Electromagnetic Theory
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Lecture - 01
Introduction to EMT

Hello everyone, Welcome to the course Electromagnetic Theory. My name is Pradeep Kumar K, and I am a faculty at the department of Electrical Engineering, IIT Kanpur. So today we will first look at what is Electromagnetic is, now before start studying a subject one has to know what is the subject that one is studying and then that essentially leads to the second question, that why should one bother studying this course.

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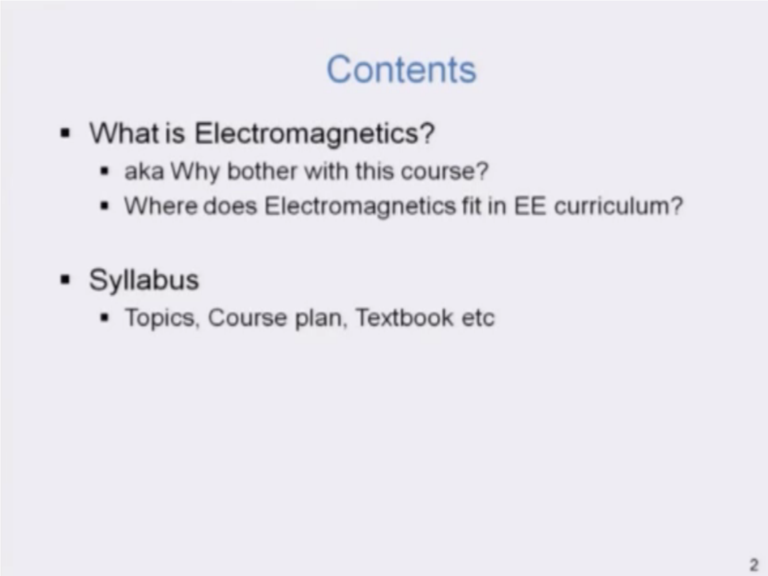

In other words, where does Electromagnetics fit in Electrical Engineering curriculum. We will also discuss the syllabus, topics, course plan, and the text book that I am going to follow in this course.

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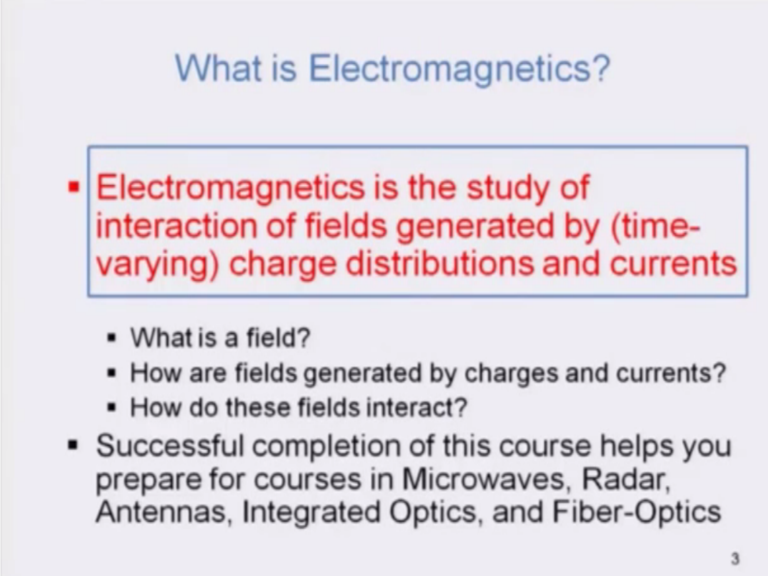

And we will begin by first defining Electromagnetics in its broadest terms. Electromagnetics is essentially the study of interaction of fields that are generated by time varying charge distributions and currents. Now this definition does not probably mean anything to you at this point because the question that you can immediately ask and that would something that you would ask is, what is a field.

We said that Electromagnetics is the study of interaction of fields that are generated by possibly time varying charge distributions and currents. So the question that should naturally come up is, what is a field. Then how are these fields generated by charge distributions and currents, how do a particular charge configuration generate a given electric field or magnetic field, and how would a current distribution generate a magnetic field or an electric field.

And then what is the interaction between these two fields. So this is a broadly the scope of this course. We will be looking at all these questions in greater detail. The reason why we are looking at electromagnetics is that, if you complete this course successfully, this is the foundational course for your advanced courses such as, Microwaves, Radars, Antenna, Integrated Optics and Fibre Optics.

So without further ado, let us just warm up Electromagnetic Theory. Most of us are coming from circuit theory background, and this course is usually taken by Electrical Engineering, Electronics and Communication Engineering, and Telecommunication Engineering students in their second or probably third year of their curriculum. So you have all been exposed to circuits, you have done couple of courses in circuits, filters, networks probably.

And you might be wondering what is this electromagnetics that one needs to study. Is not circuit enough to understand whatever that is there in Electrical Engineering?

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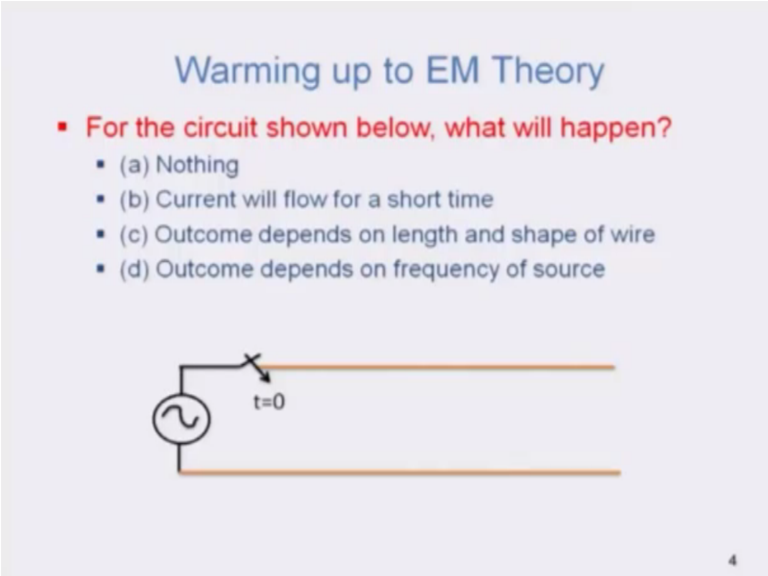

So the goal of the next few minutes is to show you where Electromagnetics is necessary to be invoked, and why circuit theory in certain situations fails to give correct answers. To do that, let us first look at this particular circuit here. We have a signal source, this signal source is possibly also be a battery, and then there are two long pair of wires, which I am showing in this, orange colour, okay.

These wires can be assumed to be ideal. Now at some time T is equal to zero, we are going to connect the two wires to the signal source. Now we ask, for this circuit what will happen. Now, one can possibly come with different answers, so the first answer that one would come up is, nothing will happen. Then one can say, no, no current will flow for some time, and then nothing will happen.

