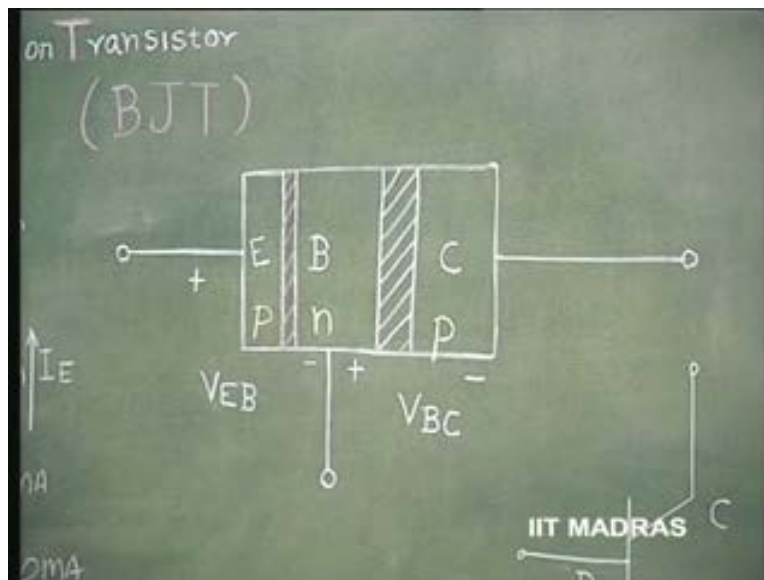


**Electronics for Analog Signal Processing - I**  
**Prof. K. Radhakrishna Rao**  
**Department of Electrical Engineering**  
**Indian Institute of Technology – Madras**

**Lecture - 20**  
**Bipolar Junction Transistor**

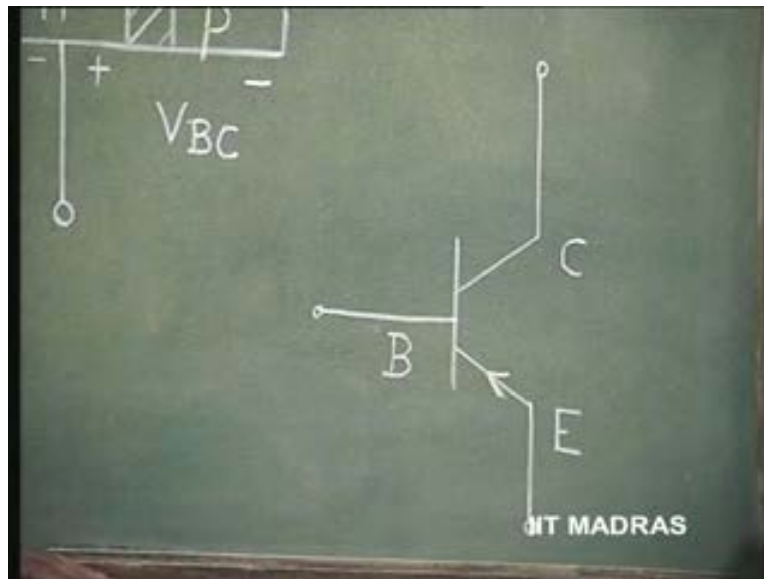
In the last class, we understood the functioning of a bipolar junction transistor as an active device; and we took for our illustration, a PNP transistor like this, and we explained how the collected current is almost only the emitter current.

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Now, for the PNP transistor, the symbol, instead of drawing it like this, the symbol for the PNP transistor is as shown here.

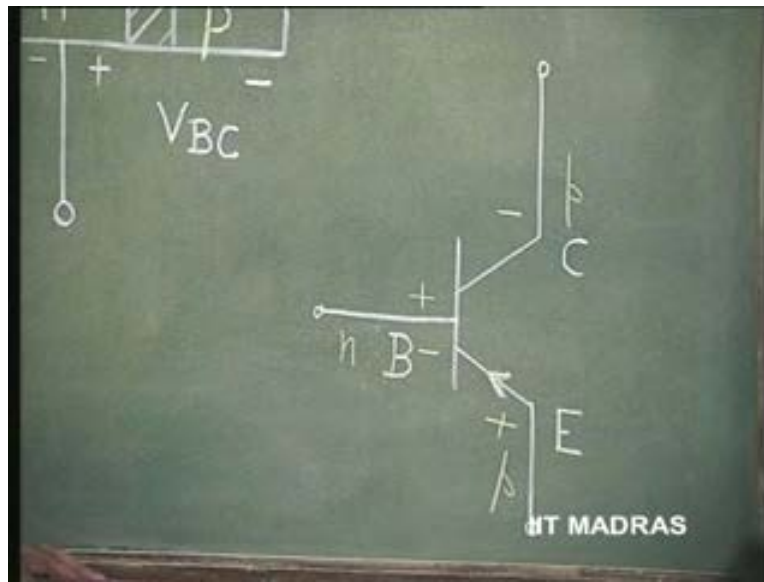
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Here, the direction of the arrow, the arrow is put at the emitter; the direction of the arrow, always indicates the direction of actual flow of current. Here, if this is forward biased, emitter base junction is forward biased, the current in this is going to be injected from the emitter on to the base; actual direction of flow of current. And therefore, arrow is always put in the emitter. And, the collector is this; and the base is this.

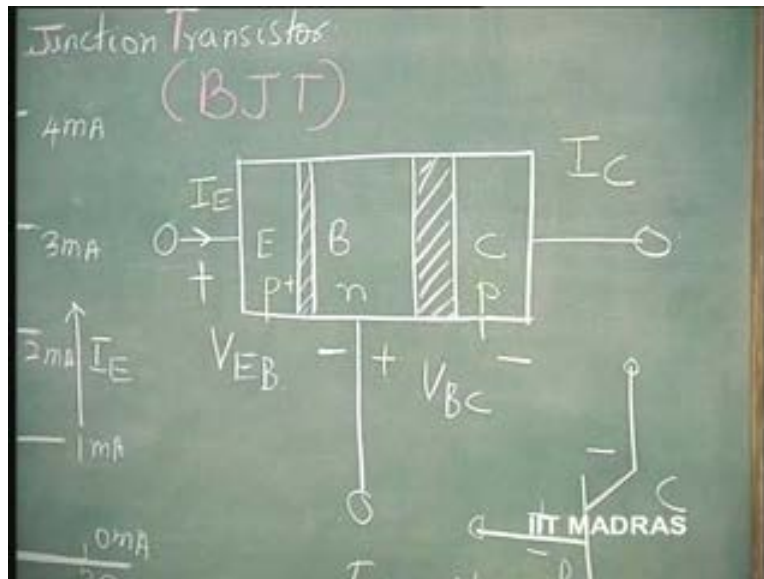
So, this kind of symbol indicates a PNP transistor. In the case of a NPN transistor, the arrow direction is opposite. Now, as far as the transistor action is concerned, emitter base junction is forward biased and the collector base junction is reverse biased, so as to make the entire collector current become equal to the emitter current; and Alpha becomes very nearly equal to 1. That is, the transistor action.

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Current in this is represented as total current, as  $I_E$ . Almost the entire current, that is emitter current, becomes part of the collector current. That is transistor action. That is facilitated by forward biasing base to emitter junction; and doping emitter very heavily; making the base width very small, so that most of the injected carriers constitute the total current. And, most of the injected carriers come to this part of the junction; and this distance is made so small that there is no recombination here so that most of them come, arrive, at this point junction. And here, there is a field which is aiding them to get collected very fast because of the fact that it is reverse biased.

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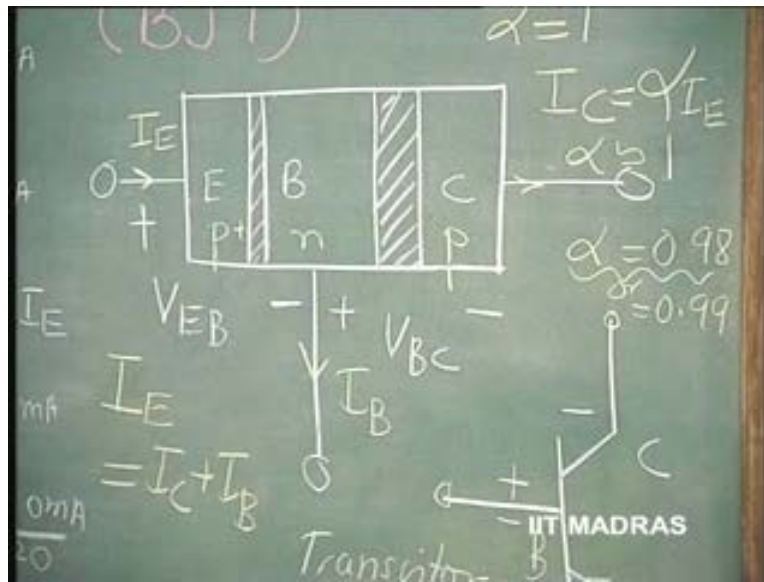


So,  $I_C$  is equal to Alpha times  $I_E$ , where Alpha is very close to 1. The ideal transistor, ideal transistor, therefore Alpha is equal to 1. So, which means, almost all the current gets collected here; and therefore, in the other terminal, there is no current. Base current is zero in the ideal transistor. In practice, Alpha is typically of the order of point 98, point 99, typically. So, Alpha is about point 98; this is the order. So, it is pretty close to 1. Please remember that.

In IC transistors, it can be even made closer to 1 than this. May be, point 995, things like that. So, transistor action means  $I_C$  is equal to  $I_E$ . Base current is zero. Actual current equation at this node therefore is, emitter current is always equal to collector current; plus, we call this, base current. So, this is Kirchhoff's law. This has nothing to do with transistor action. In this node, emitter current is always equal to collector current plus base current.

What is transistor action is  $I_C$  is equal to Alpha times  $I_E$ . In an ideal case, Alpha is equal to 1 and  $I_B$  is therefore equal to zero.

