Electronics for Analog Signal Processing - I
Prof. K. Radhakrishna Rao
Department of Electrical Engineering
Indian Institute of Technology – Madras

Lecture – 25
Transistor Biasing using Single Supply

In the last class, we had seen how dual supply arrangement can bias a transistor in the active region and how it can be used as a common emitter amplifier. Today, we will discuss an example in which the transistor is biased using a single supply. We already know how this can be made to work in the active region using a single supply. So, on working out this example, we will further clarify how it can be used as a common emitter amplifier.

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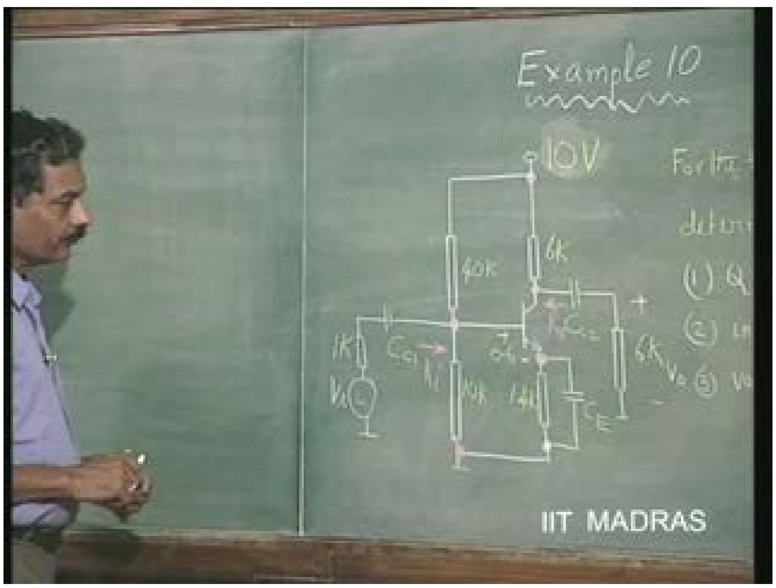

Now, using a single supply, we had seen that we have to derive another supply from this single supply, 10 volts. Another supply is derived using these two resistors, 10 K and 40 K, in this case, as 10 K divided by 10 plus 40 K of 10 volts. That is the Thevenin's voltage, which we call as V B B, which we have been calling. In this case, this comes out as 2 volts; and the Thevenin's resistance which we have been calling as R B, it comes in series with these 2 volts, is 10 K parallel 40 K, which is 8 K.

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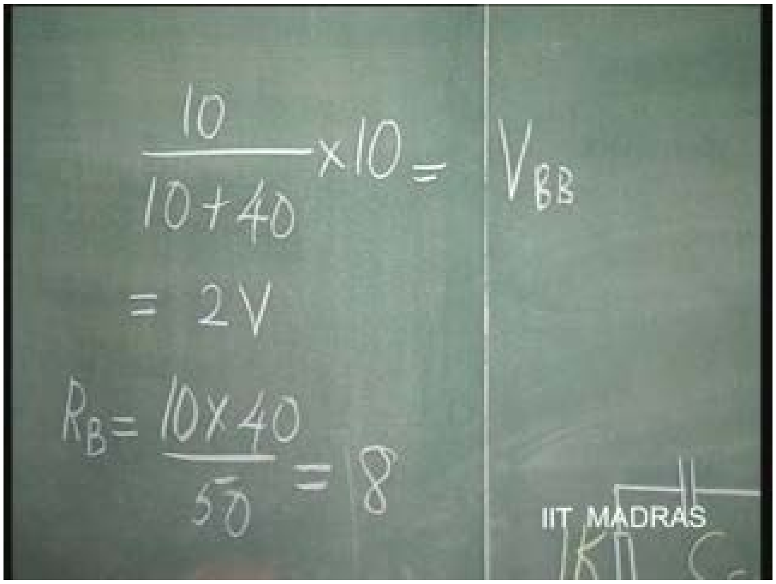

So, R B is 8 K. That means I can now replace this circuit for D C. It will be exactly equivalent to a resistance of 8 K in series with a battery of 2 volts.

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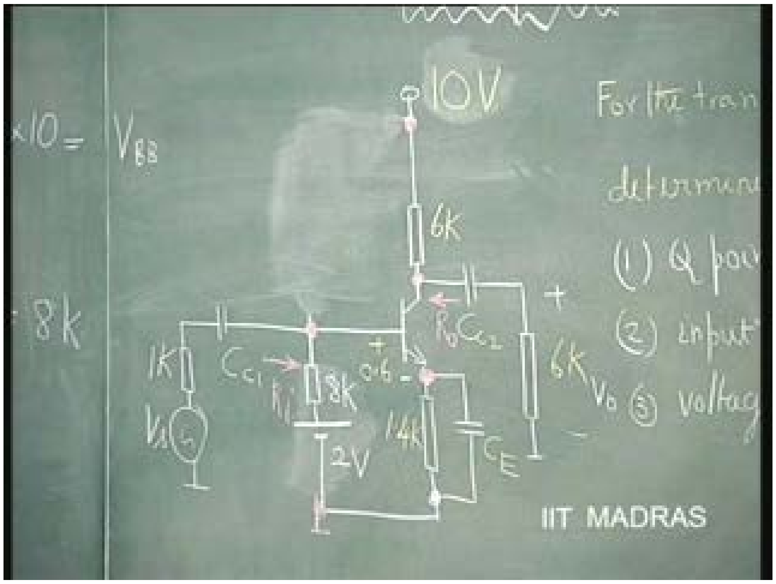

So, that is how we are able to forward bias a transistor by means of these tools. We should, in this case, have an arrangement such that this 8 K into Beta plus, 8 K divided by Beta plus 1 should be much less than 1 point 4 K. That is, 8 K divided by Beta plus 1 equal to, this should be much less than 1 point 4 K, in order that we can neglect the D C drop that is occurring across 8 K. This also we have seen. Let us assume, for the transistor, Beta is, let us say, 99, we will take.

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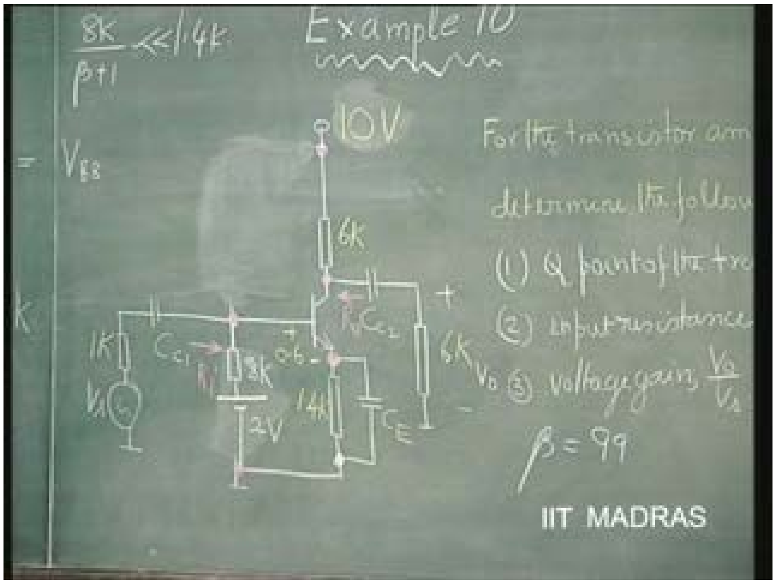

Then, in this case, we have 8 K divided by 100, is definitely much less than 1 point 4 K. So, this is valid assumption.

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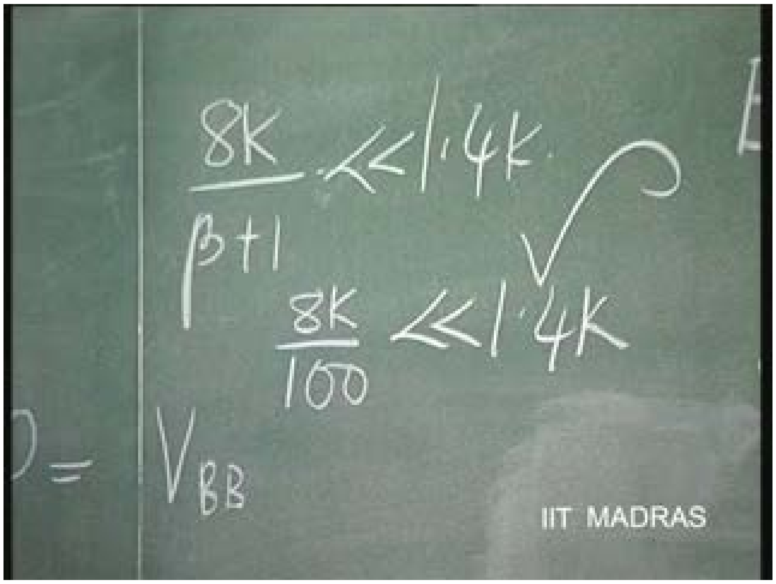

Or, 8 K is much less than 140 K. So, this is valid. That means, this can be neglected; the D C drop due to base current can be neglected, and this voltage can be assumed to be at 2 volts. So, now that we know that this is going to be at 2 volts, this is point 6 volts V B E. So, this voltage is 1 point 4 volts. So, 1 point 4 volts across 1 point 4 K gives a current of 1 milliampere.

So, we know that I E Q is equal to 1 milliampere, because we have 1 point 4 volts across 1 point 4 K. So, now the operating point is therefore I C Q, is equal to point 9; that is, 9 milliampere. That is Alpha, which is Beta divided by Beta plus 1; 99 by 99 plus 1 – point 99. So, Alpha times I E Q. And V C equals 10 volts minus 6 K into point 99 milliamperes. So, this voltage V C is going to be 10 minus point 99 into 6; that is, 10 – this is going to be very nearly equal to 4 volts; or, actually speaking, how much is it? 4 point 06 volts.

So, this is at 2 volts; this is at 4 volts or 4 point 06 volts. So V C B, which is an important... V C B Q is going to be equal to this 4 point 06 minus 2. So, we have fixed up the operating point; Q point of the transistor, I told you, measured in terms of I C Q and V C B Q; forward, that it is forward biased is illustrated by the value of I C Q. That it is reverse biased is illustrated by the value of V C B Q.