One can also say that the problem is not completely defined in the sense that I have not told you, what is the length and shape of the wire. I have also not told you what is the frequency of the source. Would all these things matter? Let us look at each of these responses individually, and we understand where the limitations of circuit theory lies.

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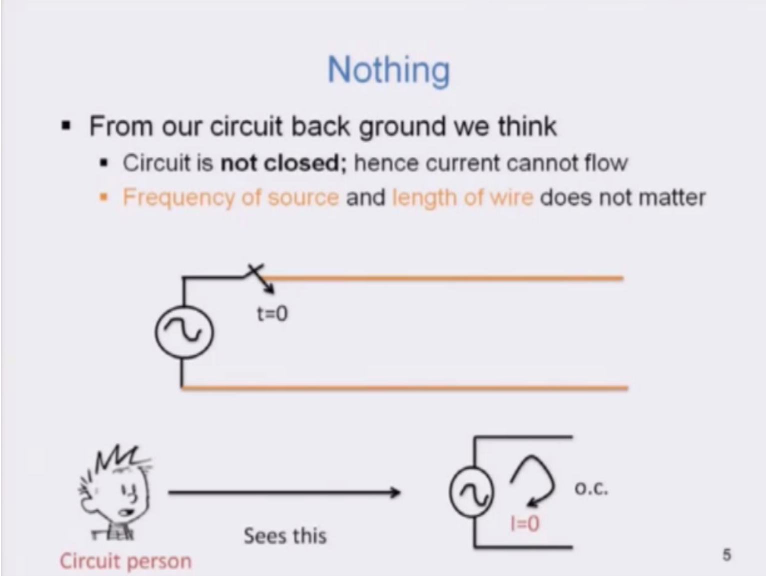

From our circuit background, we might first think that well circuit is not closed, which means that there cannot be a current flow in the circuit. Whatever the voltage that is there at the source end will directly be available at the load end, right. The open circuit voltage of the source will be equal to the voltage at the load end. Now frequency of the source and the length of the wire does not really matter to us.

Now, that is what circuit theory would tell us. So in a sense, if you are a circuit's person coming purely from the circuit background and not knowing anything about the electromagnetic field theory, you might be seeing this physical situation, in which I have a voltage source, I have a switch which is closing at T is equal to zero, and a pair of wires as something like this, right.

The important point to note is that in circuit model of this physical scenario, the length of the wire and the frequency of the source do not matter. Now, from our earlier physics course, we know that a battery is essentially source of electrons and ions probably, and if we connect that to a pair of electrodes, which are made up of metal, then there must be some amount of charging that happens.

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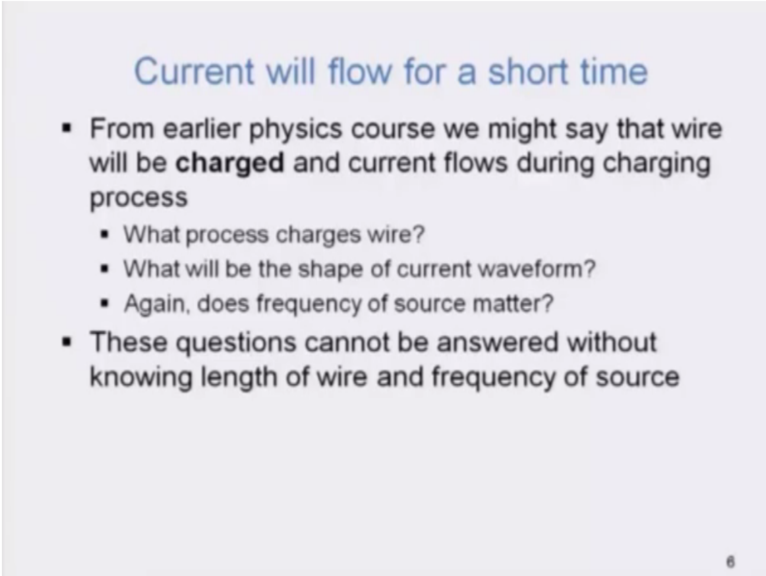

So there is a charging and this charging current must flow for some time until the wires are charged, and so the question is how exactly does this, I mean, what process causes this charging of the wire? What is the exact voltage wave formed? Does that depend again on the frequency of the source? So these are the questions that cannot be answered from the circuit paradigm, because circuit theory does not consider these issues.

So we need to know something else beyond circuit theory to answer these questions of the charging process, the shape of the current wave formed, and for how long that charging current would flow.

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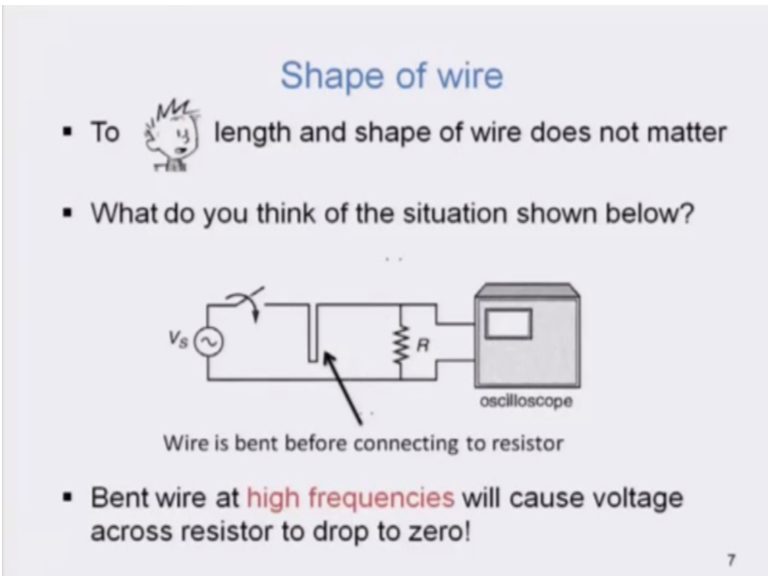

Now let us also look at the shape of the wire, I mean this is something that you can do in your lab or in your house provided you take, you substitute certain components over here. You take a signal source, or you can take a battery, does not really matter. You take a switch and then the two long pair of wires that we have considered. You take one of the wires and sort of bend it over, okay.

There is no necessary that it has to be bent in a square form, but you can just bend in anyway, but you make sure you have bent it sufficiently, okay. And then you connect a resistor at the other end, and then hook up the output of the resistor to the oscilloscope. So you can clearly see that oscilloscope is connected to the resistor end, and what is that that we would obtain at the oscilloscope from this particular physical scenario.

Well going back to circuits person, as we have already said, this length of the wire just because it is bent, does not really mean anything. The voltage after switching at this point will be exactly equal to the voltage across the resistor. So the voltage would come across the resistor and you would expect that the same voltage should be displayed on the oscilloscope.

If it is a sinusoidal wave form you would expect to a sinusoidal wave form on the oscilloscope, okay. However, as you start increasing the frequency of the source, it turns out that at sufficiently high frequencies, this wire will actually cause the voltage across the resistor to drop to zero. Now this is something that one cannot understand from the circuit point of view, because for us, for circuit people this bent wire is equivalent to a straight wire.