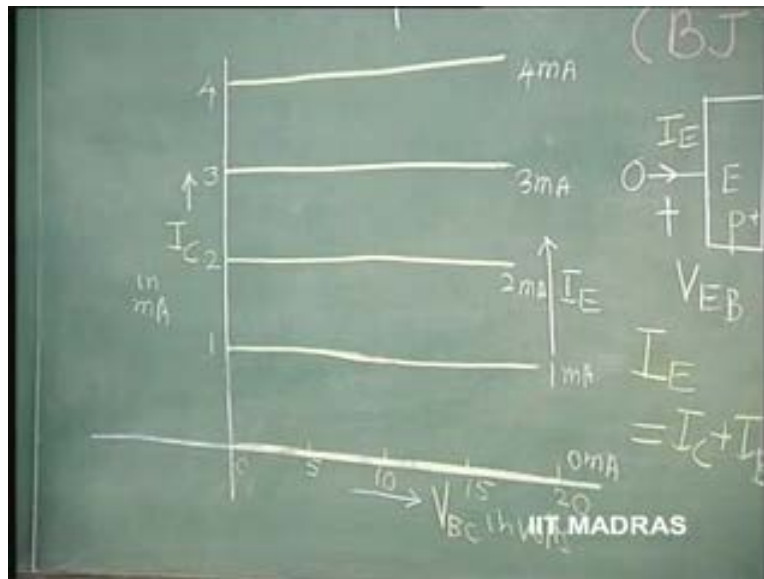
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Now, let us look at this characteristic in a pictorial sense. Whatever be the base to collector voltage, reverse bias voltage, collector current is almost independent of the base to collector voltage. So, it is independent. It depends only on emitter current. If emitter current is 1 milliamperes, for example, collector current is going to be very nearly 1 milliamperes. So, this is emitter current, this third parameter. So, as emitter current is being varied, how does collector current vary?

Collector current remains constant at nearly 1 milliamperes. If it is 2 milliamperes, emitter current, the collector current remains constant, independent of base to collector voltage, which is the reverse bias voltage, in this. It remains constant at 3 milliamperes. It remains constant at 4 milliamperes.

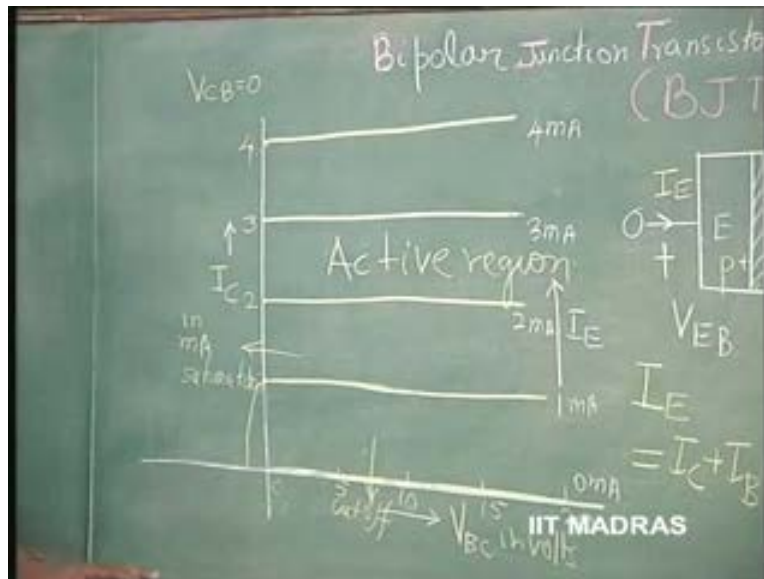
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Now, strictly speaking, beyond this point, this is the point where  $V_{BC}$  is equal to zero, beyond this point, the transistor is said to be in the saturation region; in this region. Suppose therefore, actually, the current will start falling. So, **the** this point is called saturation region. Beyond this point, beyond this point, it is cut-off. This is the active region. This region is called the active region where transistor action takes place; where the relationship  $I_C$  is equal to  $I_E$ ; or,  $I_C$  is equal to  $\alpha$  times  $I_E$  is valid.

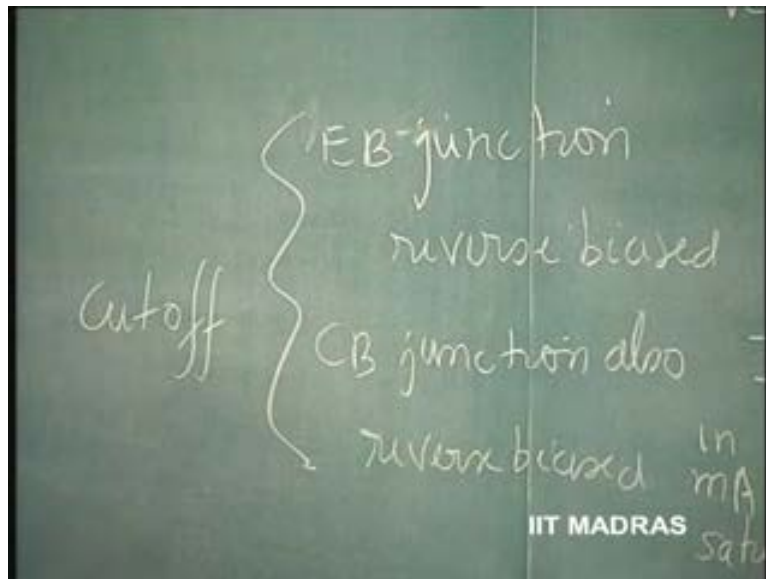
Now, therefore, we just say,  $V_{CB}$  equal to zero is the border line separating saturation and active region; and  $I_E$  equal to zero is the border line separating cut-off and active region.

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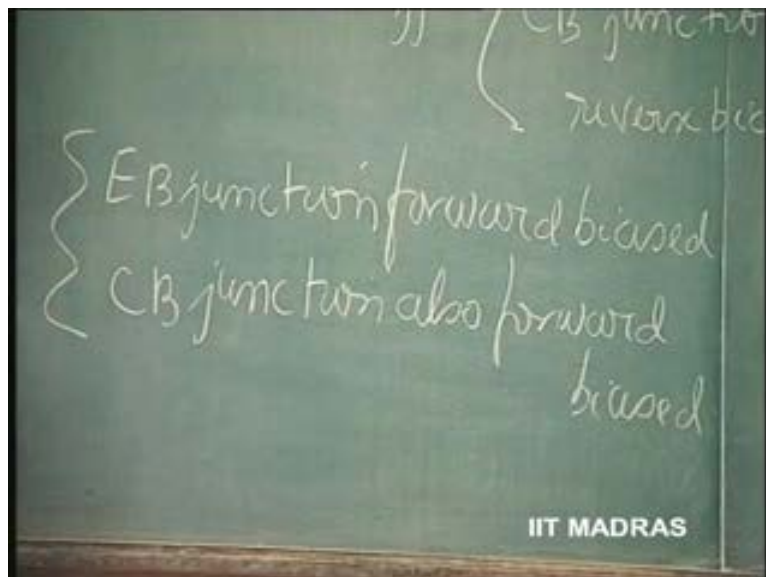
Once again, let us consider the other regions. If collector base junction is reverse biased, emitter base junction is forward biased, it is said to be in the active region. If emitter base junction is reverse biased and collector base junction is reverse biased, it is said to be in the cut-off region. So  $V_{EB}$ ; emitter base junction – reverse biased, collector base junction – also, reverse biased, the transistor is said to be in the cut-off. Ideally speaking, you can therefore consider that these are two junction diodes which are reverse biased and therefore they are all open.

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So, emitter base junction can be treated as open circuit; collector base junction can be treated as open circuit; so, this transistor is cut-off. Then, we have emitter base junction – forward biased and collector base junction – also, forward biased;...

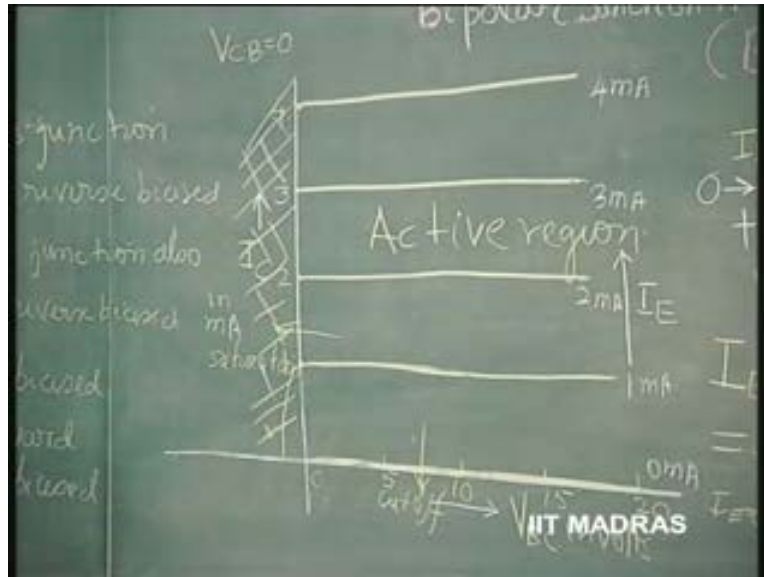
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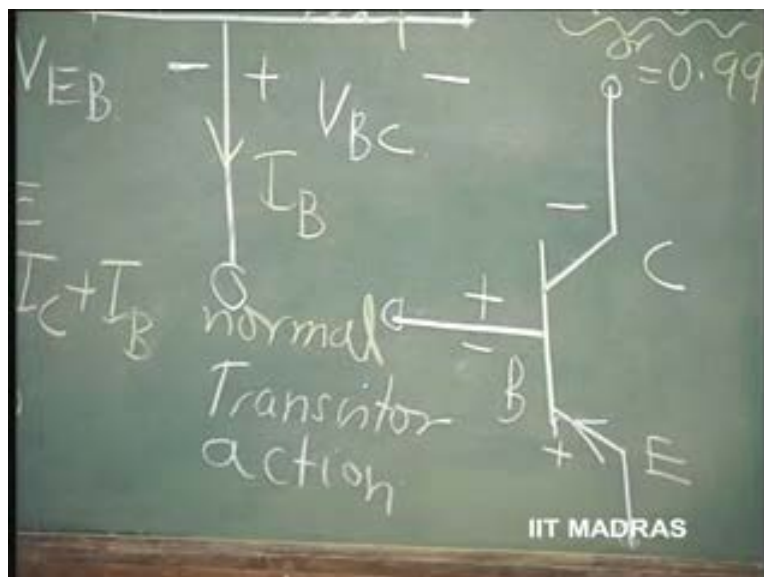
... the transistor is said to be in the saturation region; that is in this region. Transistor is said to be in the saturation region.