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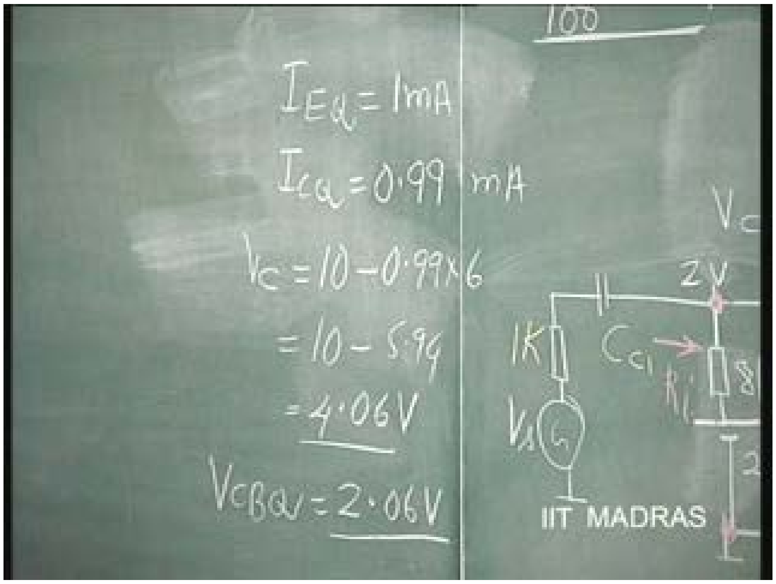

Now, input resistance R i – as far as the equivalent circuit is concerned... now, we can put down the equivalent circuit; equivalent circuit of the entire amplifier. We have v s with r s of 1 K to ground. This is called a coupling capacitor. Since this voltage is at 2 volts, I would like to decouple the signal from the DC. So, this is called a coupling capacitor. This will superimpose the signal over these 2 volts, if I use this coupling capacitor. So, it will decouple the DC.

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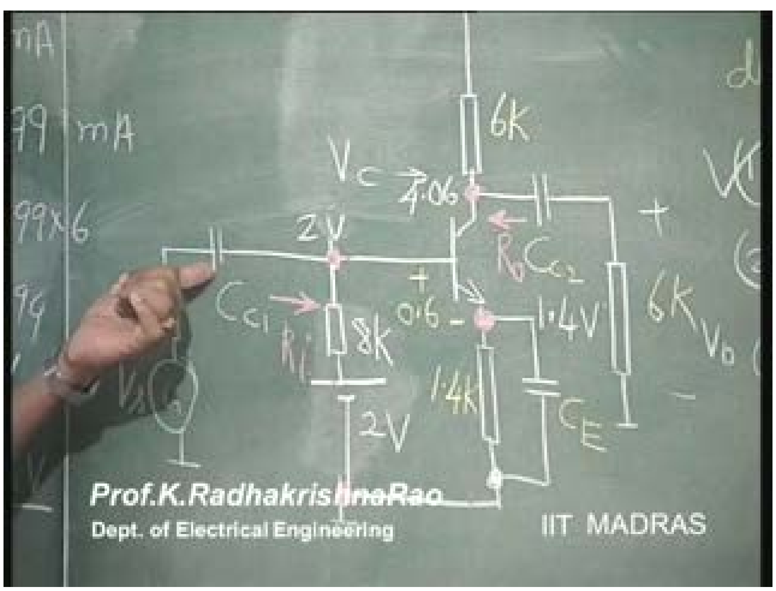

Similarly, there is a coupling capacitor used to couple the actual load on to the collector. So, again, this is because this is at a DC of 4 point 06 volts. This is going to decouple this. How does it happen? – because, the capacitor here gets charged to 2 volts. This capacitor gets charged to 4 point 06 volts. So, that will automatically get charged to the DC voltage and therefore you get only the A C here.

So now, this is automatically charged to these 2 volts. So, the signal voltage here is going to appear here, over and above the 2 volts. So, we have 2 volts; capacitor is a short circuit. Again, compared with what? Always, C C 1 should be much greater than 1 over 2 pi f minimum into resistance coming across C C 1. This is what we have used for C E also; design of C E. So, under the minimum frequency of interest, the capacitors should be so chosen that it is much greater than 1 over 2 pi f min R across C C 1.

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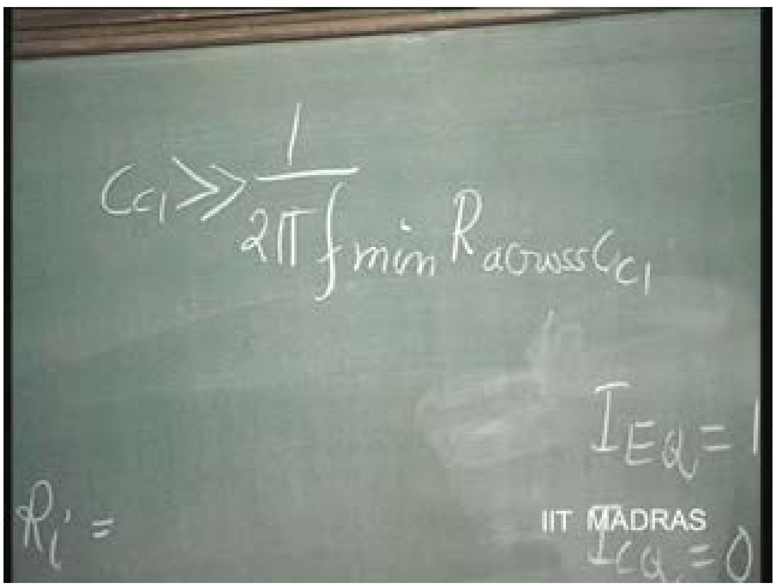

That is done. It is a short circuit. Then, we have 8 K and this is at a constant potential; and therefore, this is a short. Then, we come to the base, base. Then we have r e, the small signal resistance of the transistor between base and emitter and emitter is grounded through the capacitor; and we know how to select that value of capacitance.

So then, we have the current source, dependent current source. If this is signal current i e, this current is going to be Alpha times i e. So, we come to the collector point; this collector point. From here, we have 6 K to ground because this is a constant voltage; and from that, again, we have a short circuit to another 6 K.

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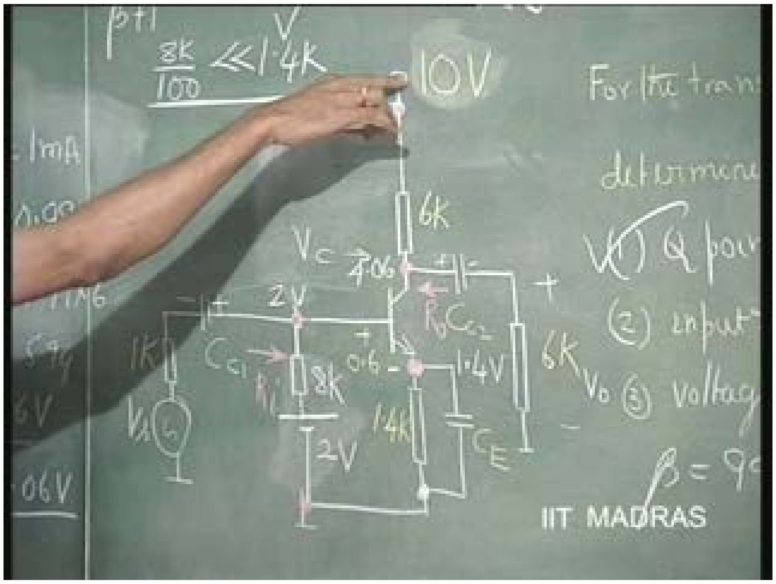

So, we have 6 K parallel 6 K. This is supposed to be the equivalent circuit of our amplifier. Is it clear?

Now, if this is v s and we have r s, this we will call as... now, instead of using all these symbols like Delta V i and all that, we have agreed that we will use r m s value of voltages here. Since most of this analysis is done for sinusoidal signals, we will use the r m s value of voltage. That is represented by V, capital V, small ((i Refer Slide Time: 13:10). So, input voltage here is V, capital V divided by i; and the current here is I i, which we have been earlier calling as Delta i, v, etcetera.

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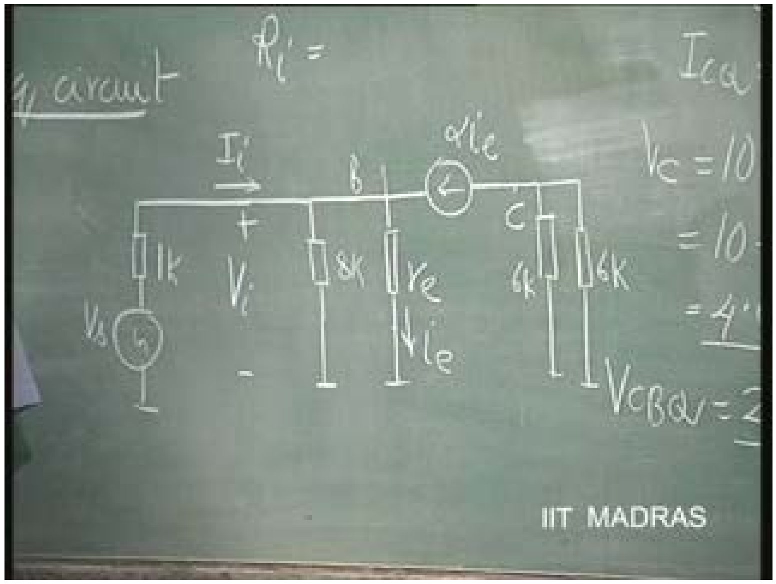

So similarly, we will convert this into what? – I e; and this one into r m s values, I c. So, this current here is going to be V i divided by 8 K; and this is V I by r e. So, the total current I i... this is nothing but V i by I i; input resistance here is input voltage V i divided by input current, that is the input resistance. So, I i – we will write in terms V i now. So, I i is equal to... this current is, this current plus this current minus this current. This current is in this direction. So, this current is V i by 8 K plus V i by r e. r e is how much? It is operating at 1 milliampere. So, r e is equal to 26 ohms. 26 millivolts divided by1 milliamperes.