There is no reason why the shape of the wire should influence the output voltage across the resistor, okay.

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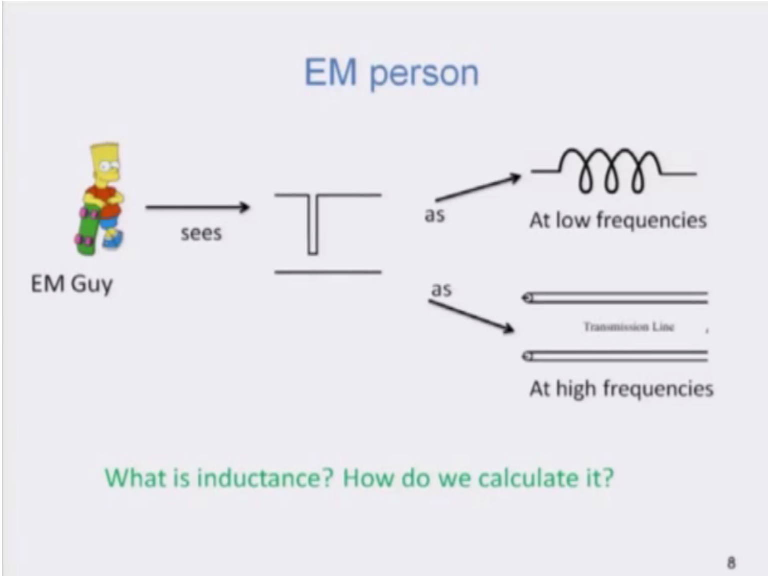

So for an electromagnetic person who will study this course, what he or she would see is that, the same bent wire plus this other unbent wire or a straight wire at low frequency looks like a inductor, okay. And at very high frequencies looks like a transmission line, okay. However, both inductance and transmission line are concepts that are not actually developed from circuit theory.

In circuit theory, if you remember we just are given that we have an inductor, we have capacitor, we have a resistor, and we are not told how we exactly calculate these things, right.

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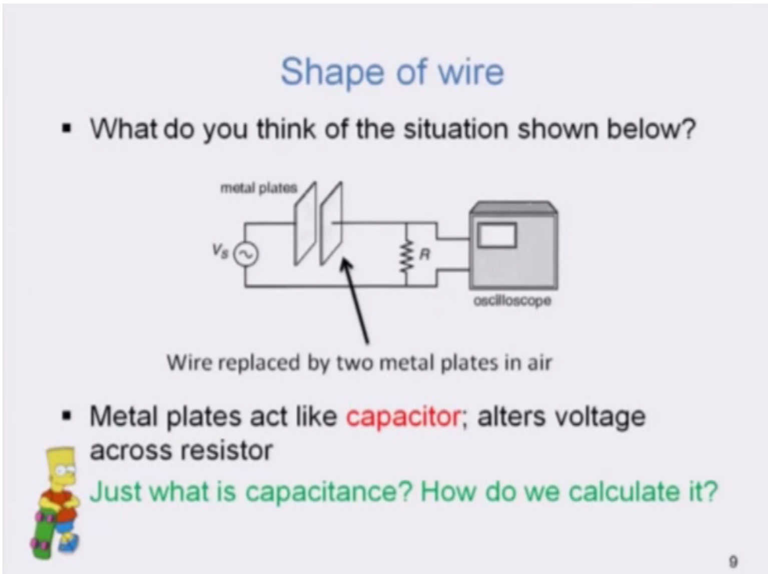

So what is inductance, and how do we calculate it, requires us to go beyond the circuit paradigm to really answer these questions. Now let us do this exercise in which we take the wire, we make it straight but then we cut the wire into two halves, and then replace the wires at the end by two metal plate. One can think of large metal plates, and then we replace this one.

Now we apply our certain voltage in our function generator and what do we expect to see at the output of the resistor. Clearly, there is no continuity of the wire between the two plates over here, because the plate is broken, there is nothing out there that will allow the conduction of electrons from one wire to another wire. However, we do know that this situation is exactly that of a capacitor, which again comes back to the same question, just what is capacitance and how do we calculate it.

We know that the current will be continuous, that is the current that is going through here must be coming out as the same current, voltage will be different phase, but the current will be all the same phase. So the current that is flowing here at one plate must also be the current that is exiting the other plate. Now what exactly goes on in between the two plates is something that Electromagnetic Theory will help us understand.

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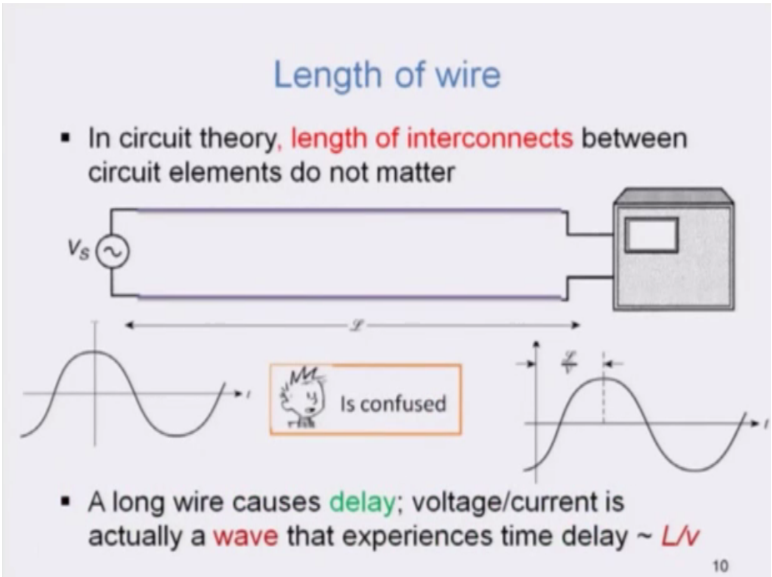

Finally, we come to the length of the wire, okay. In circuit theory again length of a wire or a interconnect between two gates or two circuit elements does not really matter. It could be any length, but what we assume is that the voltage at one end of the wire or the interconnect is exactly same at the other end of the wire, right. So that is if you can take the length of the wire to be say, one kilometre, two kilometre, three kilometres, that does not really matter.

Whatever voltage that is over here should be the voltage here. At least that is what the circuit theory would tell us. So if you apply a sinusoidal voltage that is shown over here, right. So please note where the maximum is occurring. At some T is equal to zero point the maximum of the voltage source is going through the maximum.

However, what you observe on a oscilloscope that you put at the far end or at the load side if you would think, is that the maximum does not really occur at T is equal to zero. It occurs after a certain time, and this time is L by V, right. So this is actually confusing to us, that is for circuit people, because the wire length should not matter.

The resolution of this paradox is that a long wire actually causes delay and voltage and currents are not really the scalar variables that we have thought so far. But there are other waves, and a wave that would have experience a certain time delay of L by V, when it propagates with the phase velocity of V. Now you might not really understand all these concepts at this point.

