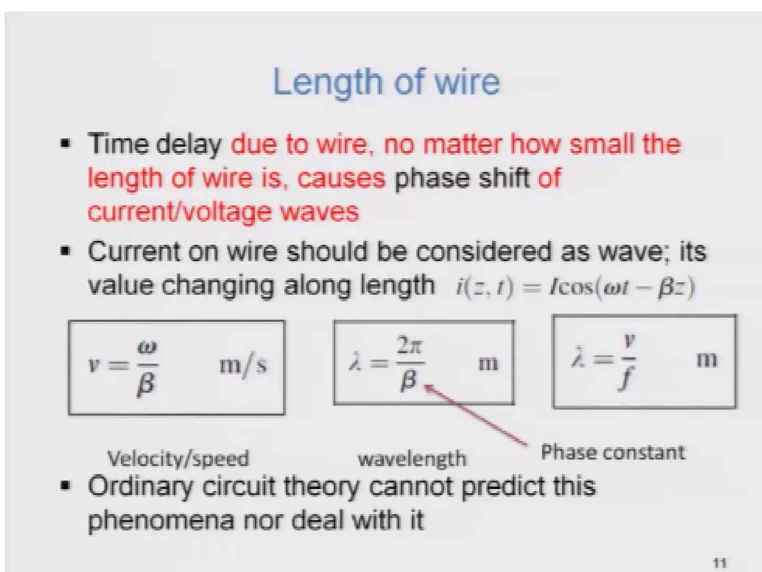

Okay so that is something that is confused the reason that happens is because circuit theory is actually only an approximation to the true behavior of a wire a wire no matter how short physically it is. It will still have some amount of physical length and we know that no disturbance that we turn it on at one end of the wire can travel faster than the velocity of light. Right so no disturbance that you create maybe you are connecting a voltage source which is kind of a physical disturbance because it has to charge the wire.

Right and this charging process cannot happen right in no wind fill it velocity in the sense that it cannot happen instantaneously there will be some delay at least Einstein tells us that there has to be a delay and we all know that is the truth because lot of experiments have been performed. So no matter how small the length of the wire is there will be delay. Delay causes phase shift of this current and the voltage wave so you might argue one thing us go back to this scenario.

Okay I take a voltage waveform here instead of collecting this long piece of wire I simply connect a capacitor right and then I look at the voltage across the kappa and current through the capacitor do not ask me how but we can do that one okay let us we assume that we can do that when actually you will have to use a small piece of resistance to do all that because capacitors ideal capacitors cannot dissipate any kind of energy.

Okay so I have to use a small resistor but let us say we use a resistor and we look at the output we know that in a capacitor the voltage leads the current by a bulk 90^0 correct so we have that voltage lags the current by 90^0 it is the current which leads the voltage in a capacitor by 90^0. So there is a phase shift here also you see a phase shift in this circuit there is a phase shift across a capacitor.

So are not these two similar why am I telling you the Circuit Theory cannot explain this behavior there is only one catch here the catch is that I am looking at the voltage at this point of the wire and I am looking at the same quantity. I am actually looking at the voltage at this point of the wire that is at the one end of wire I am measuring the voltage at the other end at the end of the wire again I am measuring the voltage.

I am not measuring current so I do not actually expect that the voltage will have a phase shift right the relationship of voltage current in an inductor or a capacitor is actually for two different physical quantities. One for voltage and one for current here the relationship is actually for voltage at one end of the wire to the other end of the wire.

Right you might then ask why is I really concerned about that I know why should I be worried about all that? There is a very good reason if you are especially you know going to work in the digital hardware kind of a thing. I mean this is just one example there are lot of other examples where this kind of a behavior of a wire will be important in microwave center. Does but this situation kind of shows you very interesting thing that actually happens every day in your high speed processors

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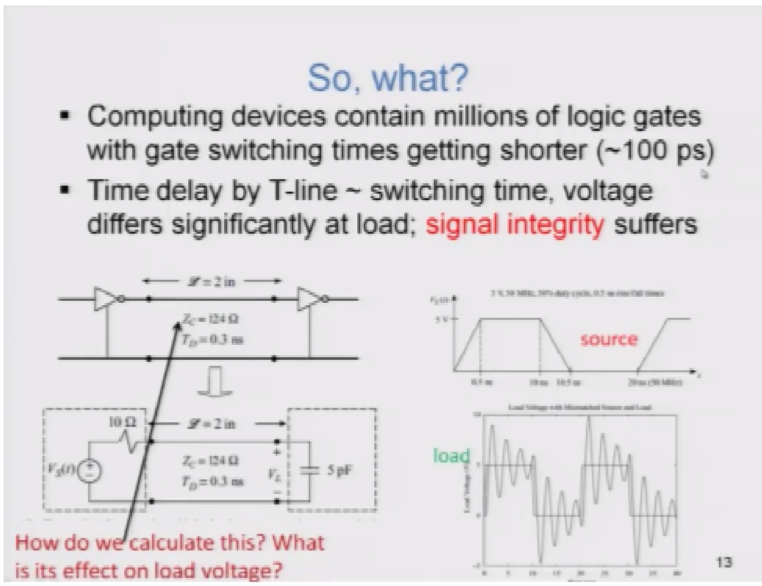

Right computing devices actually consist of millions of logic gates and these logic gates are always in the change in the state of changing. You know some bit is going from 0 to 1 some bit is going from 1 to 0 on one piece of the output line and the other output line is going to 0 the other output line may be going to the tribes.