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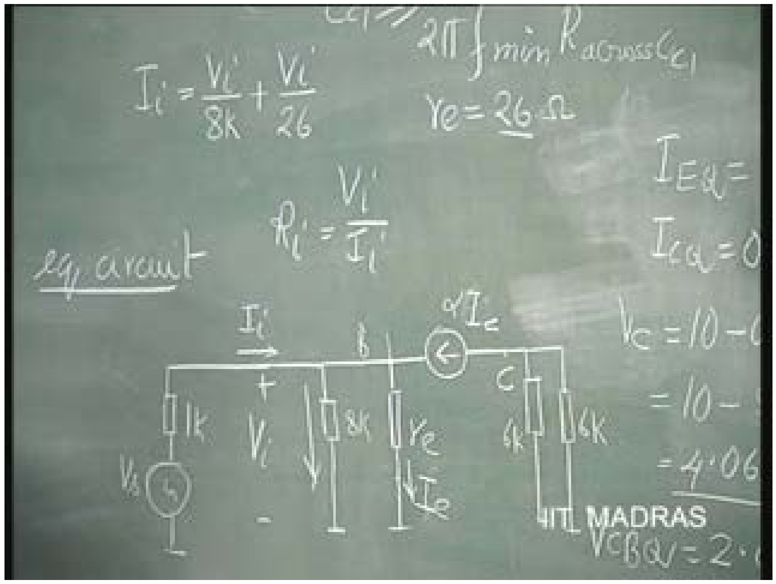

So, this is going to be 26 ohms. Or, we will write down everything in terms of ohms. V i by 26 minus Alpha times I e. What is I e? V i by r e. I e is equal to V i divided by r e. So, same thing... Alpha times V i by 26. Alpha is already given as point 99. So, this equation straight away gives us the input resistance.

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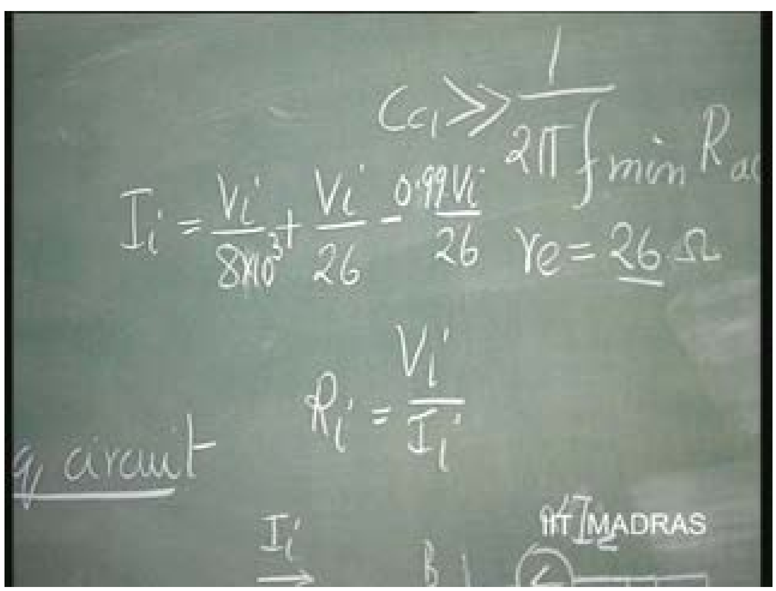

Actually, this is going to give you... I i by V i therefore equals 1 over 8000 plus 1 over 26 into 1 minus Alpha, which is point zero 1. Actually, therefore, this is equal to 1 over 8000 ohms in parallel with 1 over 2600 ohms. This is 1 by 26 into 1 minus point 99, which is point zero 1.

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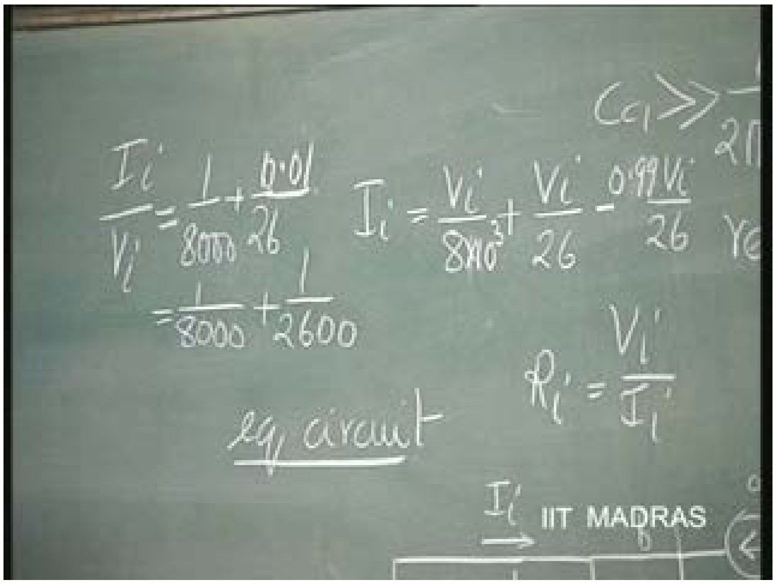

So, you can see that R i is nothing but 2 point 6 K parallel 8 K, so many Kilo ohms. How much is this? Please calculate this. This is about, around 2 K, 1 point 95 K.

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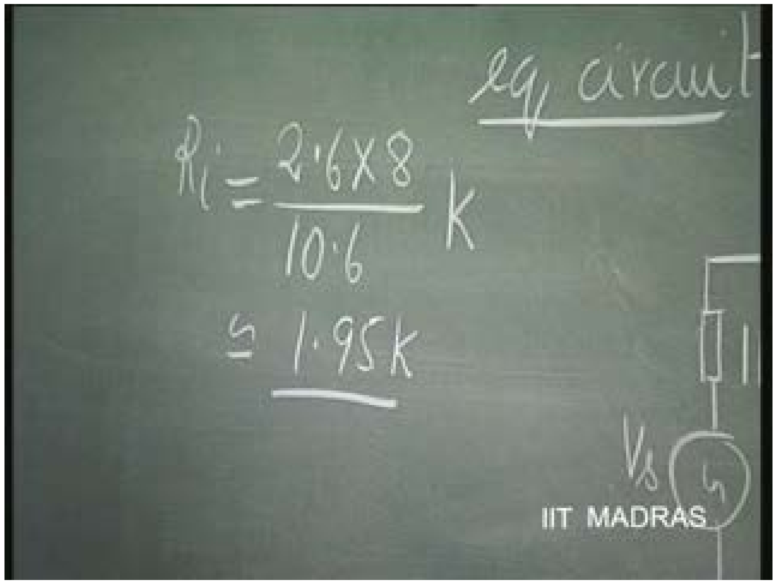

So, that is the input resistance offered by our amplifier. Please note that it is 8 K which is coming straight away here and whatever is offered by the amplifier as 2 point 6 K. So, this 8 K is also taking away certain amount of the signal current. Actually, in order that this should not take any signal current, it should have been of the order of 10 times 2 point 6 K or so; 26 K. So, the design is not good.

If you make it too high, then it will not satisfy this relationship. If you make it 26 K, it will not satisfy this relationship.

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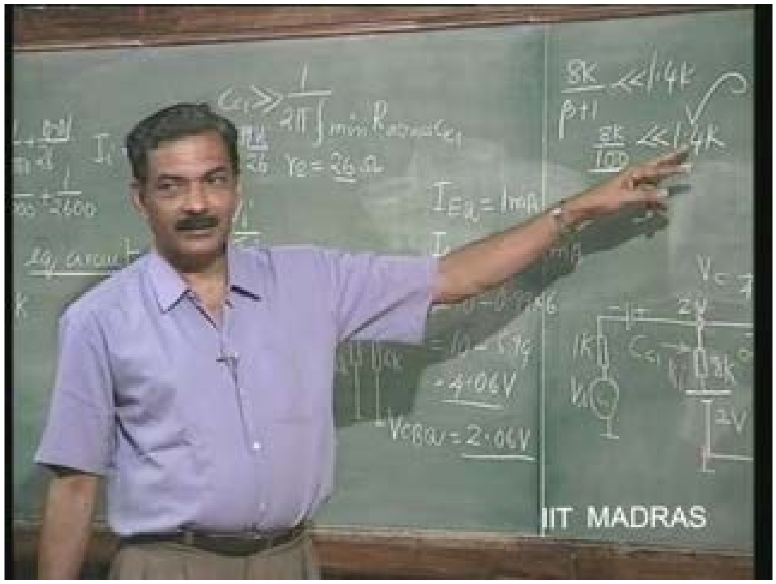

So, this will no longer be a stable 2 volts. So, these are the compromises that are made in the design. Does not matter. Some amount of signal is going to be lost because this bias resistance is going to take away certain amount of current. So, what is now the gain? This also is over – input resistance. Output resistance is very simple.

We are looking at... if from this side that we are looking at it... from here; that is, this is the 6 K load and this is the collector point. We are looking into the collector. So, this is a current source which is excited by the input. So, that current source is not at all there, when you are exciting it by the output. So just the 6 K resistance is going to be the output resistance. So, output resistance is equal to 6 Kilo ohms. Simple.

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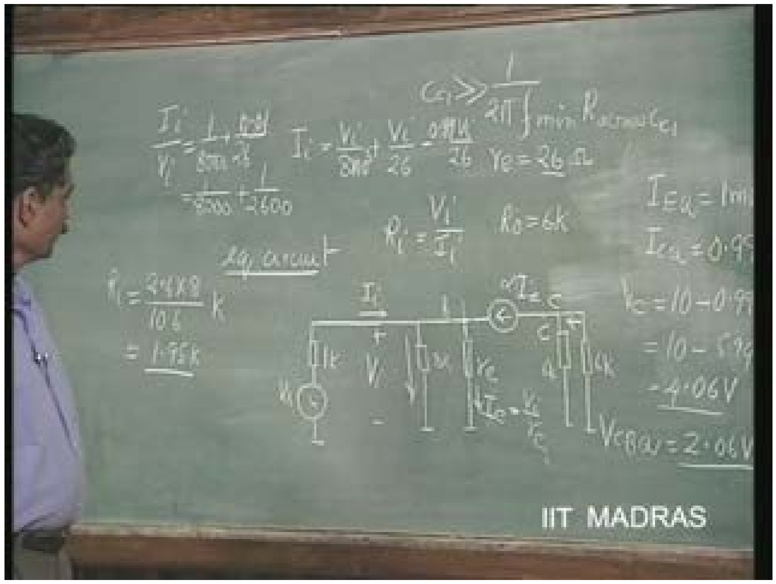

Now, the voltage gain is nothing but V naught, which is, this voltage divided by V i. This is one voltage gain. What we are asked is V naught by V s. That can be very neatly put down as... V naught by V s is going to be V naught by V i into V i by V s. This was how we have been doing. V naught by V i into V i by V s.