But just keep in mind that whenever you a source and a load which are separated by a long distance, there is some time delay involved, and this time delay is not taken into account by circuits, whereas this is explicitly taken into account by electromagnetic theory. Therefore, if you actually take this scenario of having a source at one end and a load at say, three or four kilometres at the other end.

Then you will clearly see that there is a certain amount of delay in transferring the voltage from one point that is at the source to at the load side. Now this is something that circuit theory does not tell you, that is the reason why we call circuit theory models as lumped parameter models or lumped circuit modelling. A lumped circuit is one in which one can simply neglect this time delay.

And therefore, there is no change in the voltage wave form, that is at the one end to at the other end. And in other words, the length of the wire does not really matter.

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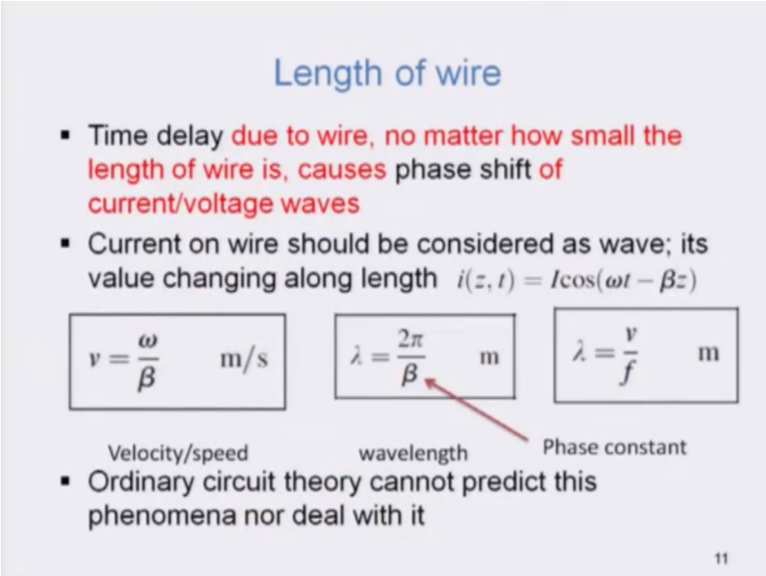

Take away from the previous slide is that there is a certain time delay whenever you have a wire that is connecting two circuit elements, and this delay can be ignored in the circuit region because of the various reasons we will talk about all this reasons in a later time. But this delay is not predicted by the circuits, whereas electromagnetic theory will incorporate this delay.

So we have to consider the time delay and if this delay is because the current on the wire is not really just independent of the distance, but it is actually a function of the length of the wire. That is if you take the direction of the wire in which you have connected as the z axis, then the voltage at any point on the wire would actually be a delayed version compared to the voltage at the beginning.

So this phenomenon of time delay and thinking of current as a wave is not predicted by ordinary circuit theory, and it cannot even deal with such phase delay effects, without explicitly involving this phase delay into circuit paradigm. So what happens at very high frequencies is that, the wires start acting like transmission line where the phase difference or the phase shift between at the source end to the voltage at the load end becomes an appreciable fraction of 360 degrees, okay.

When it becomes an appreciable fraction of 360 degrees one has to explicitly take into account the delay that is there between the source and load, okay.

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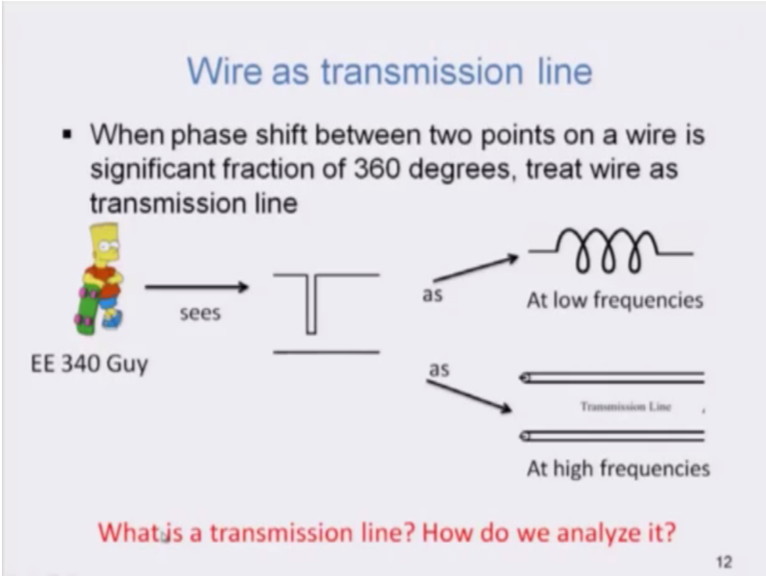

So that leads us to the question as to what is a transmission line, and how do we analyse this transmission line.

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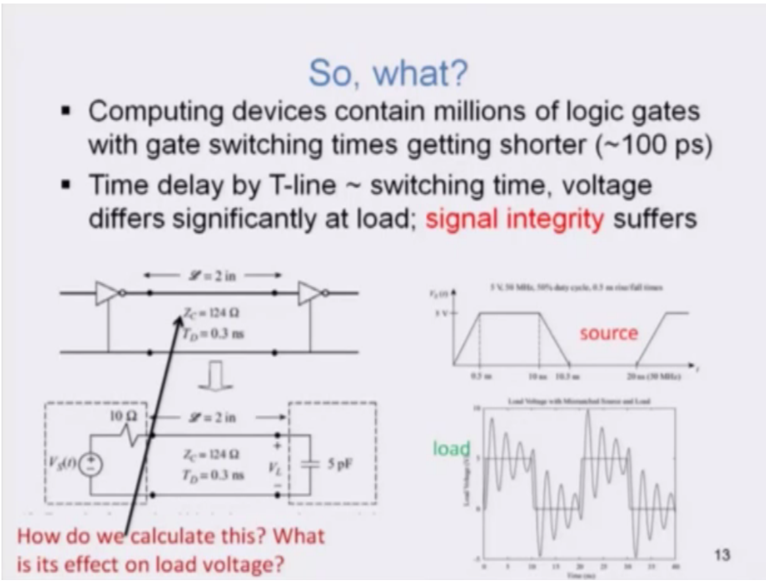

Now you might ask well so far we have talked about circuits and electromagnetic theory and we said that there are situations where circuit theory does not give you correct answers, whereas electromagnetic theory will give you correct answers or correct predictions. So what, I mean why should we bothered about this electromagnetic phenomenon.

Well, to consider a device which is very close to us, such as a computer or a cell phone, each of these devices which essentially perform computing stuff, they actually contains millions and billions of logic gates. And these logic gates are all switching at very fast, very high speed, and the gates switching time, that is if the gates go from high to low or from low to high, those switching times are getting shorter and shorter.

Now you can have fast gates, which switch in the order of hundred picoseconds. Now if the interconnect is such that the delay of the interconnect itself is about two hundred picoseconds, then the voltage which this gate is switching from logic high to logic low, the same voltage will not be available at the same time and then the second one will switch after a certain time.