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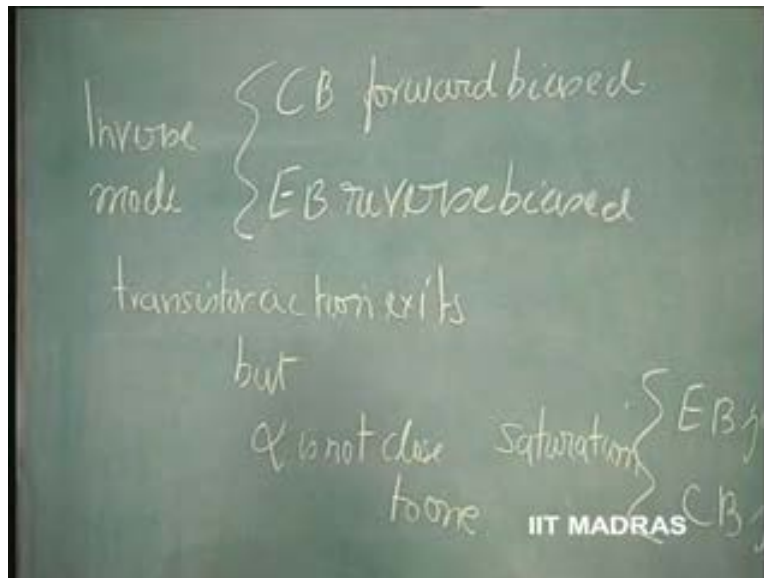
Then, there is another one. That is, collector base junction – forward biased, emitter base junction – reverse biased; transistor is said to be in the inverse mode. Not normal mode, but is in the inverse mode. This is normal mode transistor action.

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And therefore, if collector base is forward biased, emitter base reverse biased, the transistor is in the inverse mode. In this, transistor action takes place, exists; but, Alpha is not close to 1. It is not close to 1 because, this transistor has been fabricated specially to work in this normal mode.

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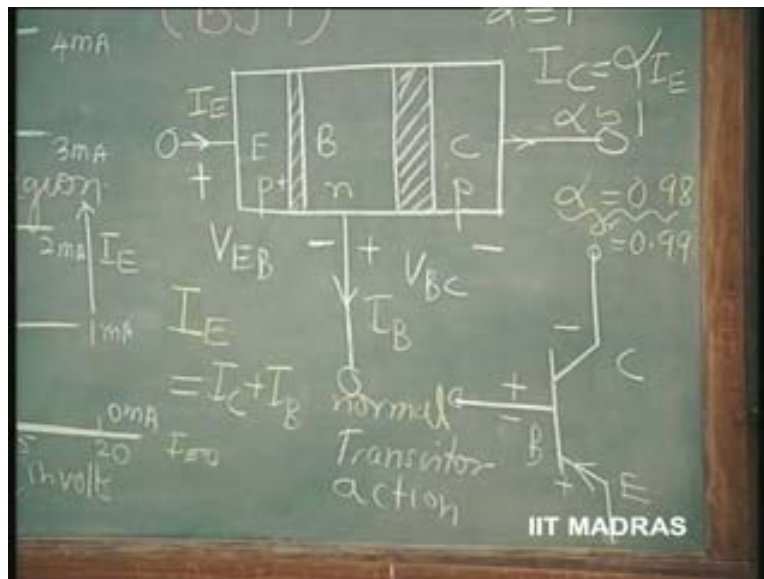


If it is symmetric; if it had been PNP without any care for any special effect regarding highly doped emitter, etcetera; if it is just PNP and symmetric; then, both could be normal modes. We can use emitter as collector and collector as emitter. In this case, it is not so. So, please remember that the characteristic curve for the transistor can be easily obtained. You yourself can draw it without any hesitation, once you know that  $I_C$  is equal to  $\alpha I_E$ .

Therefore it is not necessary, it is not important, that we should keep pictorial view of this. We can remember these equations very easily and therefore this is just done for this once; and we are not going to use this information again in our future analysis. So, this graphic way of representing the output characteristic of the transistor is going to be over with this. In further discussions, we will not use this. We will strictly use this information. It is this information which can be easily pictorially represented.

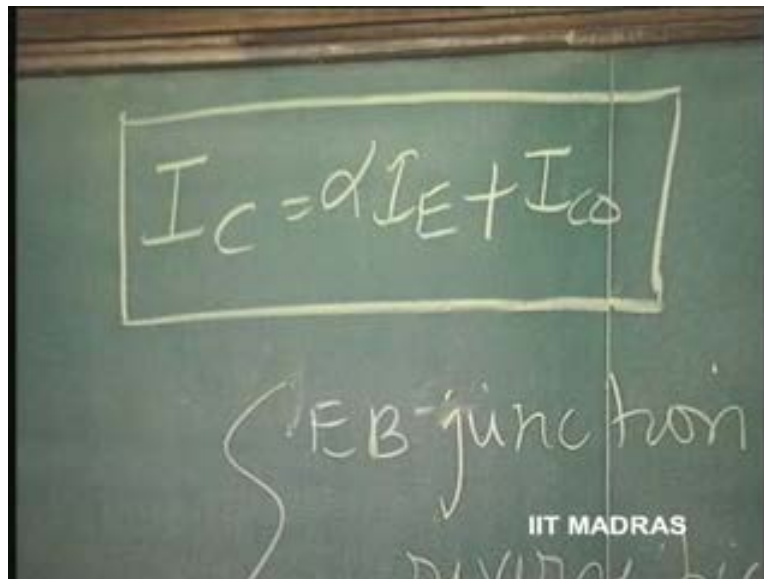
Now, as far as the non-ideality of the transistor is concerned, in the last class itself I have told you that Alpha is not equal to 1;  $I_C$  is equal to Alpha times  $I_E$ . Not only that, a better approximation is  $I_C$  is equal to Alpha times  $I_E$  plus  $I_{C0}$ ; because, this junction is reverse biased. There is this reverse saturation current also flowing in addition to the injected current.

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So, this will add on to the collector current; and actual current is going to be Alpha times the injected current, plus  $I_{C0}$ . Now, this equation can be normally used whenever we want fairly accurate information about the transistor.

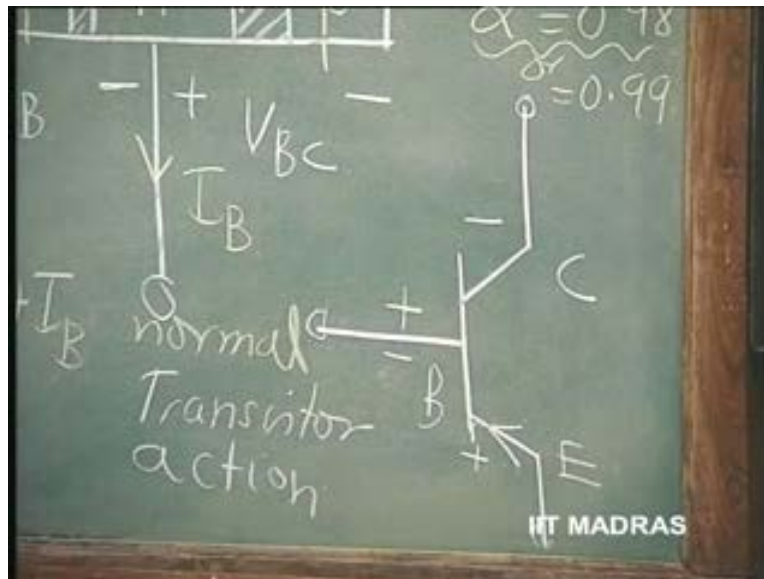
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Otherwise, most of the applications, we can just use the information that Alpha is equal to 1. That is going to simplify the analysis of any of these transistor circuits; particularly in situations where we have systems built with large number of transistors, where we would like to only approximately analyze the circuit. And therefore, we would like to quickly arrive at the results; in which case, the easiest approximation for the transistor is Alpha is equal to 1.

Now, with Alpha equal to 1, we have shown that  $I_B$  is equal to zero. Now, look at this structure.  $I_B$  is zero. Alpha equal to 1; because of that,  $I_B$  is zero. And, emitter base junction is forward biased; which means,  $V_{EB}$ , ideally, should be equal to zero. If it is an ideal diode, emitter base, if it is replaced by a ideal diode drop, will be zero. Otherwise, it is point 5 to point 7 volts. So, ideally speaking,  $V_{EB}$  is equal to zero, if it is an ideal diode approximation and  $I_B$  is equal to zero.