V i by V s...This is V naught by V i into... What is V i by V s? If this is R i, so, R i by R i plus R s. So, R i by R i plus R s, potential divider action; because this is R i; we have replaced it by an equivalent input resistance; R i by R i plus R s is V i by V s. So, it is left for us to determine V naught by V i, because we know, R i is this 1 point 95 K and R s is 1 K. So, this is equal to V naught by V i into 1 point 95 divided by 1 point 95, plus 1 K. Now, what is V naught by V i?

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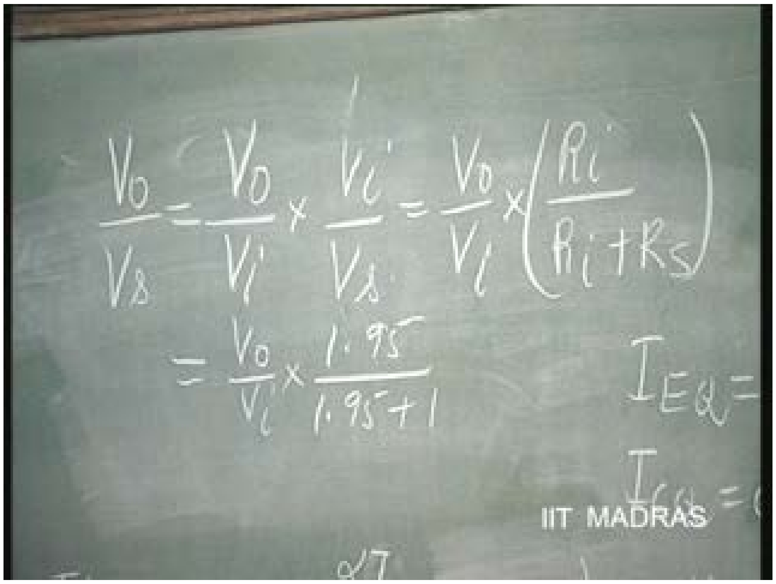

This also we have already determined earlier; but we will again illustrate. This 6 K parallel 6 K is 3 K. So, Alpha I e into 3 K is minus V naught. So, minus V naught is equal to Alpha I e into 3 K. Is this clear? This is assumed as plus and this as minus. So, Alpha I e will produce plus here and minus here. So, minus V naught is equal to Alpha I e into 3 K and I e is already known as V i divided by r e. So, I e is equal to V i divided by 26. So, this is actually 3 K, means 3000.

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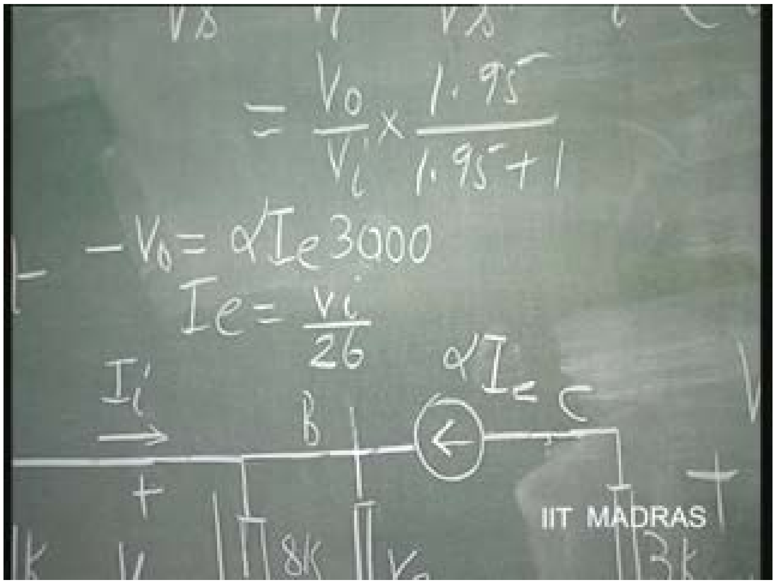

So, we get V naught over V i equal to... from that, replacing I e by V i by 26, minus Alpha 3000 divided by 26; or, minus point 99 into 3000 by 26. This is roughly... please calculate this – about 120. How much is it? Point 99 into 3000 by 26 – 114, 114, minus. So, that is the voltage gain.

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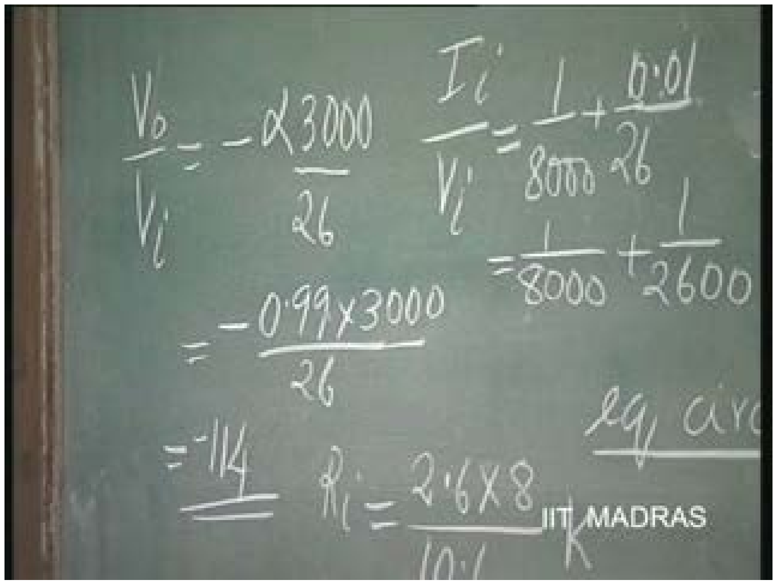

Now, I would like to further add certain questions to this example so that the complete design is understood by us. First of all, this C C 1 and C C 2 and C E... let us now exactly determine how to evaluate the value of C C 1, C C 2, C E. Now, I just said that the reactance of all these capacitors should be much less than... at the minimum frequency of interest, the resistance across. This is the basic design rule.

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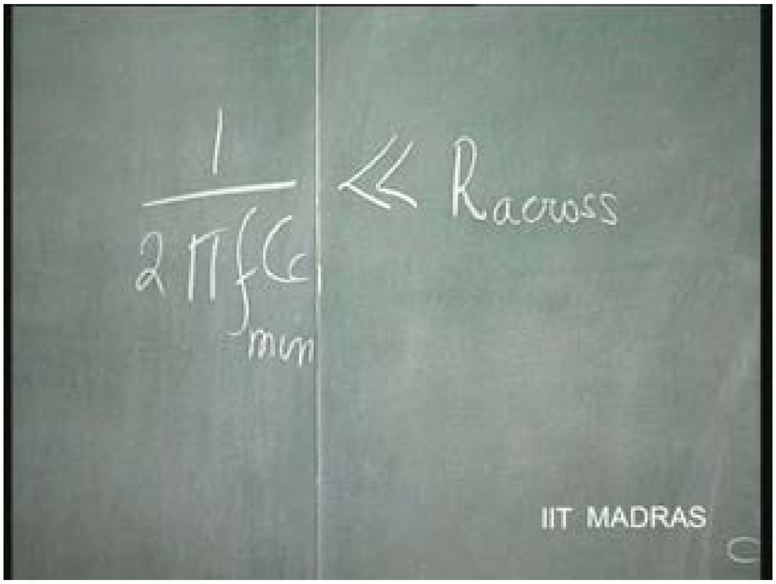

When we say much less, we will say, one tenth the short circuit means, the resistance offered by these reactances should be one tenth the resistances by these reactances. Now, let us find out in each of these cases, what this resistance is going to be. Let us assume that f minimum is 200 Hertz. Then, R across C C 1 equals 1 K; we can see this 1 K; then, nothing but the input resistance.

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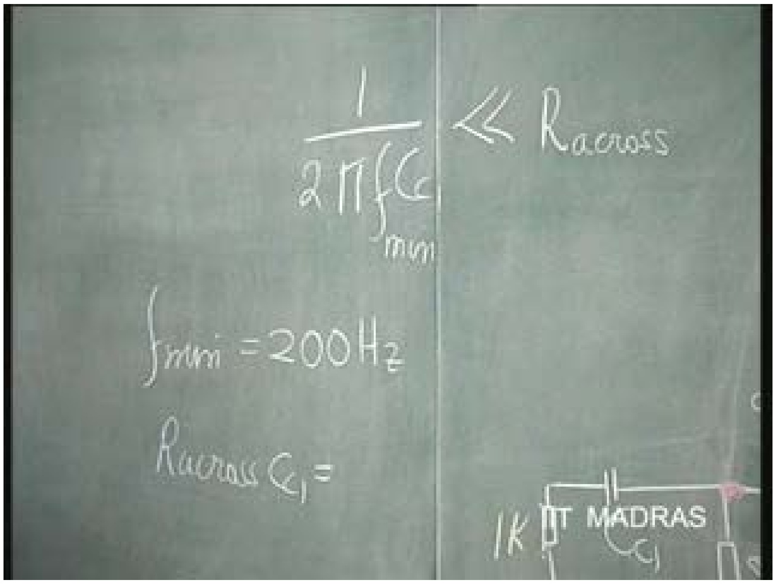

So, 1 K plus R i, which we have already evaluated as 1 K plus 1 point 95 K; this we had already evaluated. So, this should be 2 point 95 K; or, the resistance seen by the capacitor should be less than 295 ohms. One tenth; we will take it as one tenth.