Now when you have such interconnects connected, you know you have this different elements or logic gates connected together, if the difference between the two interconnects is large, then the voltage because of the same source will not be the same at one logic gate compared to the voltage at the other logic gate. Therefore, this might lead to inconsistent result, and completely inaccurate results.

The correct model of this scenario is to treat this as a logical element, whatever that you are considering, and this is another logical element which is switching. However, the space between these two, which is connected by a piece of metal or a wire, and on the left side, these are known as interconnects as transmission lines. Now transmission lines are characterised by several characteristics.

One of the most important characteristic of a transmission line is that of its characteristic impedance. So here you can see that the characteristic impedance ZC is given to be 124 ohms and the time delay of the transmission line or the interconnect is given as 0.3 nano second, and if this is the source voltage, you can see the that source is switching from logic low, which can be represented as zero voltage to logic high, which is five volts.

And this is switching from logic low to logic high in about 0.5 nano seconds, okay. And there after it is constant for about up to 10 nano seconds and then switch back to logic low at again with an interval of 0.5 nano seconds. This is at the source end. Now if you take this source end that is the voltage at this point and see what is the voltage that you would observe here at the load end, you would actually see something like this.

There will be ringing effects, this square wave is just for the comparison. So you will see over shoot and you will see under shoot. Now this is something that one would not expect if you go simply by the circuit theory. So in order to obtain the correct output, in order to predict this one, one has to replace the interconnect by a pair of transmission lines, or actually a single transmission line, okay.

So we model this source by a voltage source with a resistance and the load by say capacity load for example, and then this piece of wire, which is called as the interconnect that connects the two logic elements as a transmission line. Now you might ask how do we calculate this transmission line characteristic impedance, what is a transmission line, and how do we calculate this time delay TD and what do this ZC and TD variables have any effect on the load voltage.

We know that there is a load which is not exactly equal to the source, but how is this voltage at the load related to the transmission line effects.

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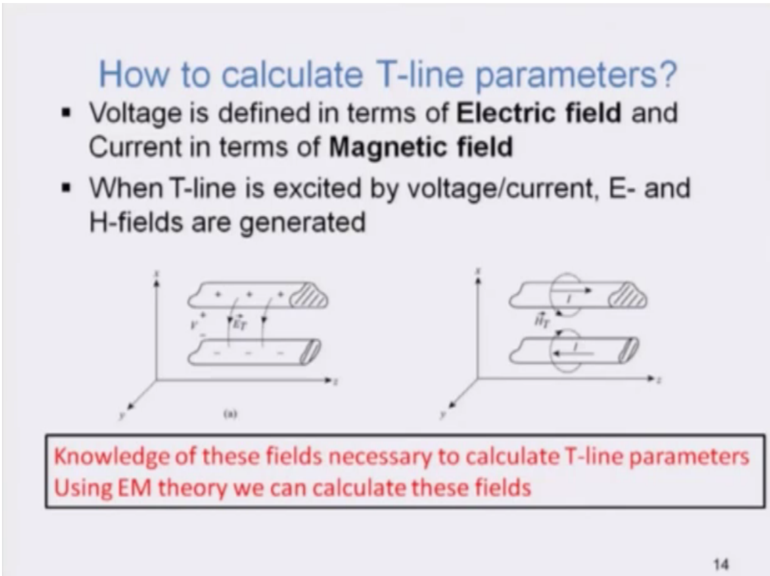

Again we have to go back to electromagnetic theory to understand where these parameters are coming from. For example, if you want to calculate the characteristic impedance, if you remember the impedance definition, the impedance definition is voltage divided by current. However, we have seen that voltages and currents are not just numbers, they are dependent on where you are measuring them, right.

So this voltage and currents are more accurately defined in terms of electric fields and magnetic fields. So voltage is defined in terms of the electric field and current is defined in terms of magnetic field. And when we excite a transmission line by a voltage and current, we say that electric and magnetic fields are generated. So here you can see that electric fields are generated, and the current is generating a magnetic field.

And then to obtain the characteristic impedance we have to relate the voltage V to the generated electric field, we have to generate the current I to the generated magnetic field. And one cannot do so, or one cannot obtain, or one cannot understand the electric and magnetic fields unless one studies electromagnetic theory. Electromagnetic theory tells us how voltage is related to the electric field, how current is related to magnetic field.

And these relationships in turn give us relation for a resistor, they also give a relationship for an inductor and a capacitor. This is how we actually can model the physical phenomenon that we have so far discussed. Now, I think this is right time to just summarise what we have done for the first twenty minutes over here. Wire is more than just a wire, right. What we see as a wire at low frequencies and at the circuit level is not just a wire.

Because it can act as an inductor, it can act as a resistor, it can act as a capacitor or in a worse scenario it can act as a complicated or a complex circuit that is, that can be modelled as a combination of resistance, inductance and capacitance, okay.

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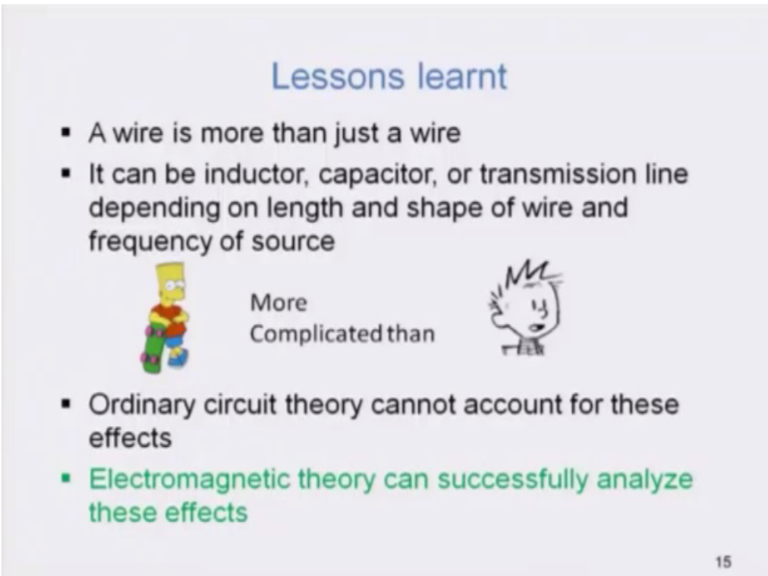

It can also act as a transmission line when the frequency of the source is very high, and there is a relationship between the length of the wire and the frequency of the source, we will discuss that later. But again the point is that a wire is not just a wire, it exhibits lots of secondary effects, such as inductance, capacitance and resistance, and all these combinations. And we need to understand electromagnetic theory to be able to account for these secondary effects.

Now secondary effects are very, very important, when you are defining say high speed digital systems or you are designing a RS circuit. Unless you understand these effects your designs will not probably work in the correct way or as you have intended. The reason why this electromagnetic theory has to be studied, is because the ordinary circuit theory cannot account for these effects, whereas electromagnetic theory can successfully analyse these effects, okay.