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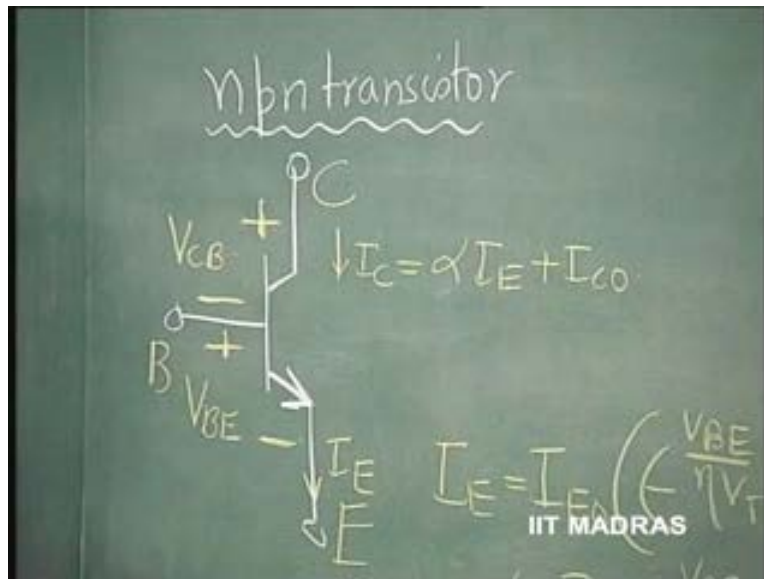


So, you can see here that at the input,  $V_{EB}$  is going to be very nearly zero and  $I_B$  is going to be very nearly zero. This concept of input voltage zero and this current being zero can be represented later on by an equivalent element. This, we will discuss later. But, remember that input voltage is zero and this current is zero, in the case of an ideal transistor.

Now, as far as output current is concerned, it can be always anything; but it is dependent upon the input current  $I_E$  here. So, it is equal to  $I_E$ , very nearly equal to  $I_E$ ; and it can flow into any resistance and develop any potential. So, you have any potential getting developed at this point, strictly speaking. So, this is a source, dependent source.

So now, let us consider the other type of transistor, NPN. So far, we had discussed PNP transistor. So, the other type of transistor, NPN transistor. The transistor action again occurs according to the same condition; that, base to emitter junction is forward biased and collector to base junction is reverse biased. But the polarity is ((...Refer Slide Time: 18:00)) just now will be the opposite. So, base is now made positive with respect to emitter and collector is made positive with respect to base, in order to achieve transistor action.

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So, the equations will remain the same as here. Only the direction is going to be different. Now, emitter current is going to be, actual direction of current is indicated by the direction of the arrow; so, it is in this direction. So, the collector current is going towards the node and base current also will be towards the node; actual direction of the current.

So, the equation still is valid;  $I_C$  plus  $I_B$  is equal to  $I_E$ . This is the Kirchhoff's law; this is still valid. Only thing is, emitter current is going away from the node; collector and base currents are going towards the node.

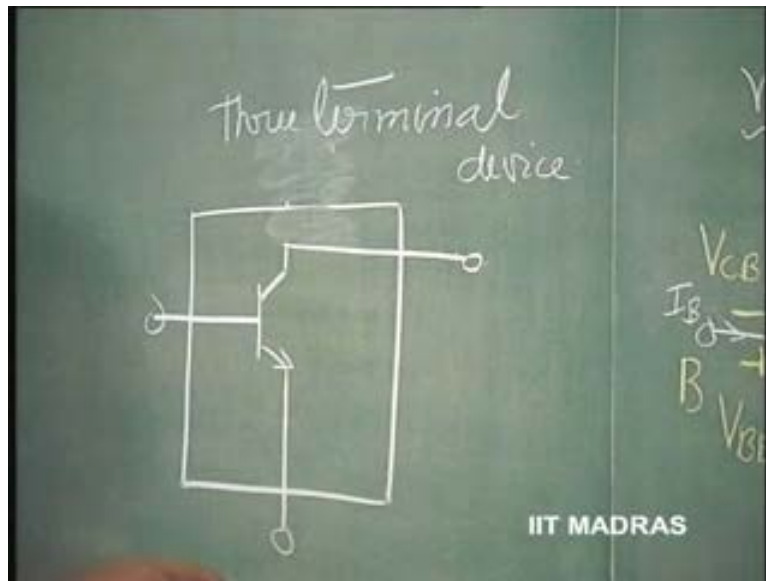
So, that is the difference between NPN transistor and PNP transistor. Only the biasing is going to be different; in the sense, bias voltages will be opposite to that of the earlier situation. But, base to emitter junctions should still be forward biased and collector base junction should still be reverse biased.

So, in future, in our all our discussions, we will be only using this symbol, these symbols, for NPN and PNP transistors; and automatically, please remember, the arrow direction will so actual direction of current will flow in the circuit, if it is biased properly.

Now, let us consider this as a three terminal block. So, assume that this has been put inside a block, supposed to be the amplifier block. So, we have now a three terminal block available here. Differently... So, this is the input port and that is the output port. We have had earlier, the general discussion about two port network and the two ports were independent.

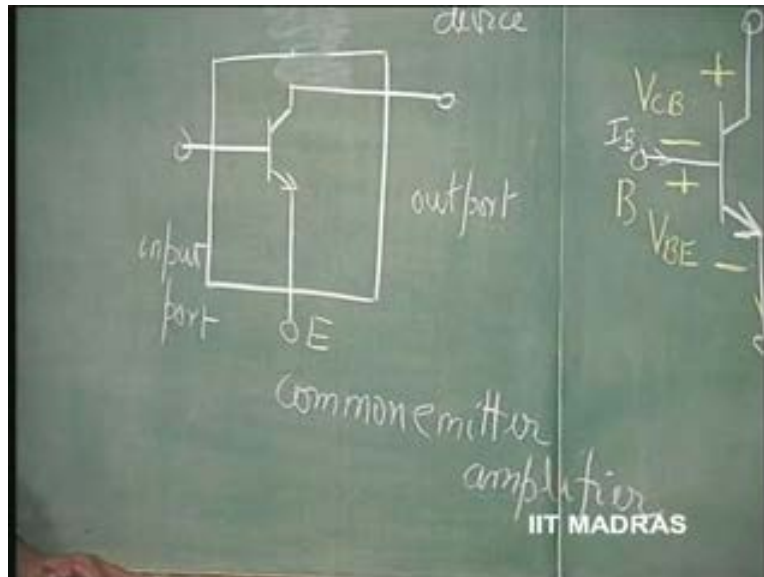
Here, one terminal is common to both input and output. So, this is actually a three terminal device, obviously, with input port and output port having emitter as common.

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In this case, in this device, we have input port and output port with emitter terminal as common terminal between input and output; so we can call this a common emitter amplifier.

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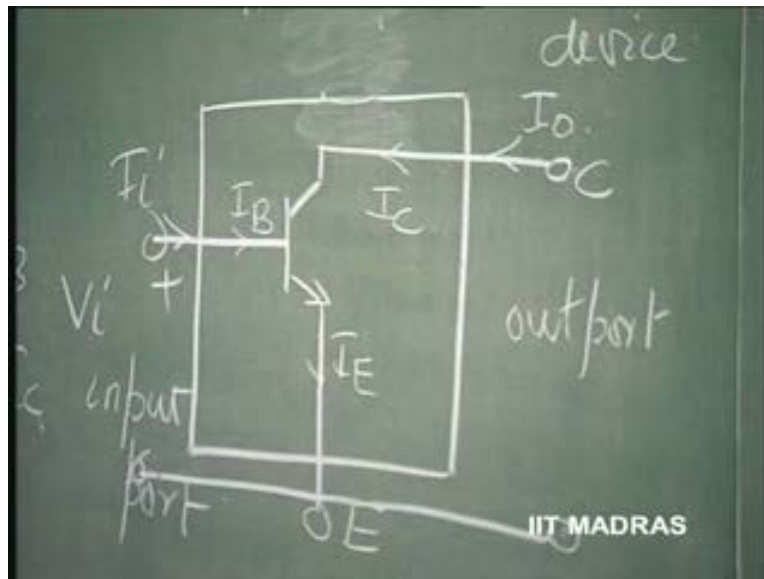
The idea is, this emitter terminal is common between input and output. So, we have a common emitter amplifier here. Let us now represent this therefore this way. The input voltage here,  $V_i$  for this, is same as  $V_{BE}$ . The output voltage is same as  $V_{CE}$ . Input current in this case... So, input voltage is equal to  $V_{BE}$ . The output voltage is equal to  $V_{CE}$ .

So, E is common, you can see. Input current is same as base current. You can look at this; this is the base current. And, output current is same as collector current.

You can write down this; this is  $I_E$ , emitter current; this is base current; this is collector current.



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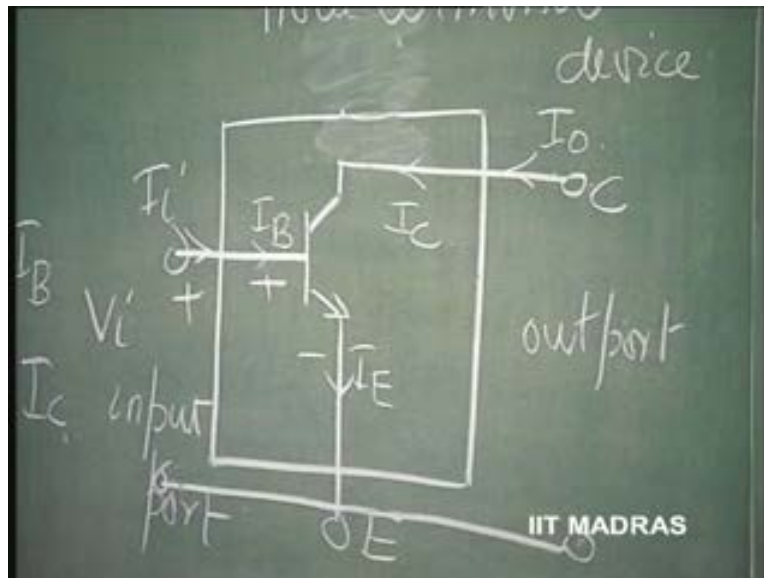
So, in this common emitter amplifier which is put inside an amplifier block, we can now represent  $V_i$ , which we have earlier used for our two port network. Here, it is same as  $V_{BE}$ .  $V_{naught}$ , which we have used in our two port network, is same as  $V_{CE}$ .  $I_i$  is same as  $I_B$ .  $I_{naught}$  is same as  $I_C$ .

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$$V_i = V_{BE}, I_i = I_B$$
$$V_o = V_{CE}, I_o = I_C$$

Now, let us consider the ideal transistor situation. So, ideal transistor. In an ideal transistor, for the transistor action to take place, we must have this forward biased. So, this has to be forward biased. This junction has to be forward biased. And, if it is an ideal diode, the junction drop is zero.