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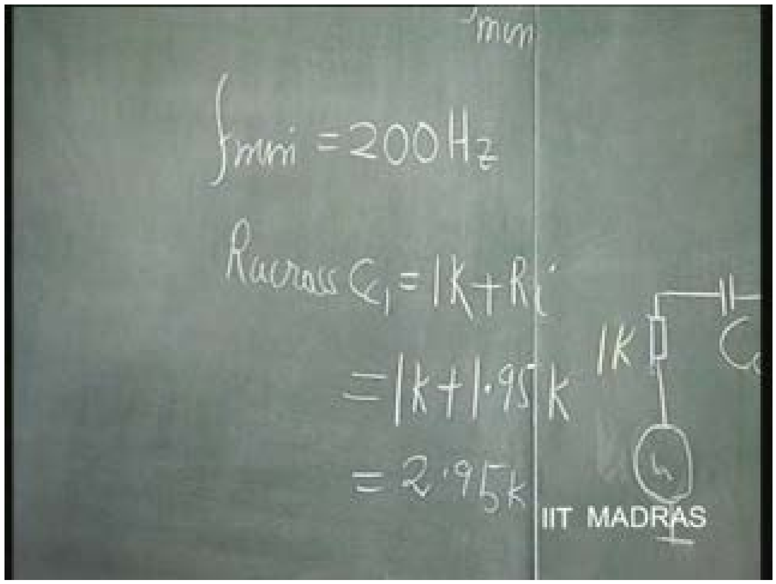

The resistance actually seen across the capacitor is 2 point 95 K. The resistance offered by the capacitor at the minimum frequency of interest should be of the order of one tenth; let us say, 295 volts. That means, 295 is equal to 1 over 2 pi f minimum into C C 1. So, if the capacitor now offers the resistance which is 295 or less, we are happy. So, C C 1 therefore is equal to 1 over 2 pi into 200 into 295. This will be 300, 6, 2000, around. Yes, how much is it? 2 point 6 microfarads.

That means, if I use any capacitor greater than 2 point 6 microfarad, it is going to satisfy this. So, this is the design rule.

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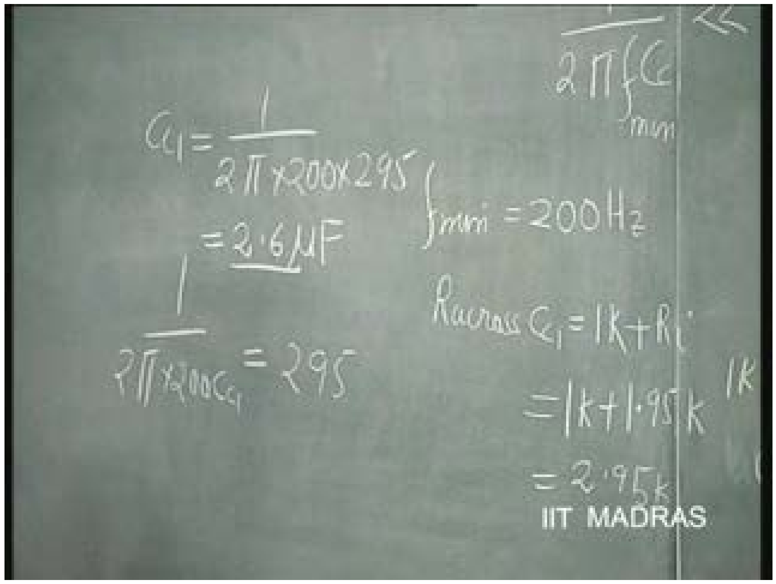

Similarly, you can find out the value of C C 2 as... Let us do that without going into all these equations. We know, 1 over 2 pi into 200 into... What is the effective resistance across this capacitor? 6 K plus output resistance. 6 K, plus output resistance which is 6 K; so, 12 K. That means, the resistance offered by the capacitor should be less than 1 point 2 K. So, this is 6 K and this is 6 K; so 12 K. One tenth of that is 1 point 2 K. So, 1 point 2 K. So, how much is this? About 10 microfarad; larger than this obviously; point, point 66 microfarad. This is about one fourth this; because, it has to offer only a resistance of 1200 ohms whereas this has to offer about 300 ohms.

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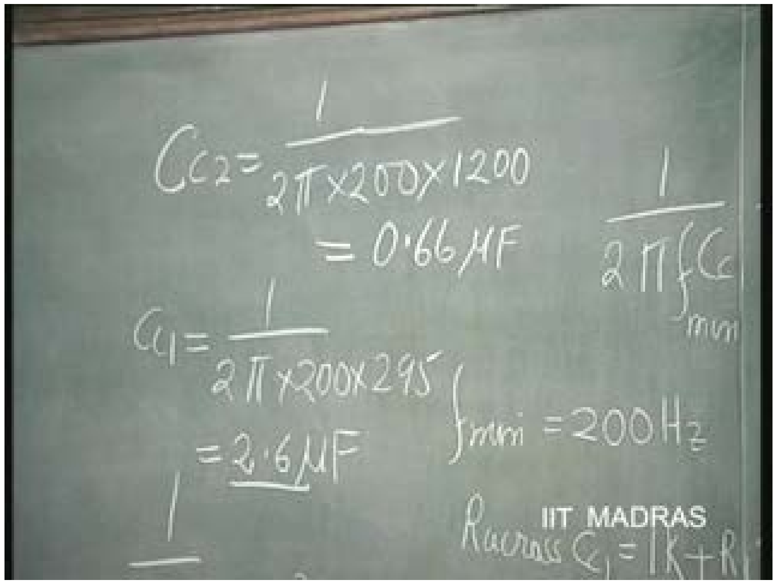

Finally, C E. Once again, I would like to see the resistance across this capacitor. We have already done it earlier. Resistance across this capacitor is 1 point 4 K parallel r e, which is 26 ohms. Then you come here. 8 K parallel 1 K divided by Beta plus 1. Effective resistance from here to ground is 8 K parallel 1 K. That divided by Beta plus 1; because the relationship between this current and this current may vary by the factor of Beta plus 1.

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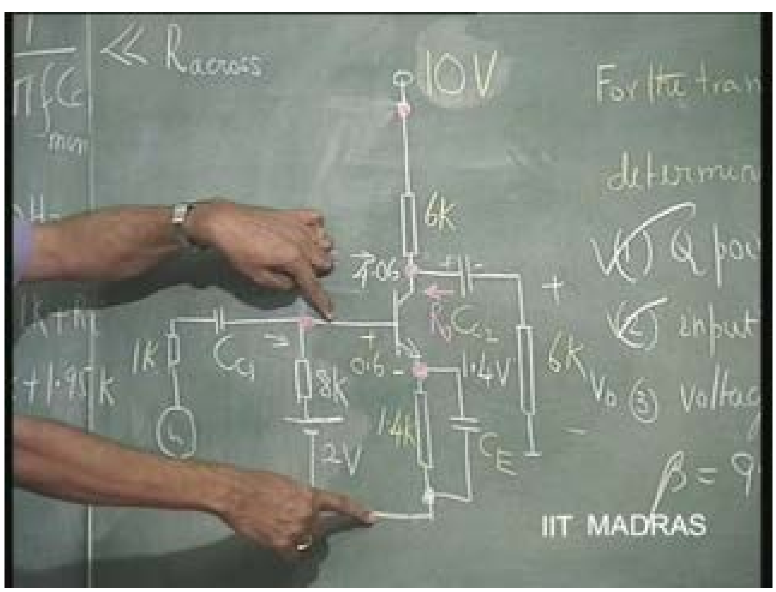

So, the resistance across C E is equal to 1 point 4 K parallel 26 ohms plus 8 K parallel 1 K divided by Beta plus 1; that is 100. So, this is going to be equal to... in fact, this resistance, 8 K parallel 1 K is 8 by 9 K; that divided by 100. So, 8 by 9 K; about 900 ohms. So, this would be offering about 9 ohms. This is offering about 9 ohms plus 26 – 35 ohms. So, we can ignore the effect of 1 point 4 K. So, this is about 35 ohms. Is this clear?

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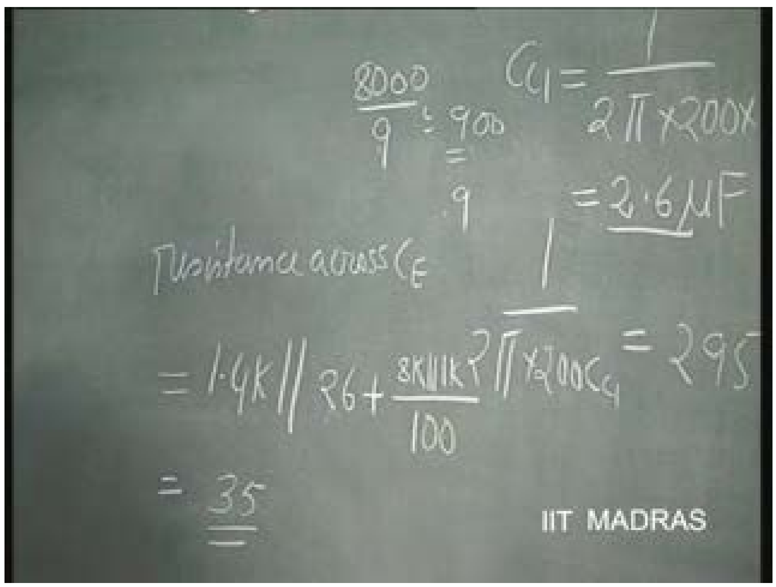

26 ohms plus 8 K parallel 1 K is 8000 by 9 K, which is 900 ohms. That divided by 100 – 9 ohms. 9 plus 26 is 35. 35 parallel 1 point 4 K is 35. So roughly, 35. You do not have to calculate these values exactly because our selection of capacitor is always going to be the higher value than whatever is given. So, 35 ohms.

That means, this capacitor should act as a short circuit and that reactance corresponds to 3 point 5 ohms. So, C E is equal to 1 over 2 pi f minimum into 3 point 5 ohms. So, somebody can calculate this. So, about 250 microfarad. How much is it? 227 microfarad.

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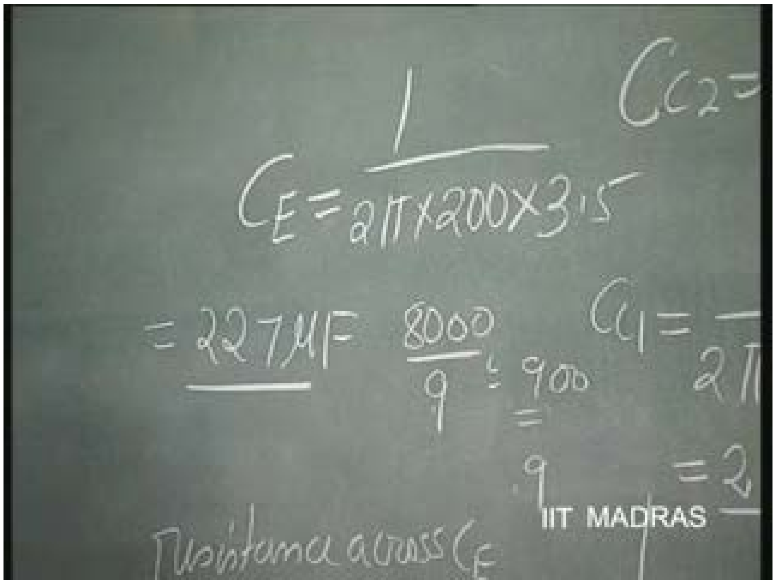

You will see that in a typical design, it is the highest capacitor that is costlier than the other capacitor. So, this is given, which determines really the, what is called as, lower cut-off frequency. If they are not acting as short circuits, they will reduce the gain; they will take away some voltage here and some voltage here. So, they will reduce the gain and that will bring about a poor lower cut-off frequency.