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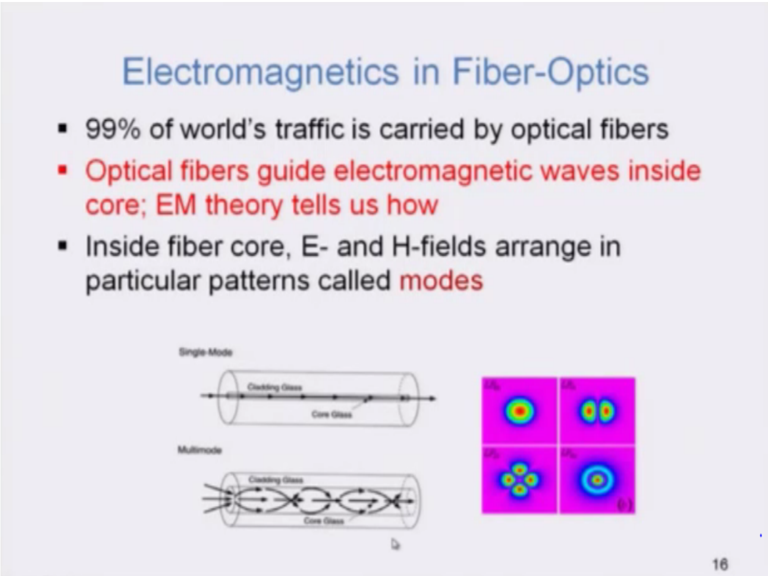

It is not just circuits where Electromagnetics comes up often, it is also that electomagnetics opens up a wide array of topics that one can specialize in, that is one can find applications of Electromagnetics in. Now, you must certainly have heard about fibre optics and optical fibres are the ones which can carry 99 percent of the world's traffic, right.

So all the high speed advantages that, I mean all the high speed data transmission that we are now familiar with is mainly due to the optical fibres and the ability of the optical fibres to carry this large amount of data with very little attenuation. Now how exactly data which is actually an abstract quantity or a voltage or a current, in the abstract quantity mapped in to voltages and currents how would they be excited inside an optical fibre.

How would they travel inside an optical fibre is something that electromagnetic theory will tell us. It tells us that light, which is appropriately modulated by the source that we are, by the data that we want to transmit actually goes through as modes inside a fibre, and these modes would travel, okay. So there are these different modes which I have shown, these modes have certain numbers, and certain superscript, there are certain letters.

You do not have to worry about these numbers or superscripts. These are just the different types of light distribution inside the optical fibre. To understand this one needs to know electromagnetic theory, one views on fibre optic cable or an optical fibre as example of solution of Maxwell's equation and whatever that comes out of the solution are called as modes.

And these modes are essentially the electric and magnetic fields of the light that are distributed inside the fibre, okay. So in order to know that, in order to know what is Maxwell's equation, we have to study Electromagnetics.

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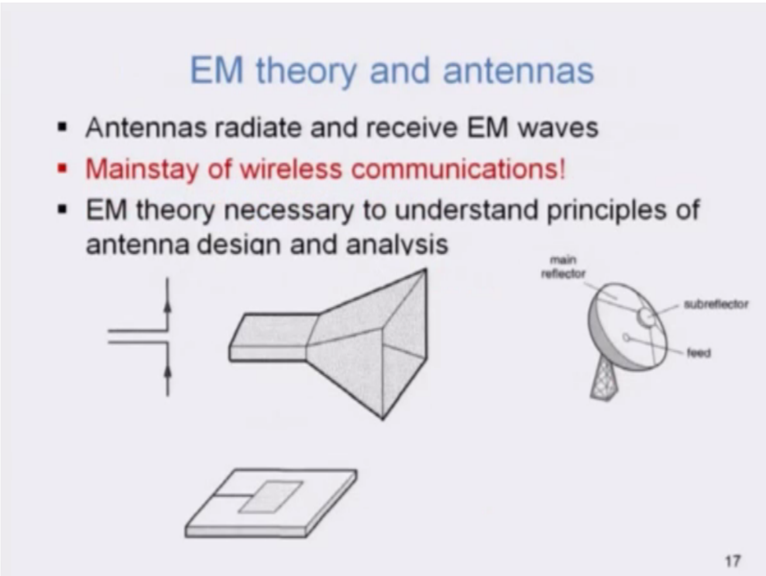

Now you might go to antennas or radars, in radars antennas are one of the major components and in wireless communications antennas are there everywhere, right. Without an antenna, one cannot have wireless communication possible, now to understand how there, I have shown different types of antennas over here. This is simple dipole antenna, this is a horn antenna, this is a reflective antenna, and this is micro strip antenna.

The question is how exactly does this antenna, the dipole antenna differ from a horn antenna, or a pyramidal horn antenna, and how does that differ from micro strip antenna. What parameters makes the radiation pattern of this antennas be different and how do we analyse them and how do we make use of this radiation effects and radiation patterns is something again the electromagnetic theory will tell us, okay.

So just to give you an overall perspective of Electromagnetics, I am just going to list up here, you can see this later.

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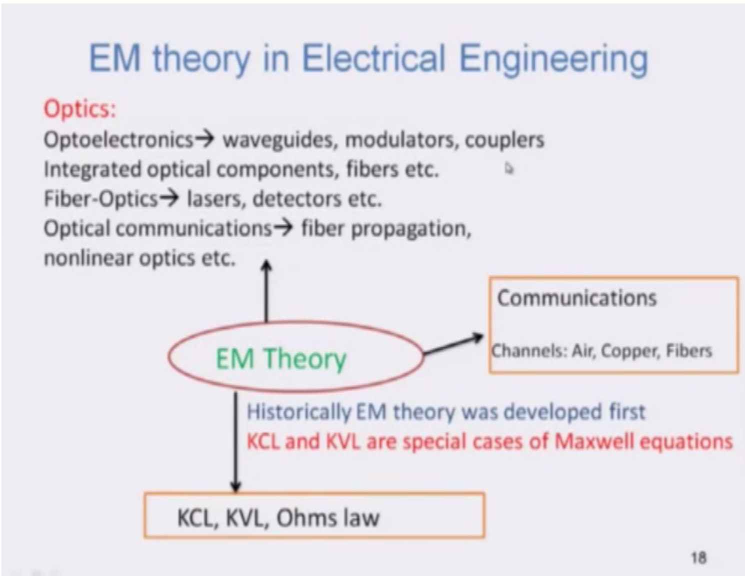

Electromagnetic theory opens up vistas in optics you have optoelectronics which is concerned with how do you fabricate a waveguide, how do you analyse a waveguide, how do you analyse a light modulator, how do you couple light from one waveguide to another waveguide, and how do you generate integrated optical components, how do you understand fibres and so on.

If you also want to understand lasers, photo detectors, photo diodes, again you have to understand them from with certain help from electromagnetic theory. And if you want to understand the non-linear properties of light propagation or linear properties of light propagation inside a fibre as something that you would find in optical communications, you again require electromagnetic theory.