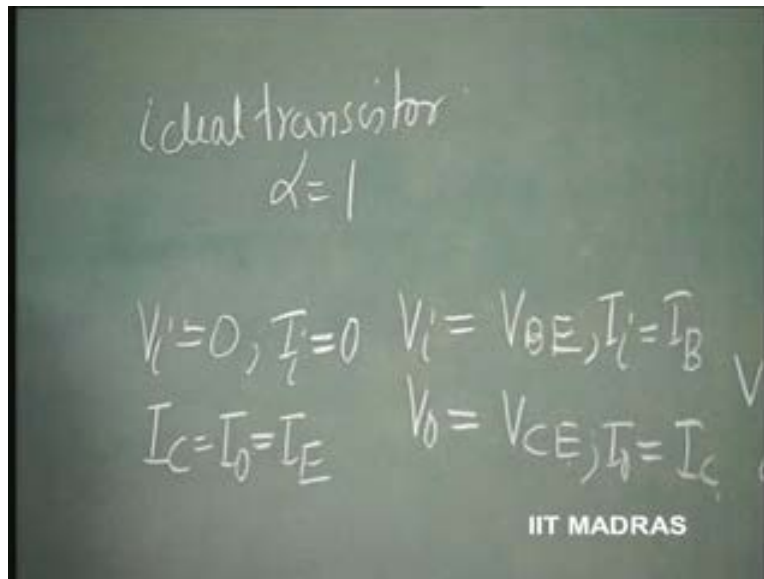
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So, which means,  $V_i$  is zero. So, in an ideal transistor, in this case,  $V_i$  is going to be very close to zero. In practice, it is about point 5 to point 6 volts. Please remember that in practice, it is a semiconductor diode and it has a cut-in voltage of about point 5 to point 6 volts; and  $I_i$  is going to be equal to zero, because ideal transistor, Alpha is equal to 1.

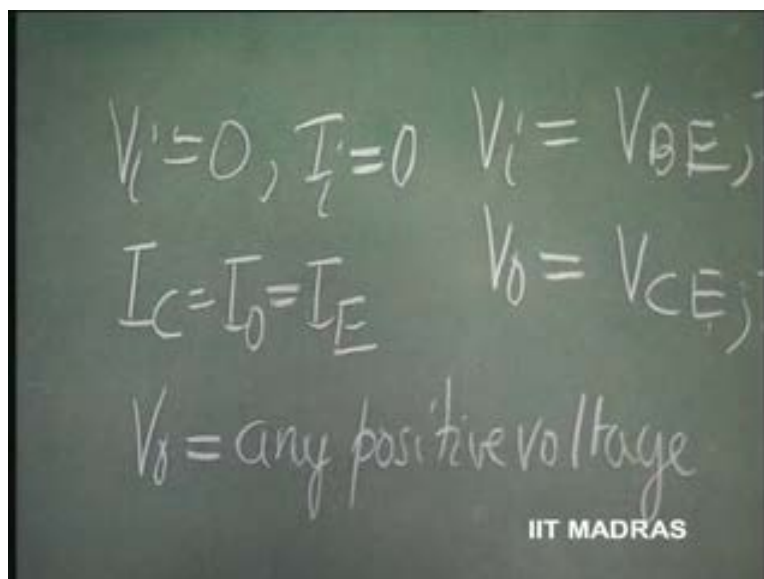
$I_C$  is equal to  $I_E$  and from our this thing,  $I_C$ , if it is equal to  $I_E$ ,  $I_B$  is equal to zero, according to this.  $I_C$  is equal to  $I_E$ ;  $I_B$  is equal to zero, automatically. That means this is the situation of the input for a common emitter amplifier.  $V_i$  is equal to zero,  $I_i$  is equal to zero; then  $I_C$  which is nothing but  $I_{naught}$ ,  $I_C$  is equal to  $I_{naught}$ , is going to be equal to  $I_E$ .

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So, this is the output current and  $V_{CE}$  which is  $V_o$  can be any, anything; any positive voltage.

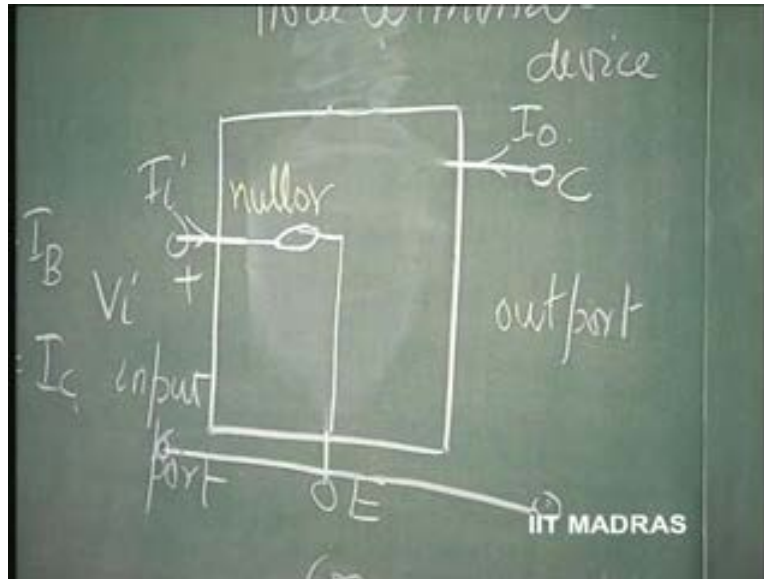
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So, any voltage...  $V_o$  can be anything. That means, actually speaking, I can now represent this by means of an equivalent circuit; the simplest equivalent circuit.

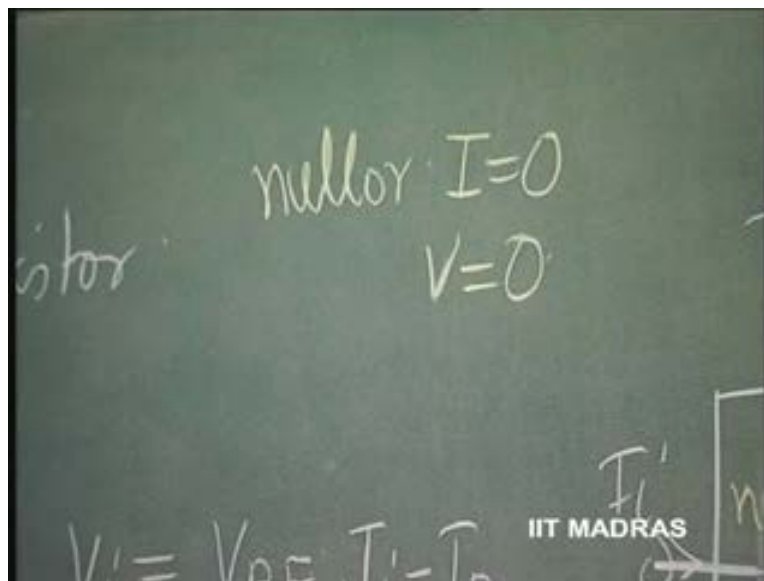
So, we will put down this transistor in terms of its equivalent. I now put here what is called as some block here; what it says is, this is what is called as a nullor.

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What is a nullor? By definition, nullor is something which has current  $I$  through it equal to zero and voltage across it equal to zero. Nullor. Both are nulls.

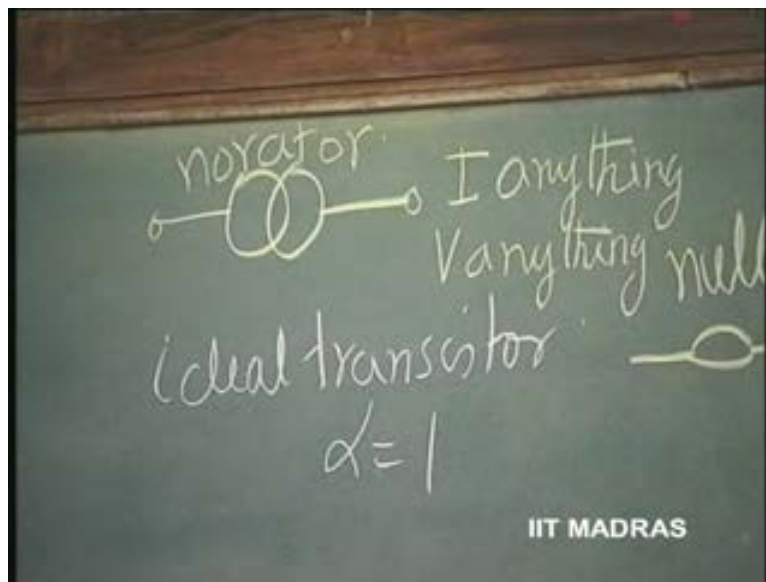
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Current through it equal to zero; that means it will not allow any current to flow through. And, voltage across it is equal to zero. So, this is called a nullor.

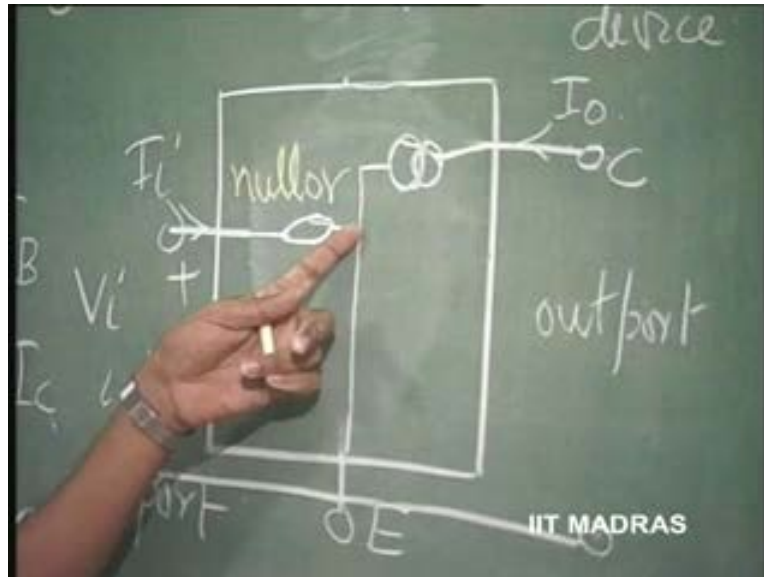
And here, I put a source; which is to say that, this current has to flow through this. So, this source is something that can deliver any amount of power. That means, any voltage or any current, depending upon what is applied here. So, this is called a norator. I is anything. V is anything. This is called a norator.