If this kind of design is done, it will assure that up to 200 Hertz, the gain is not reduced at all. So, these coupling capacitors bring about a lower cut-off frequency in the amplification factor. So, the amplification will not be 114 up to very low frequencies; it will be 114 up to about 200 Hertz. Thereafter, it will come down to zero as you approach the D C. So, that brings about a lower cut-off frequency. Therefore, the lower cut-off frequency in an amplifier is always determined by these capacitors.

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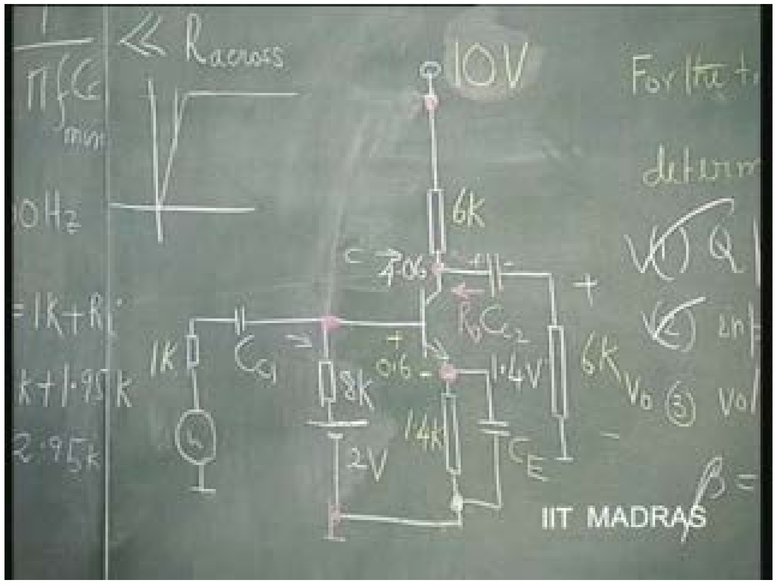

Now, you can select any one of the capacitors to determine the lower cut-off frequency exactly. Other capacitors are designed to be short circuits. So, that is the way design is done. Now, the final thing about this amplifier is that, as you apply the signal, keep on applying the signal, this output will keep on getting amplified. This signal, let us say, is increasing. This is getting superimposed over 2 volts signal, but it is getting amplified by 114 or so, which is quite large.

Now, essentially therefore, you can consider that this is going to remain at 2 volts, even when the signal is present. So, this signal variation here is going to be very small compared to 2 volts. Suppose it is 1 millivolt here; here, it will be 114 millivolts. If it is 10 millivolts here, it will be 1 point 14 volts. Already this has gone up to volts range. Even then, this voltage is remaining very nearly constant at 2 volts.

So basically, we can assume for all practical purposes, this is remaining unaltered at 2 volts. But, this voltage is going to keep increasing and decreasing. When this is increasing, this will decrease; when this is decreasing, this will increase, because of the phase shift. But now, for large signal, I can still assume that this voltage remains essentially constant at 2 volts. Now, this voltage is changing from 4 point 06 volts.

Suppose I apply 10 volts. This will be swinging from 4 point 06 all the way down to 4 point 06 minus 1 point 14 and 4 point 06 plus 1 point 14, if it is assumed to be linear.

Now, I am asking you a question as to when will this go to saturation and when will it go to cut-off? So, this is some question that you have to answer. How do we answer this? We know, cut-off it reaches, when i c becomes equal to zero; instantaneous value of current becomes equal to zero; which means, the signal swing in collector current becomes equal to I C Q. This is always something that you can remember.

If this is operating at 1 milliampere, obviously it can swing up to 2 milliamperes and zero milliampere; around 1 milliampere. 1 milliampere plus 1 milliampere – 2 milliamperes. 1 milliampere minus 1 milliampere – zero milliampere. So that 1 milliampere change may have been brought about by a disproportionate change here because of the non-linearity. Now, that is of no consequence.

So, this swing here, current swing; for it to go to cut-off is 1 milliampere. If it is 1 milliampere, swing peak, that is flowing into the resistance combination of 6 K into 6 K parallel 6 K which is 3 K. So, the voltage swing possible before it goes to cut-off is 1 milliampere into 3 K, which is 3 volts. So, before it goes to cut-off, it can go to a swing of 3 volts. Is this clear?

Now, as far as the other thing is concerned, instantaneous value of V C B should go to zero when it goes to saturation. The actual V C B Q is 2 point 06 volts. 4 point 06 minus 2 volts. So, the voltage swing possible here is, how much is it? 2 point 06; because, when it goes from here down by an extent of 2 point 06, this potential will become same as this potential. So, 2 point 06 volts is the swing on the other side. On this side, the swing is 3 volts.

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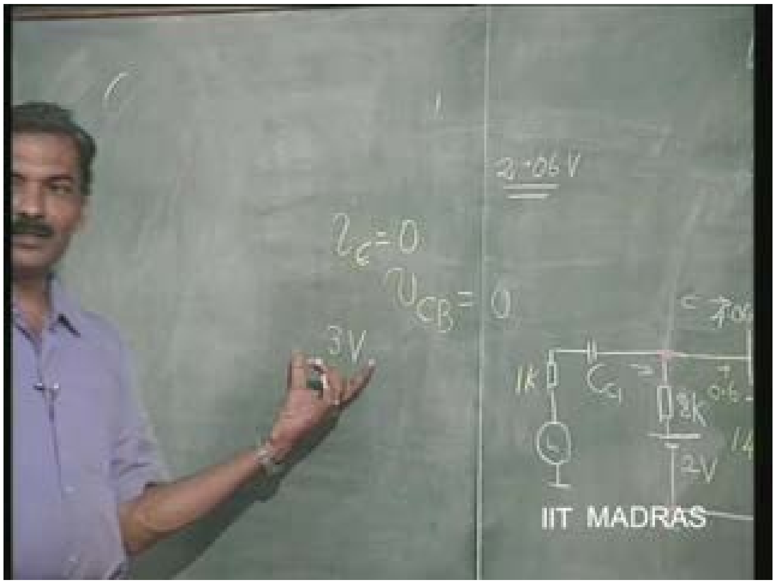

It is asymmetric. This is not a design problem where you have been asked to design the operating point such that it is symmetric swing. What it means is the amplifier goes to what? – saturation region; the transistor goes to saturation before it goes to cut-off. If you apply a sine wave, the first distortion that will appear in this case is due to what? – saturation. So, this is important. This will not occur... It is this that is important. So, the symmetric signal swing here is how much? – 2 point 06 on either side, because here, it can go as much as 3 volts. So, it can easily go to 2 point 06. So, the lower of these two will set the limit for symmetric swing at the output.

So, with this, the complete discussion of common emitter amplifier is over. However, I would like to just say one thing. The characteristics of the transistor; we have assumed as a current source, Alpha times i e. So, the equivalent circuit of the transistor is very simple. r e which is equal to V T by I E Q and a current source... please, always put down this, dependent current source i e, if it is. This is Alpha times i e. This is the simplest equivalent circuit we have used so far.

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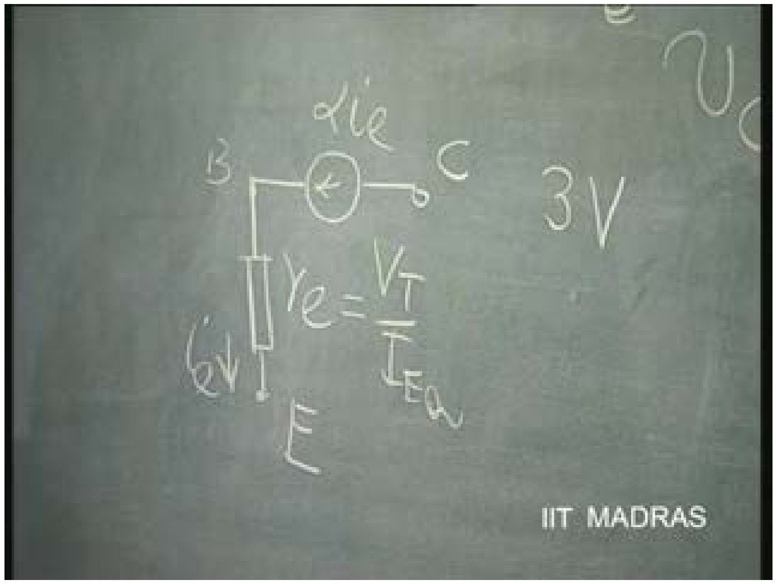

Another one simpler also we have used wherein, we just said this is a short circuit; and if this is i e, that is Alpha times i e. Simpler than that, which is nullator norator one; we just said this is I e and Alpha is equal to 1and there is no base current at all.

So, that is the simplest equivalent circuit. So, what we said was this is a short circuit and this is Alpha times i e; this is i e. This is simpler than this; and further, we just said this is i e. This is i e. Alpha equal to 1. The ideal transistor equivalent circuit; and you see here, if you represent this by an equivalent circuit like this, i e if it is taken, i e is the current, source current here; that means, the current in this is always zero.

Between these two points, potential is zero, the current here is zero; and therefore, these two points were replaced by what is called a nullor; because current through this is zero, voltage across it is zero. That has been brought about by definition of an ideal transistor here. This is i e and this is i e; in which case, only when this is i e, this current is going to be zero.