If you go to communications and you want to understand different channel such as, air channel or a copper cable or a fibre or ionosphere for a radio wave propagation or for radio astronomy, you again have to know electromagnetic theory. Now you also need to know electromagnetic theory for circuits to give you a philosophical justification. See historically electromagnetic theory was developed first.

Then the simplification of electromagnetic theory for circuits was formulated in terms of Kirchhoff's laws of KCL and KVL and Ohms law. These are fortunately very special cases of Maxwell's equations, where we can neglect the time delay between any two points in a circuit, okay. So electromagnetic theory gives you the reason why KCL and KVL should be true.

They are not true by themselves, they are only special cases of electromagnetic theory via Maxwell's equations.

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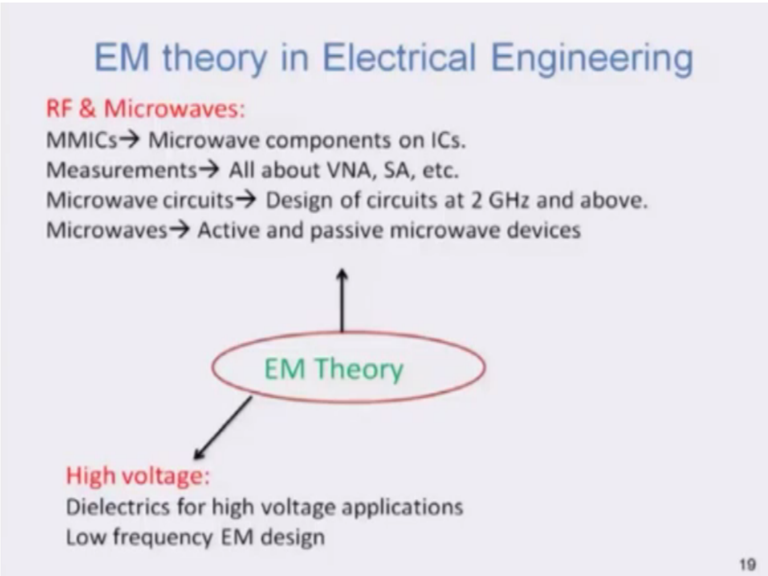

You can go to RF and microwaves where you will be designing microwave components that is components on an integrated circuit. You will be doing measurements such as VNA, spectrum analyzer, VNA stands for vector network analyzer, microwave circuits you might be designing them to make an RF transmitter or an RF receiver, or a radar transmitter or a radar receiver, and many other cases.

Essentially with frequencies typically over two gigahertz and above, again to understand microwave circuits you need to electromagnetic theory. Of course, there is an entire area of microwave engineering, which deals with active and passive microwave devices, again electromagnetic theory forms the main stay of understanding these different fields. One can also go to its different area altogether called high voltage.

Where the idea is to design dielectrics, we will study what dielectrics are later, for very high voltage applications. We are talking about kilo volts or tens of kilo volts of voltage out there. Electromagnetic theory is also used in dynamos, you know generators, which is typically called a low frequency electromagnetic design. Electromagnetic theory also used in biological system, sometimes called as bio-electromagnetic phenomena.

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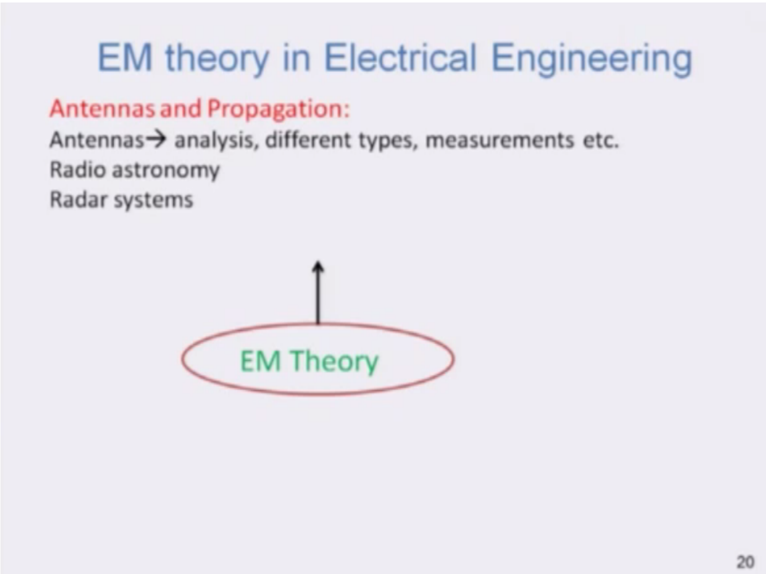

Finally, from electrical engineering perspective antennas are one of the major application where we are going to require electromagnetic theory. What we study there is, what is antenna, how do we analyse it, what are the different types of antenna, what are the different types of measurements that one has to perform on an antenna, and how are they justified by electromagnetic theory, radio astronomy and radar systems.

So I hope that, an entire this one that we have talked about so far, gives you a basic idea that electromagnetic theory is very important, it is indispensible to electrical engineering, and a good knowledge of Electromagnetics will take you far and wide in to different areas of electrical engineering, okay. So with this background as why one should be bothered about studying Electromagnetics.

Let us now look at what is the course plan and some of the suggested text books and then start discussing electromagnetic theory itself. The course plan goes something like this:

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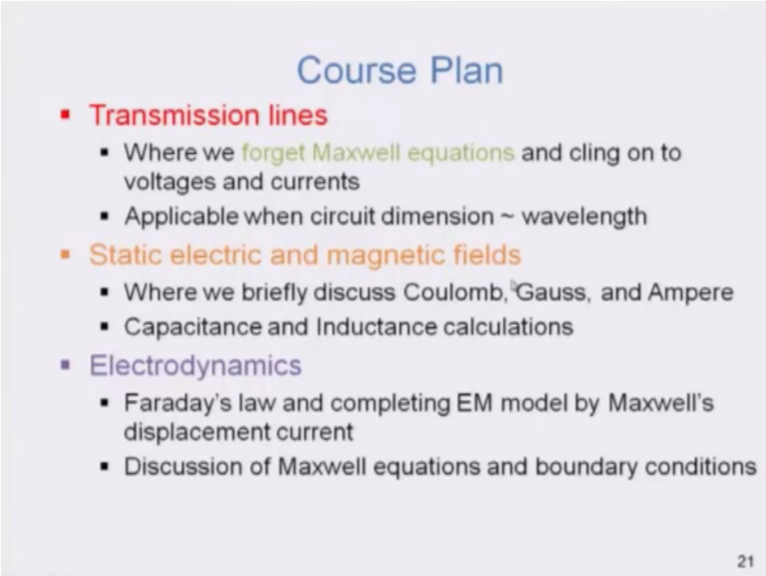

The course plan actually starts with static electric and magnetic fields, where we briefly discuss Coulomb, Gauss and Ampere. We also discuss how to calculate capacitance and inductance, remember I talked about capacitance and inductance of elements, and how do we calculate those in capacitance and inductance of physical systems is what we will deal with here.