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An ideal transistor therefore, is a combination of nullator and norator, with a junction between nullator and norator.

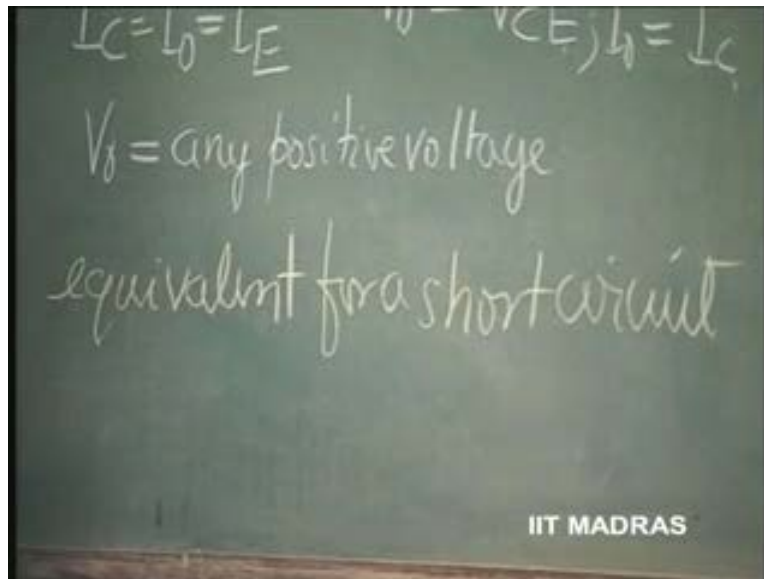
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This is the simplest equivalent circuit, in terms of networks, for a transistor. Is this clear? Another thing I have to tell you is, this nullator, is  $I$  equal to zero,  $V$  equal to zero; and norator is something with  $I$  anything and  $V$  anything.

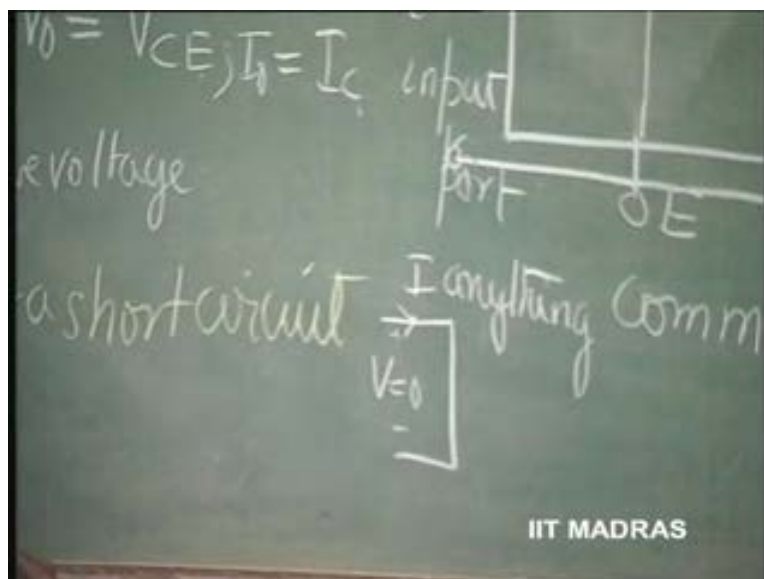
This concept can be made clear by defining an equivalent for simplest things that are possible in electrical engineering. It is a short circuit and an open circuit. Let us therefore find out the equivalent for a short circuit in terms of nullators and norators.

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What is a short circuit by definition? Short circuit is something like this. Let us say, here the voltage is zero and current is anything, not defined. Current can be anything.

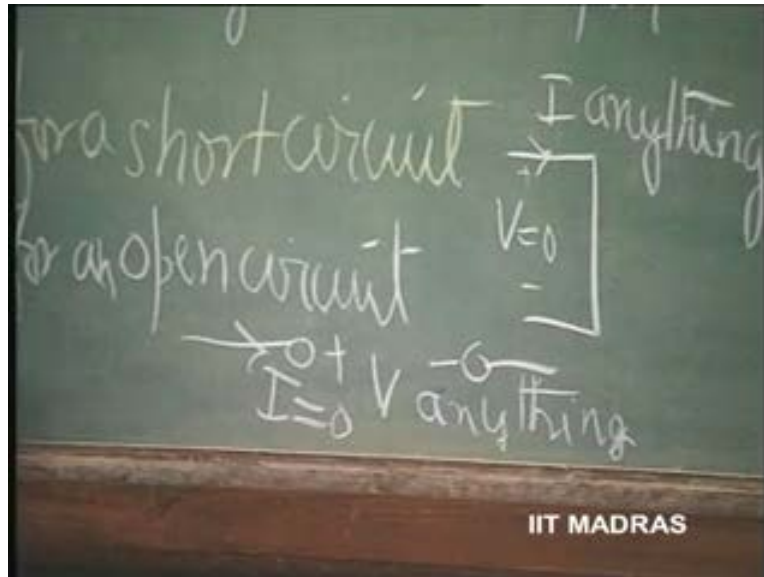
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That is called a short circuit.

What is an open circuit? For an open circuit, the current is zero. Current through the open circuit is zero; but voltage can be anything. This voltage can be anything.

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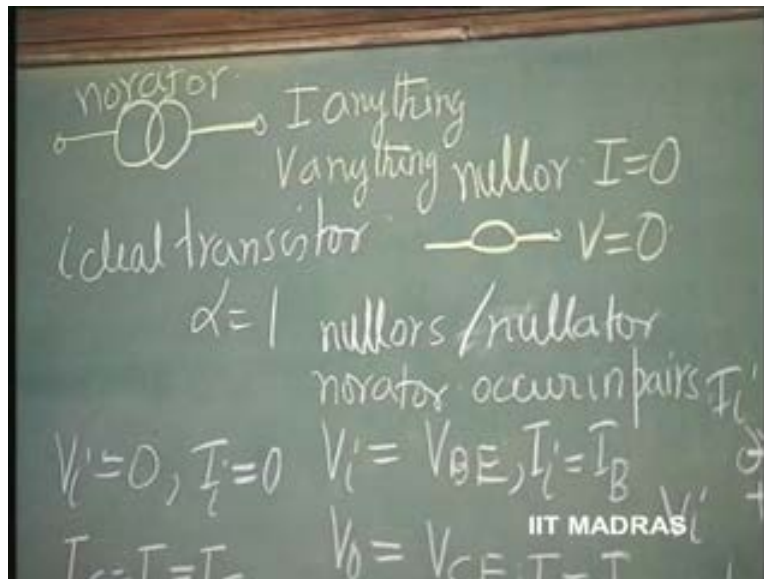


Whereas, in a short circuit, current can be anything but voltage equal to zero. Suppose, therefore, I want a nullator norator equivalent for this. It is very simple. I want a nullator norator equivalent.

Another thing - according to the theorem, nullators and norators cannot occur individually. They always occur in pairs; in, for physical existence of these blocks, nullators and norators occur in pair. Nullors and... nullor or nullator it is called, occur in pairs.

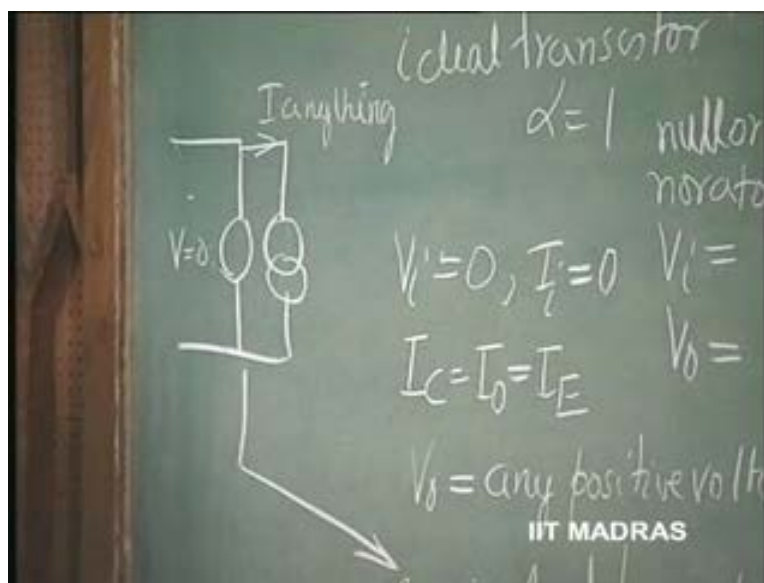


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That means, if there is a nullor, there should be a norator corresponding to that, somewhere in the network. They always occur in pairs. So physically, you cannot have only nullor existing or norator existing; in which case, equivalent circuit for a short circuit will be...