These logic states are all changing at the output and these switching times are getting shorter and shorter today switching times are approximately100 picoseconds. You can imagine you know this is a very small time right but the wire that we connect are not able to instantaneously transport this logic state on to the other end that is thesis a driver and this is the load whatever the drivers changes this drive change voltage is happening at 100picosecondsunfortunately my wire being a physical length of a wire cannot really transport.

That to the other end you know in zero time so because of that you will have to deal with the fact that the wire is not you know ideal it has delay and what is the implications of this delay it also turns out that the wire does more than just give you delay it also has inductive and a capacitive type of behavior so we need to understand completely the model of a wire to better represent this situation and to avoid having this kind of a behavior you can actually see that if I somehow do not manage or match this load and the source then my voltage waveforms do not come out as expected but they will have lot of non idealities.

The distortions overhear so one of the objectives of understanding electromagnetic behavior of a wire is to predict and minimize this type of distortion okay and we do this by a process called as translation line right transmission lines.

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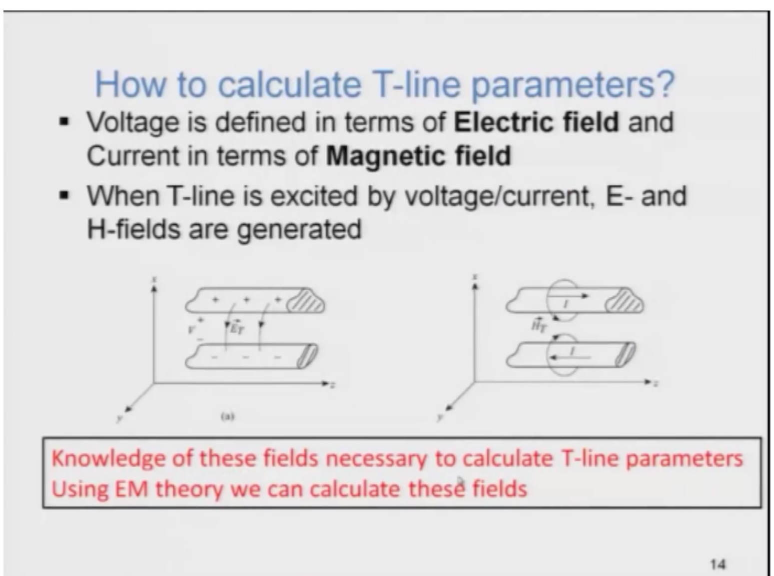

As I said will you know we will talk more about the transmission lines this transmission line will have described the parameters of this transmission line by resistance inductance conductance and a capacitor and these quantities are all connected to electric fields and magnetic fields so if you want to calculate how to calculate that if you want to calculate the inductance of a transmission line or capacitance of a transmission line you need to study electric and magnetic fields okay.

So in order to understand transmission line parameters where they are coming from you need to understand electromagnetic theory so just to summarize what we have been saying a wire.

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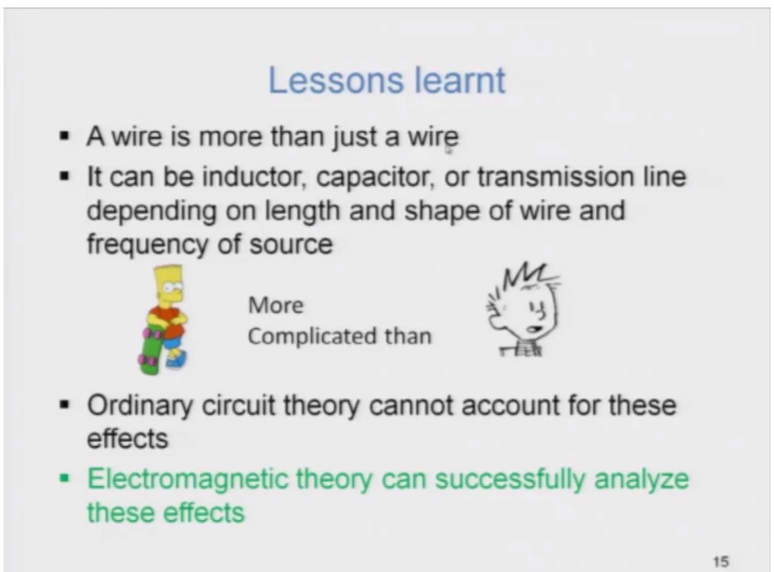

Is more than just a wire it can bean inductor capacitor or a transmission line depending on length and shape of the wire and frequency of the source so electromagnetic is slightly more complicated than just a circuit theory unfortunately ordinary circuit theory cannot account for these effects and electromagnetic theory is the one that can successfully analyze these effects therefore it is important for you to understand electromagnetic.