Then we will go to electrodynamics, where we will be studying Faraday's law and complete the electromagnetic model by look at Maxwell's contribution, which is called displacement current. And we will also discuss Maxwell's equations and we also need to understand something about boundary conditions. The subject of boundary conditions will come up even in static electrical magnetic fields.

However, when we complete the electromagnetic model the boundary conditions will undergo a small change and we are going to discuss about that. Then, we come back to transmission lines, so far the two topics that I have shown here, static electric and magnetic fields and electrodynamics are what you can say as building up to electromagnetic, building up to Maxwell's equations.

There after one has to apply those Maxwell's equations to physical scenarios to really make use of Maxwell's equations in designing some systems, okay. Those systems, which are useful to us. So the first system that we are going to discuss is transmission line. In transmission line discussion, we will initially forget everything about Maxwell's equation and then we still cling on to voltages and currents.

Now this might sound very, very suspicious, like so far we have built up ourselves to Maxwell's equations, and there after we are completely forgetting. I mean I am saying that, we will forget Maxwell's equation and still deal with voltages and currents, the reason why we do this is that, transmission lines are an example where there in between the static and the completely dynamic scenarios, okay.

So one can get away by changing the voltage and current in to, from scalar quantities in to waves and then talk about transmission line. So it is kind of a bridge, that you can build from Maxwell's equations to circuit theory. That is what we do first, and the reason why transmission lines can be done, we will see the reasons later, is that this is applicable when the circuit dimension is in the order of wave length.

If the circuit dimensions are very high compared to wave length or very low compared to wave length. You have two different models we will discuss all this later. So transmission lines are where we are still trying to understand the theory in terms of currents and voltages, because currents and voltages let us face it or something that we all know pretty well.

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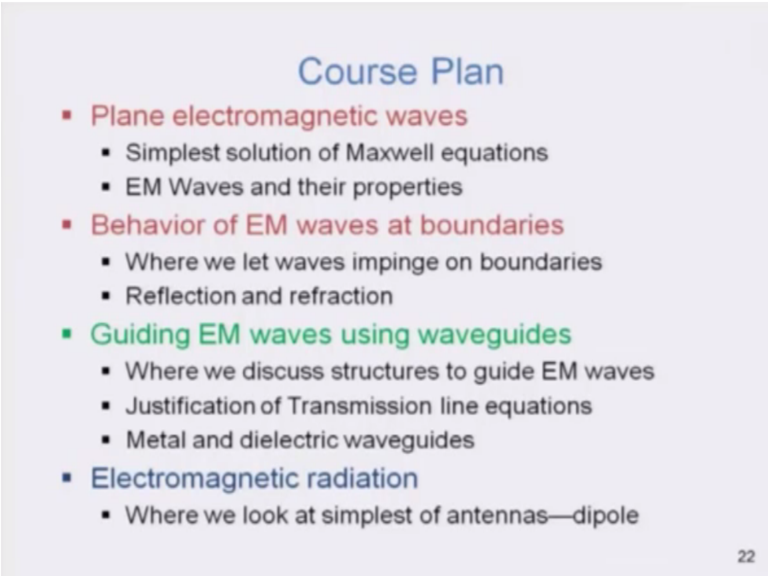

However, when we come to the subject of waves we cannot continue to ignore electromagnetic nature. So we will start by looking at simplest solutions of Maxwell's equations which are plain electromagnetic waves. It is at this point that we will show that light is also electromagnetic wave, and whatever we study in terms of EM waves are directly applicable to light.

So electromagnetic waves and their properties is what we are going to study. We will then look at what happens if light or electromagnetic wave approaches a boundary. When you have something approaching a boundary, what happens to the electromagnetic field. So that is something that we are going to look at. Will the field just penetrate the boundary or will it come back from the boundary, if it comes back how much it is coming back.

If it penetrates how much of it is penetrating. This are the questions of reflection and refraction we are going to see, where this I mean how to describe this phenomenon using electromagnetic waves. Finally, we will start looking at other applications of Electromagnetics, the application that we will look at a wave guide as its names suggests a wave guide is something that guides the wave along a certain direction, okay.

While transmission lines also guide waves, they do not enclose the electromagnetic waves between a boundary, where as a wave guide will enclose all the waves inside a boundary, okay. And that is why we call this as a wave guide. We will also see some justification of transmission line equations. Remember that in transmission line equations, we simply forgot everything about electromagnetic theory.

But we have not really forgotten, we have simplified Maxwell's equations and we will see how that simplification comes up when we look at wave guides and we understand that transmission line is also a wave guide, albeit of a different nature, okay. We will also consider the more popular metallic and dielectric wave guides, and finally we will look at radiation, which is electromagnetic radiation through an antenna.

We will not have too much time to discuss all the aspects of antenna, we will only be looking at the simplest of those called a dipole antenna, okay.

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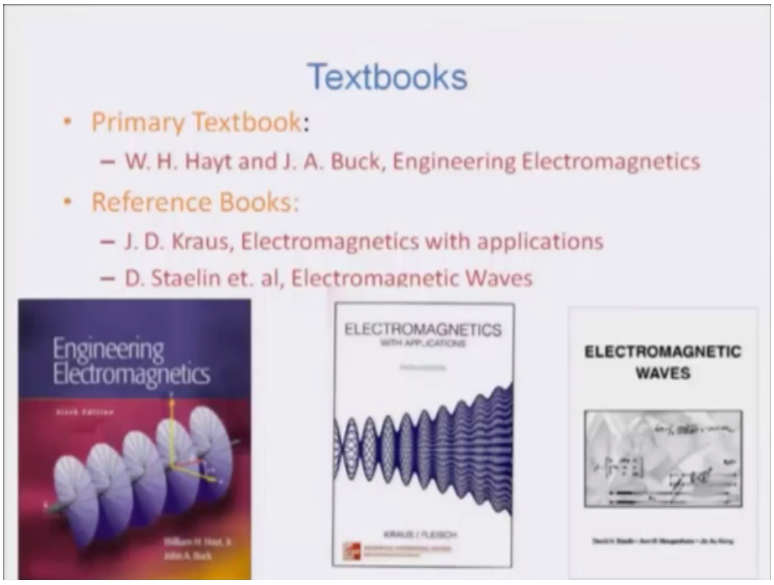

So here are the text books that I am going to use for this course. The primary text book that I am going to use is Engineering Electromagnetics by William Hayt and John Buck. This is, I think the current edition is eighth edition, but you can read up any edition from fifth to eighth. The topics have not really changed much the recent editions incorporated extra material on wave guide and transmission lines.

So you can pick up any edition after fifth, and this is what we are going to follow. I am going to follow sixth edition, because that is what I have it with me. We will also use couple of other books for references, one of them is called Electromagnetics with Applications by Kraus and Fleisch, and Electromagnetic Waves by Staelin, okay. This Kraus text book is interesting in the sense that is talks about theory less, but it includes a lot of application.

So if you are, someone who wants to know where Electromagnetics is applied after every concept, you can consult this reference book. We will of course be discussing about the applications of Electromagnetics as and when time permits to us.