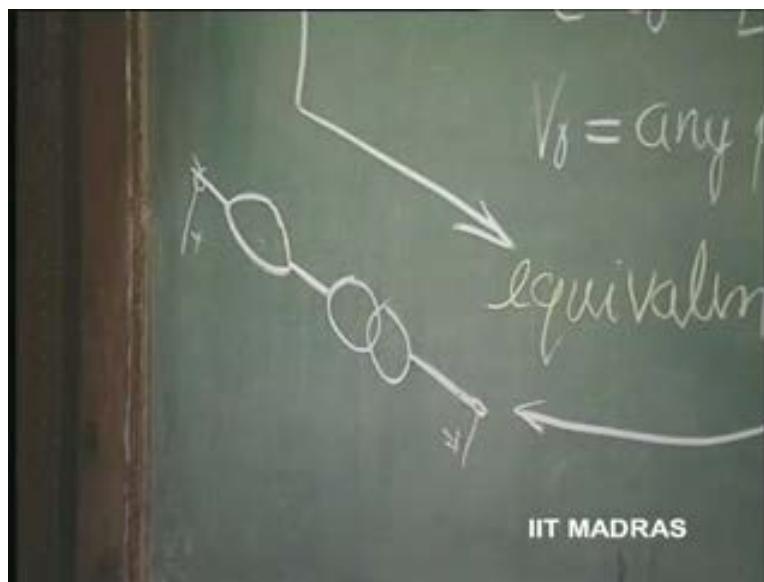
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This is the equivalent circuit for a short circuit, so that, this nullor makes the voltage zero, this norator will permit any current to flow through. So, this nullor will make the voltage zero, and this will permit any current; so effectively, you have a short circuit.

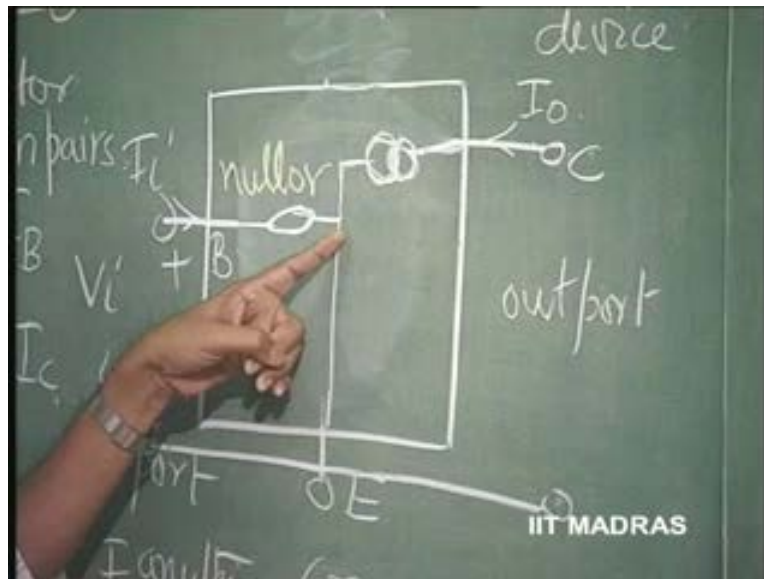
More importantly, we can have an open circuit in series. This will prevent the current to flow. So, this will make the current equal to zero. So, nullor will come in series. It will make the current equal to zero. And therefore, since this is coming in series, the voltage here can be anything, because of the norator. The voltage across this is zero. The voltage here can be anything. So, voltage can be anything, current is zero; which is an open circuit.

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So, these two are equivalents in terms of nullators and norators for short circuit and open circuit. Now, for the transistor, what is the equivalent? Nullator and norator will occur in pair and this end is the collector; this end is the base, and this is the emitter. The junction point of nullator and norator is the emitter. So, if you have in a network, nullator and norator forming a junction, such a network can be realized using transistors.

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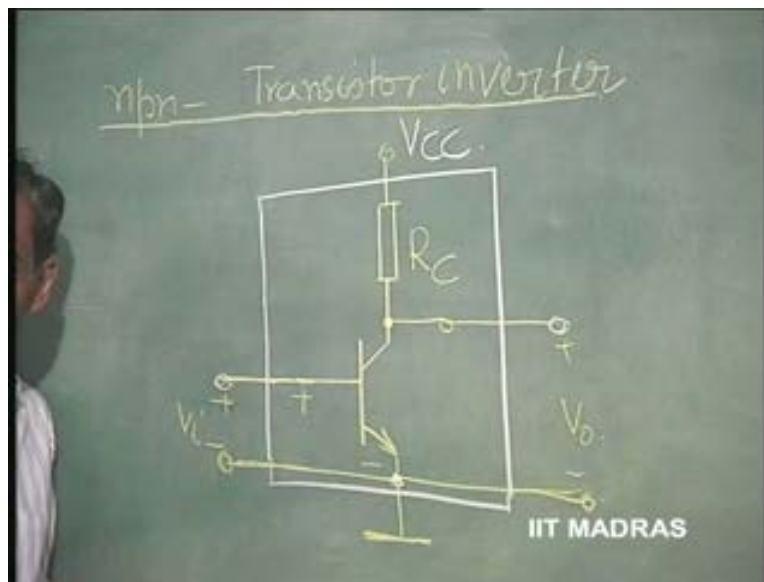
If you have a nullator norator formulating a junction, such a network can be used using, realized using, transistors. If you do not have such a junction, then, we can formulate a junction by using these open circuits. Open circuit, putting an open circuit will not disturb any circuit. So, by putting an open circuit, we can introduce junctions and realize the bipolar transistor versions of the same network.

So, please remember that we have evaluated from the NPN transistor... for that matter, we could have started with PNP as well; we would have arrived at the same equivalent. As far as equivalent circuit is concerned, whether it is NPN or PNP transistor, the same equivalent circuit is valid.

Now, only thing is that the initial voltage in these cases, we said ideal cases, it is going to be zero; and practically, we must have this going positive. In the case of the PNP, it will have to go negative. That is all. So, as far as the equivalent circuit of a transistor, in its simplest form, is concerned, we can say that, for a common emitter amplifier, the nullator comes in series at the input and norator comes in series at the output. And the nullator norator junction is common to both input and output; and that is the emitter.

We had now discussed the three terminal device, NPN transistor, as common emitter amplifier. Let us now consider, how in practice, this is biased. So, with respect to emitter as common, let us consider the supply voltage is  $V_{CC}$  positive. So, this is a positive supply voltage,  $V_{CC}$ . Then automatically, this collector is going to be at a higher potential than the emitter; and, it can be made as high as you please by selecting  $V_{CC}$ . So, this  $V_{CC}$  automatically biases, reverse biases this, and simultaneously forward biases this.

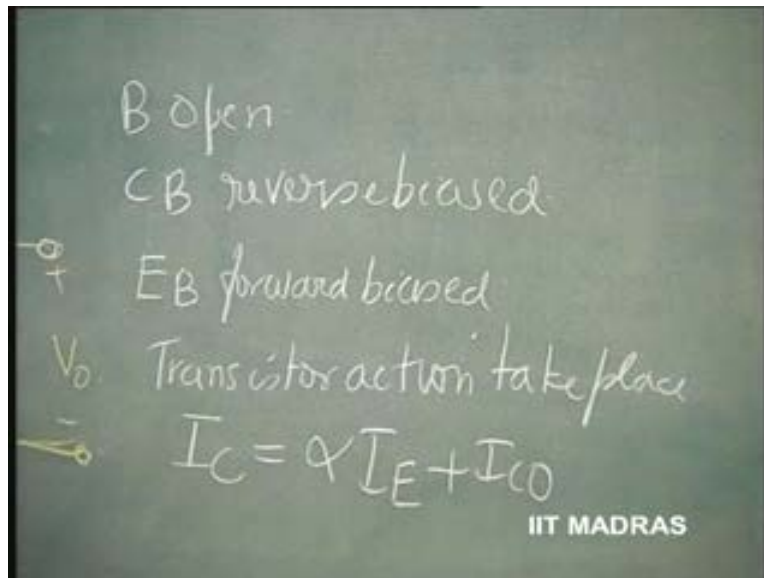
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So, by using a single supply, if we use emitter as common and put down your voltages, this would be automatically plus, minus, plus, minus. Even if we keep this base open, the junction, these two junctions come in series with one another. So, one junction will automatically get forward biased; that is, emitter base junction. The other one, collector base junction will automatically get reverse biased. The forward bias junction will take a voltage of about point 5 to point 6. The rest of it has to come across the collector base junction, which is adequate for reverse biasing it. So, this is called a single supply biasing of a transistor.

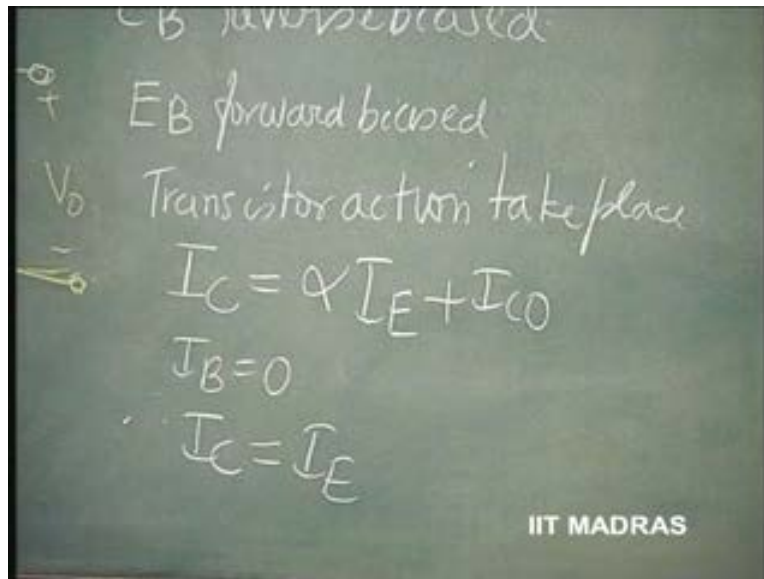
Now basically, if I keep this base open, what will happen? Let us see. If the base is open, collector base is reverse biased; emitter base is forward biased in this arrangement. That means transistor action should take place. Transistor action takes place. What is transistor action? Transistor action is  $I_C$  equals Alpha times  $I_E$  plus  $I_{C0}$ .

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This is valid; and one thing else also is valid. Base is open; so base current is zero. So, according to Kirchhoff's law,  $I_B$  is zero; therefore  $I_C$  has to be equal to what?  $-I_E$ ; because, this current has to be equal to this current.