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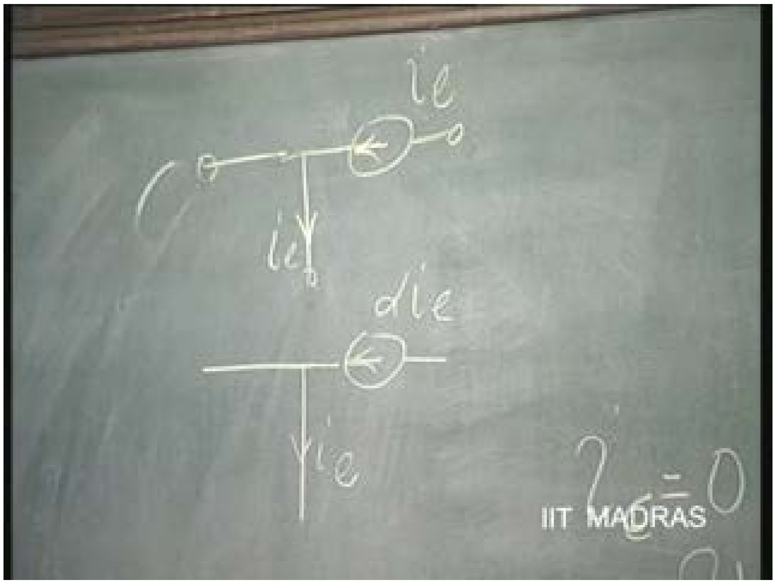

Therefore, between these two points, you represent it by a nullor and here this is a norator. This is a source which can give you any current across it; any voltage can be sustained. So, this is the root to the ideal network representation of a transistor. So, this is the base, this is the emitter; so, junction between this and the collector, this is the emitter and this is the base. Through the base, there is no current.

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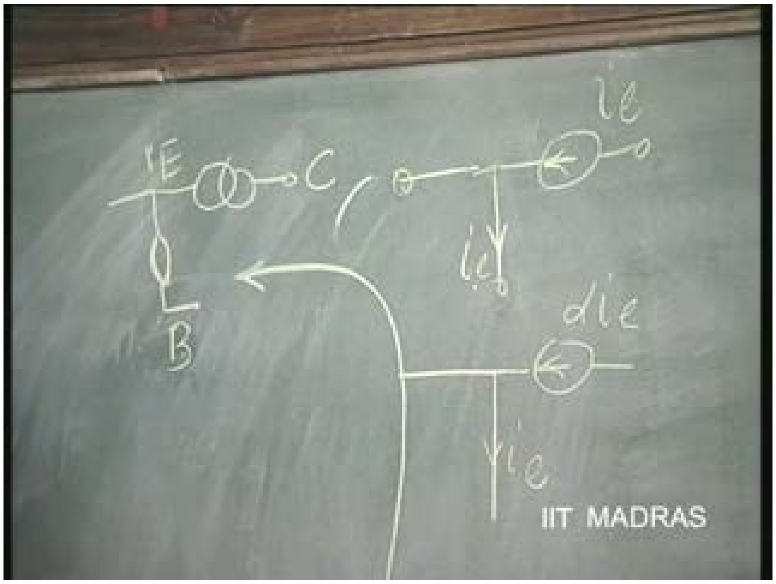

So, you can therefore see the development of the equivalent circuit. In most of the non-ideal things, we will use this equivalent circuit. In a very big circuit, we can even use this nullator-norator equivalent. Is this understood now? This, we had already discussed earlier.

Now, I just want to modify this slightly and bring about non-ideality here. This is not a current source which is ideal; there might be a large resistance of the order of tens of megaohms across it because, it is a reverse bias junction. Collector base junction is a reverse bias junction. So, it is not a current source; there is a resistance which we will call as r c across this. So, please remember that this is a new thing that we have brought about here. Across collector base junction, there is a resistance which is of the order of tens of megaohms, which we have been earlier ignoring.

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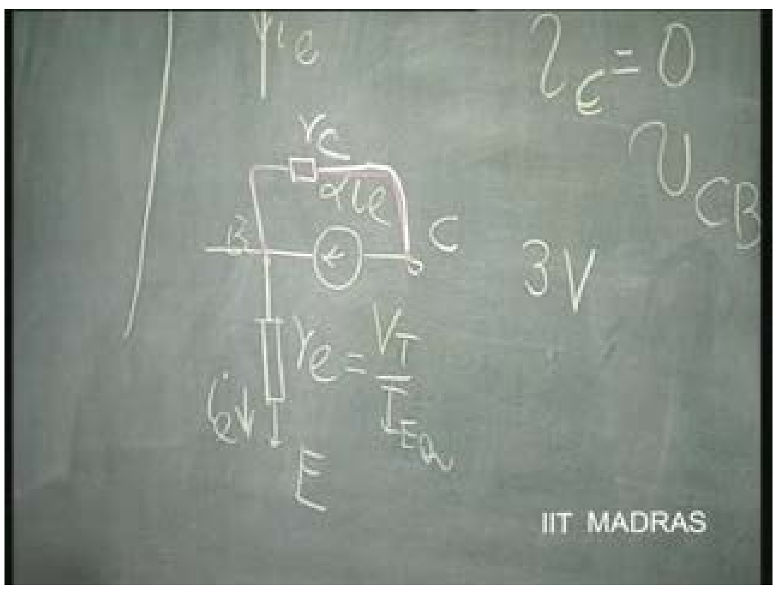

What does this mean? That at any given operating point, we had assumed that the characteristic is an independent... it is independent of collector base voltage. But, there is a dependence on collector base voltage for this current. That is why... collector base voltage dependence comes about because of r c. Earlier, it was independent of collector base reverse bias voltage; but there is a dependence on collector base voltage now; and this slope at any given point is what is called r c. This is a small signal resistance; which is, r c is nothing but Delta V C B divided by Delta I C; change in the collector base voltage for a change in collector current, by definition, at a certain operating point. This is typically of the order of tens of megaohms.

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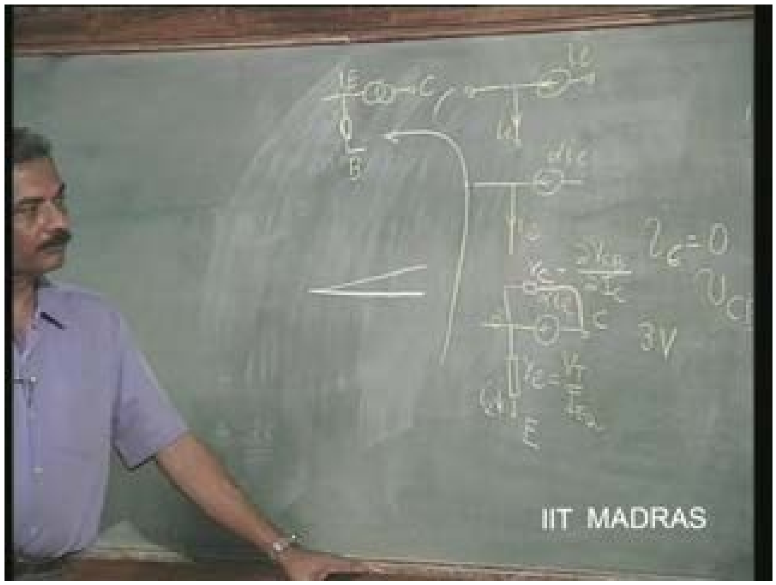

Let us try to learn more about this output resistance for this transistor, bipolar junction transistor. This effect that we are going to discuss is called Early’s Effect. What is it? We know that... again, we will take the same p n p transistor that we have used earlier. This is the emitter current; we have the collector; we see most of the emitter carriers at the collector and very little of it is left as the base. Alpha, very typically, is made close to 1, when it is forward biased at the emitter base junction and reverse biased at the collector base junction.

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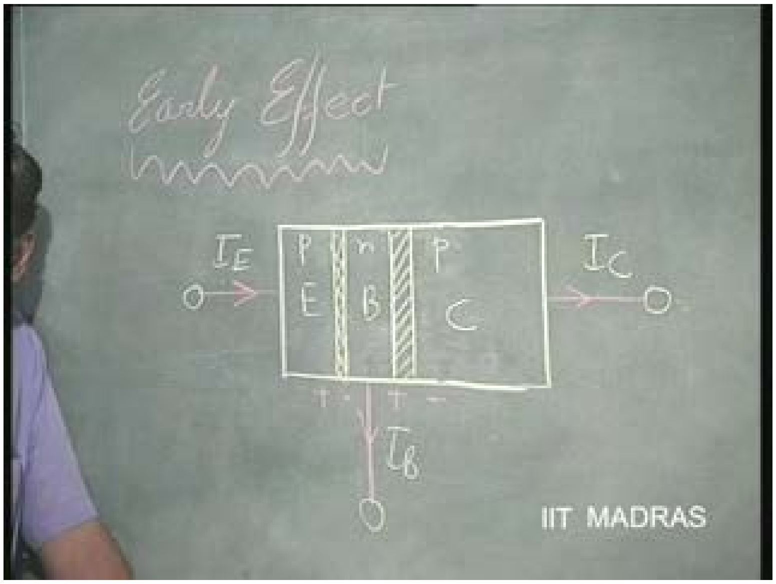

Now, the depletion layer width here keeps increasing as this voltage V B C keeps increasing. So, when this voltage V B C increases, the depletion layer width increases. Now, what happens? Of course, the field here will assist; it will increase and it will assist these to fast come to this side. But, first of all, these things have to come to this side. That does not depend upon the field. But what happens here is that because because V B C increases, the base width decreases; and those holes which are injected down to the base, a larger number of these will get collected here. That means Alpha is going to be becoming closer to 1.

So now, Alpha depends upon V C B. That means Alpha will become closer to 1; or, I C is going to increase as V C B increases. This is what is called Early Effect. Is this clearly understood? Because the depletion layer width increases, the base transport factor is going to become closer to 1 as V C B increases. That means I C is going to increase because I C is equal to Alpha times I E. For the same I E, let us say... earlier we said, for a given I E, and this is V C B variation, this is going to remain constant at Alpha times I E. if Alpha is now going to increase as V C B increases because of Early Effect, then what you will see is going to be the effect like this.