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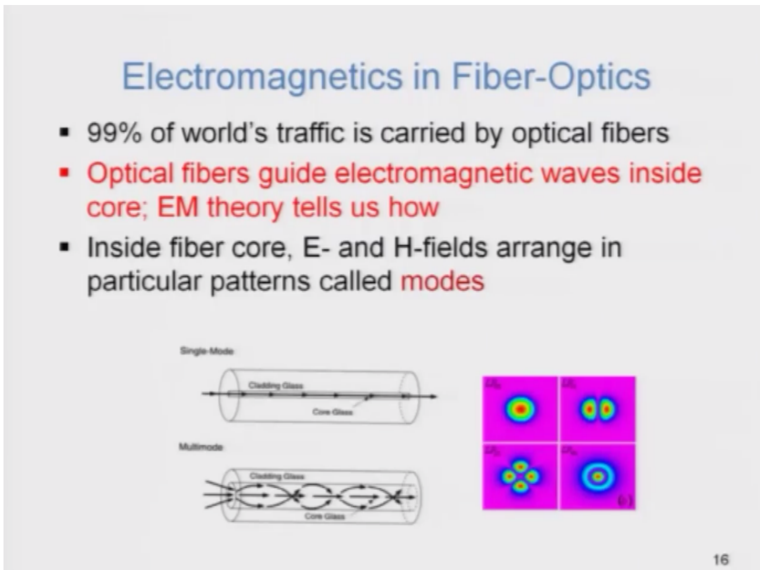

Is also important in understanding fiber optics okay because fiber optics guide light and light is electromagnetic wave how would light beguiled is given by the fundamental principles of electromagnetic is also important to understand.

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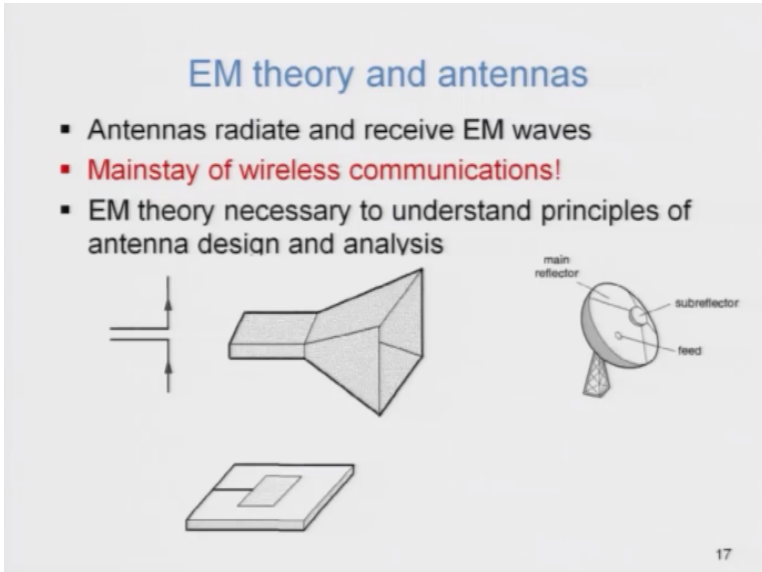

You will be seeing lot of applications of electromagnetic okay it is applied in optoelectronics fiber optics optical communications to understand channels you know behavior using electromagnetic behavior of the channels and all that in fact electromagnetic also gives you nice philosophical basis for circuit theory because circuit theory was actually developed as an approximation of electromagnetic, electromagnetic is also very important for RF and microwaves.

As well as for high voltage engineers and for antennas and propagation so we will end this module by lifting out the textbook the full syllabus and the lecture plan is given on the website the textbooks that we will be using is the primary textbook is electromagnetic with applications and these are other textbooks I will upload list of references as well as notes on the website thank you very much.

Acknowledgement
Ministry of Human Resource & Development

Prof. Satyaki Roy
Co-ordinator, NPTEL IIT Kanpur

NPTEL Team
Sanjay Pal
Ashish Singh
Badal Pradhan
Tapobrata Das
Ram Chandra

Dilip Tripathi
Manoj Shrivastava
Padam Shukla
Sanjay Mishra
Shubham Rawat
Shikha Gupta
K. K. Mishra
Aradhana Singh
Sweta
Ashutosh Gairola
Dilip Katiyar
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