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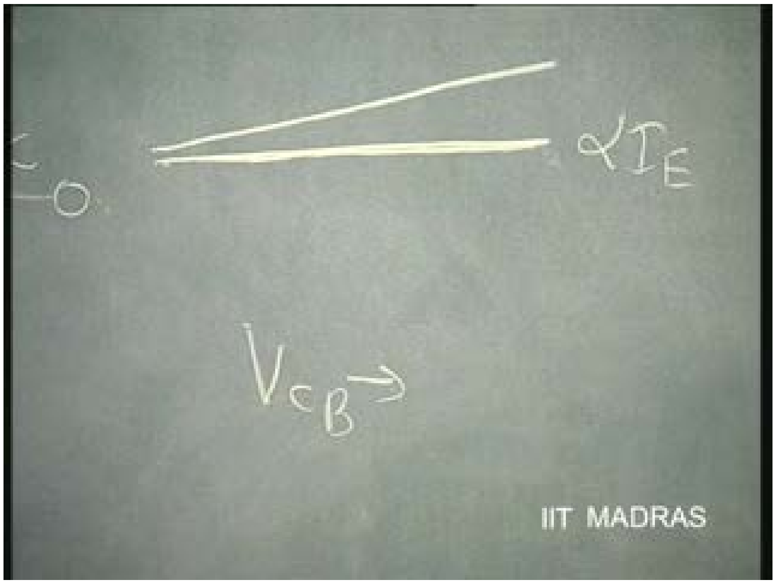

That means, actually speaking, in our sort of characteristic curve, if this is I C for different V C B and for all values of I E you are putting down here, these will go on increasing. Now, what happens because of Early Effect is, this effect is going to be felt more at higher currents; and therefore, this whole characteristic can be expanded like this and it will intersect at a particular point and this is called early voltage.

For the next current, it might be something like this and all these things will intersect at a particular point in this axis and that is called early's voltage; or mathematically, I can say, I C is equal to Alpha zero times I E, which is the independent factor compared to V C B, 1 plus V C B divided by V E where V E is the early's voltage.

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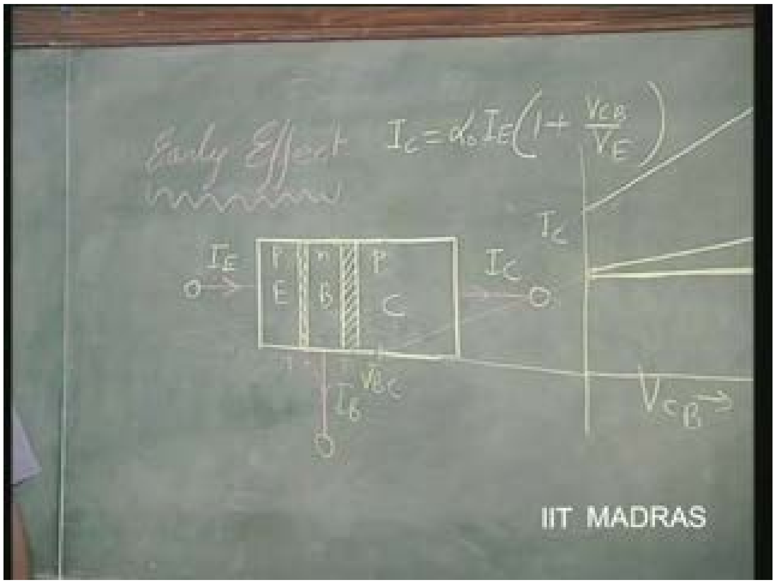

So, it is a factor dependent upon V C B. For an ideal transistor where this effect is not there, V E is infinity. So, I C is equal to Alpha naught times I E. Otherwise, it is Alpha naught – Alpha naught is the Alpha which is independent of V C B, into 1 plus V C B divided by V E. This voltage, V E is called early voltage.

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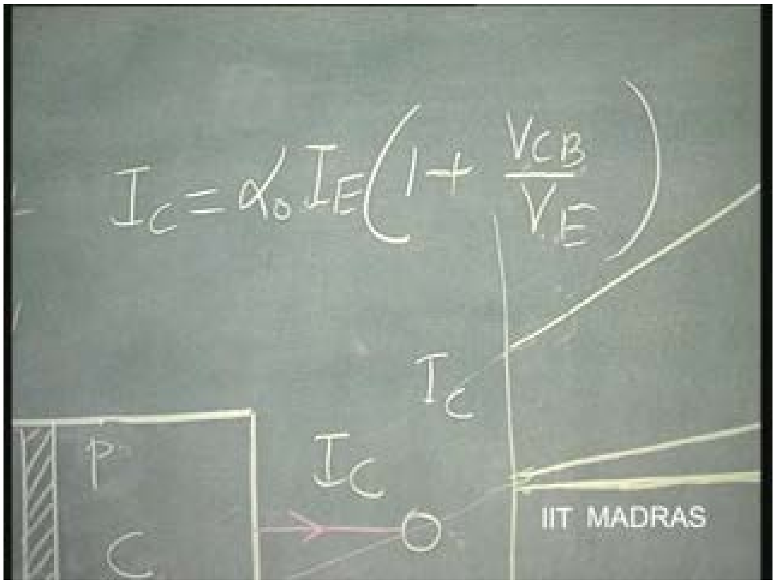

So, once again, I can draw the characteristic here clearly to show you this is V C B, I C versus V C B for different values of I E. So, you will get something like this. You extend this. This is minus V E. This this is actually V B C. This is positive. V B C is positive for p n p. So, for another transistor, another current, this is going to be the characteristics. For a lower current ... So, these are going to be extensions. Otherwise, actually, characteristic is going to... actual characteristic, because this is... this region, the transistor goes to saturation. So, this will be the actual characteristic. So, these extensions join at a particular point. This is an important voltage which is called early voltage.

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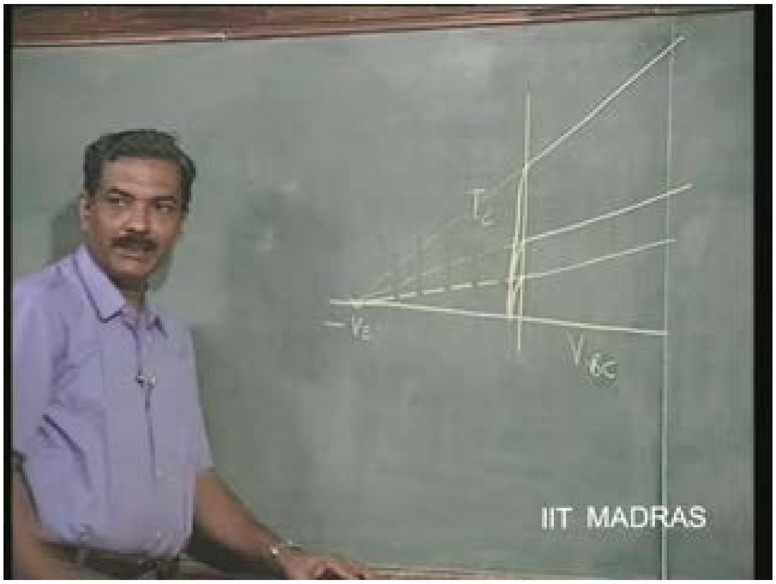

In our expression therefore, please remember. You have to give this value if you want to see this effect of output impedance. So, output impedance is nothing but what Delta V C B divided by Delta I C. So, that is equal to, let us say, Delta I C by Delta V C B is nothing but... from this expression, Alpha naught I E by V E; it is nothing but the coefficient of V C B. So, V E divided by Alpha naught. So, given the early voltage as well as the operating current and Alpha naught, we can find out the value of what? What is this? r c.

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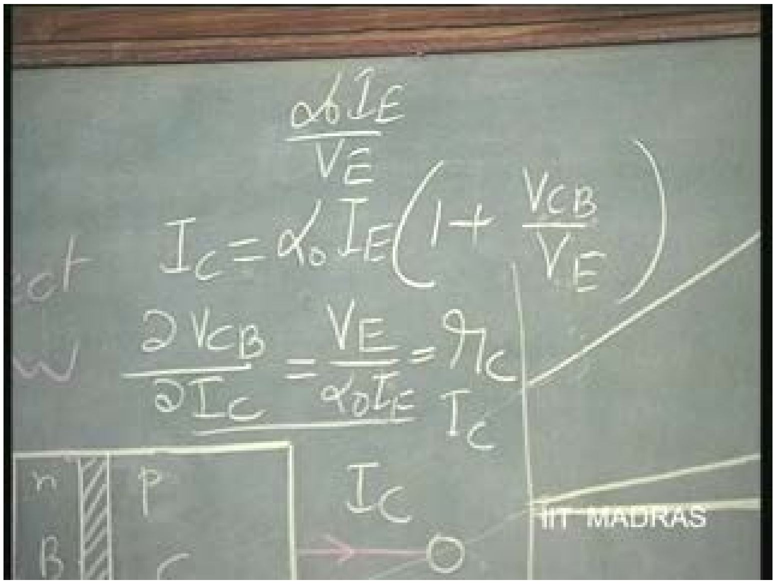

So, this is an important small signal parameter. If you are therefore analyzing your circuit using Spice programs, etcetera, you have to give the early voltage.

Now, I would like you to therefore compute the value of output impedance for the example that we have chosen, Example 10. Determine the output resistance if r c is given as 1 megaohms. r c is given as 1 megaohms. Determine the output resistance.

Now earlier, output resistance was 6 K for the example. Now, how much is it going to differ from 6 K? You will see that it is not going to differ much from 6 K in spite of the finite r c of 1 mega ohm. So, but, you please use the equivalent circuit and find out for yourself. This will be worked out. This is a problem. This is problem, what is the number? – 2.

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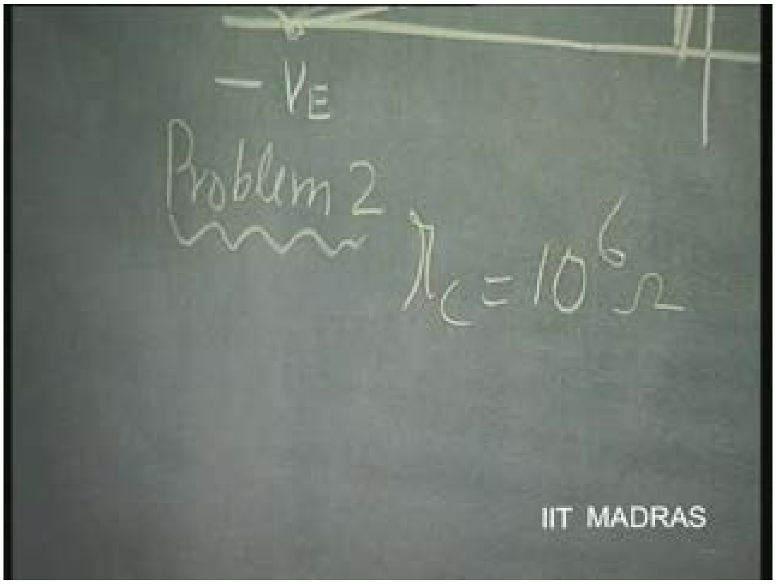

Determine the output impedance for Example 10, if r c is equal to 1 mega ohm.