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If that is the case, then you have very interesting thing happening here. Under this kind of biasing arrangement, we have  $I_C$  equal to  $I_E$ . So, replacing that,  $I_C$  equals Alpha times  $I_C$  plus  $I_{C0}$ . Or,  $I_C$  equals...  $I_C$  into  $1 - \alpha$  equals  $I_{C0}$ . Or,  $I_C$  equals  $I_{C0}$  by  $1 - \alpha$ .

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$$I_E = \alpha I_C + I_{CO}$$
$$I_C(1-\alpha) = I_{CO}$$

reverse biased

$$I_C = \frac{I_{CO}}{1-\alpha}$$

forward biased

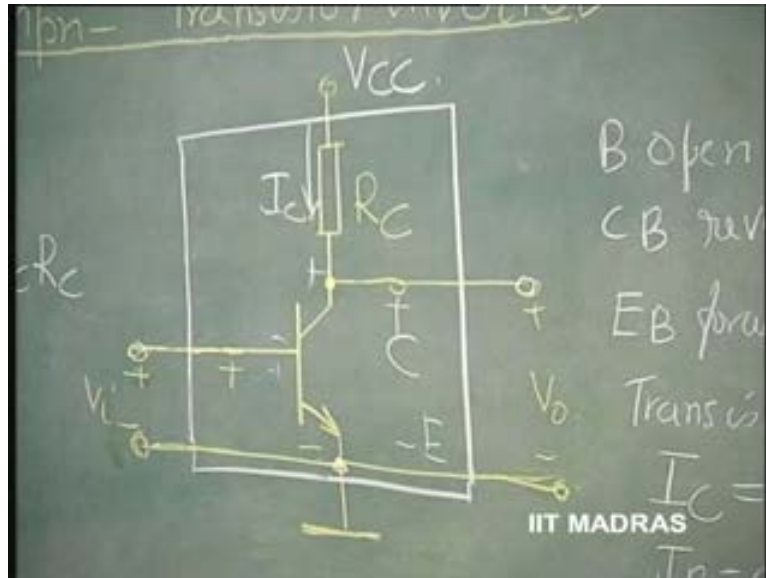
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So, there is a collector current now flowing, even though base is open. There is a collector current flowing because of the leakage current, which is,  $I_{C0}$ . Not only that, that is amplified by an extent of  $1/(1-\alpha)$ .  $\alpha$  is close to 1. So, this factor,  $1/(1-\alpha)$  is going to be much greater than 1. And therefore, this leakage current, under this situation of biasing, is going to be more than  $I_{C0}$ . If  $I_{C0}$  is of the order of nanoamperes, this might come under the range of hundreds of nanoamperes.

So, anyway, we are going to ignore the effect of  $I_{C0}$ . It is still very small; and therefore, we can assume that there is almost no current flowing.  $I_C$  equal to  $I_{C0}/(1-\alpha)$ ; that we remember. But, it is going very small; therefore, the voltage here is going to be very nearly  $V_{CC}$ . Or actually, the voltage is  $V_{CC}$ , strictly speaking, minus  $I_C R_C$ . This is the voltage  $V_{CE}$ .

This voltage  $V_{CE}$  is going to be  $V_{CC}$  minus  $I_C$  times  $R_C$ .

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This is nothing but  $V_{CE}$ , always. So, this equation is always valid. Another equation is,  $V_i$  equals  $V_{BE}$ , in this, for this circuit.

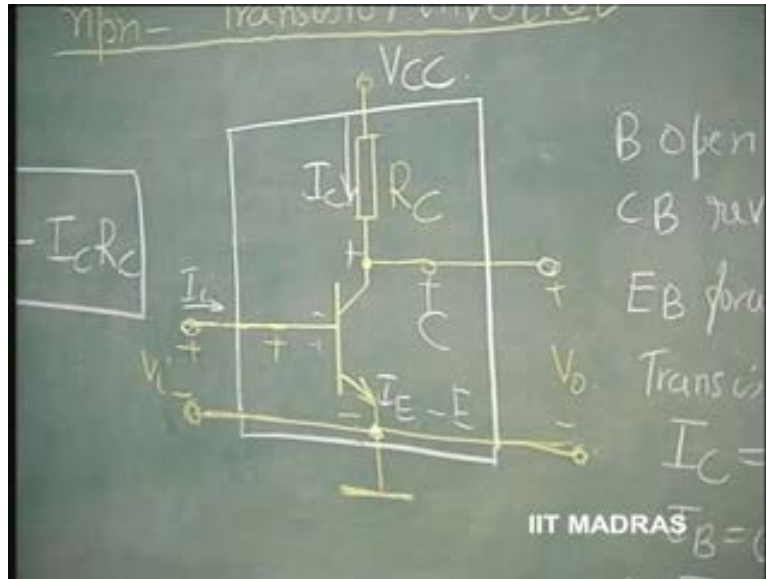
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Handwritten equations on a chalkboard. The first equation is  $V_o = V_{CE} = V_{CC} - I_C R_C$ , enclosed in a rectangular box. The second equation is  $V_i = V_{BE}$ , also enclosed in a rectangular box. The text 'IIT MADRAS' is visible at the bottom right of the slide.



So now, we can find out the effect of this, let us say,  $I_B$ . The relationship between  $V_{BE}$  and, let us say,  $I_E$ ; this is  $I_E$ , this is known.

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Because,  $I_E$  is equal to  $I_E \exp(V_{BE} / \eta V_T)$ ; minus 1 we will ignore; so it is approximately equal to this, this we know.

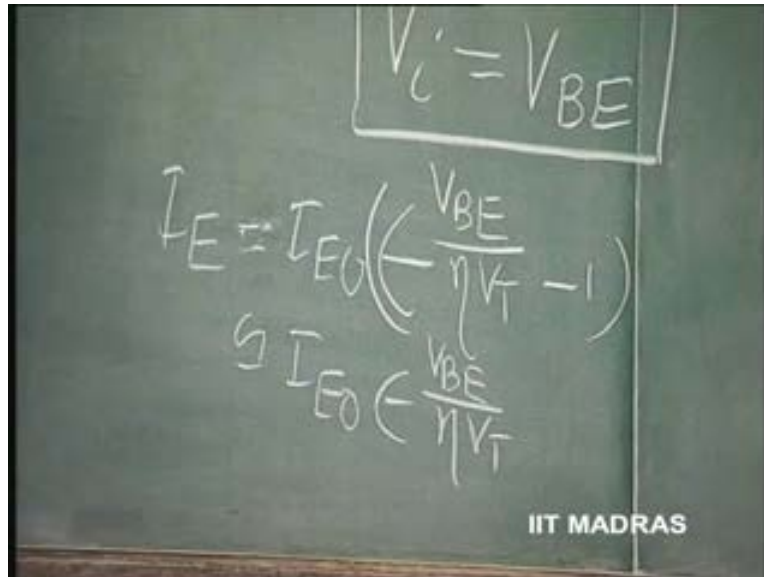
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$$V_i = V_{BE}$$

$$I_E \approx I_{E0} \exp\left(\frac{V_{BE}}{\eta V_T}\right)$$

Or, I will put it as, equal, minus 1, approximately equal to  $I_E$  naught exponent  $V_{BE}$  by  $\eta V_T$ .

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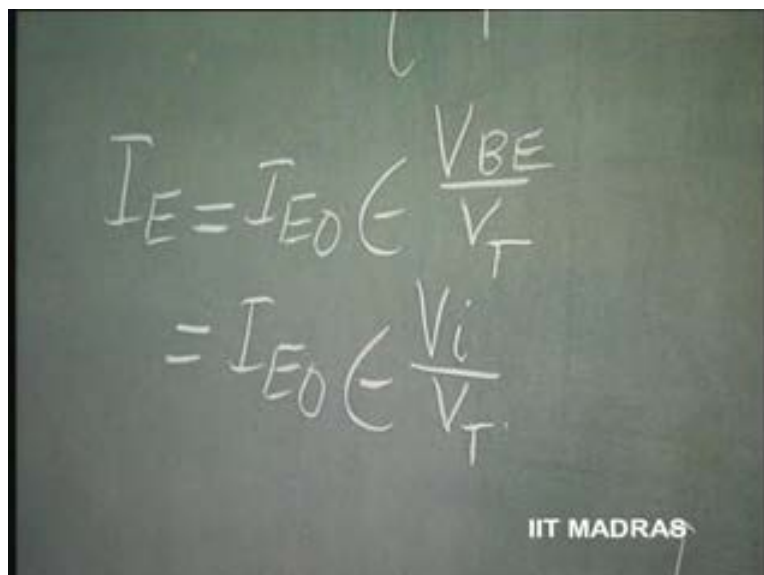
The chalkboard shows the following equations:

$$V_i = V_{BE}$$
$$I_E = I_{E0} \left( e^{\frac{V_{BE}}{\eta V_T}} - 1 \right)$$
$$\approx I_{E0} e^{\frac{V_{BE}}{\eta V_T}}$$

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Let us assume  $\eta$  to be equal to 1. We have said  $\eta$  is between 1 and 2. So,  $I_E$  is equal to  $I_{E0}$  naught exponent  $V_{BE}$  by  $V_T$ . This is equal to  $I_{E0}$  naught exponent...  $V_{BE}$  is same as  $V_i$ .

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The chalkboard shows the following equations:

$$I_E = I_{E0} e^{\frac{V_{BE}}{V_T}}$$
$$= I_{E0} e^{\frac{V_i}{V_T}}$$

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So, we have  $I_E$ . And, what is  $I_C$ ?  $I_C$  equal to Alpha times  $I_E$  plus, what?  $I_C$  naught. And this  $I_C$  naught, I am neglecting now; so equal to, Alpha times  $I_E$  naught exponent  $V_i$  by  $V_T$ .

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The image shows a chalkboard with the following handwritten equations:

$$I_E = I_{E0} \left( e^{\frac{V_{BE}}{V_T}} \right)$$

$$= I_{E0} \left( e^{\frac{V_i}{V_T}} \right)$$

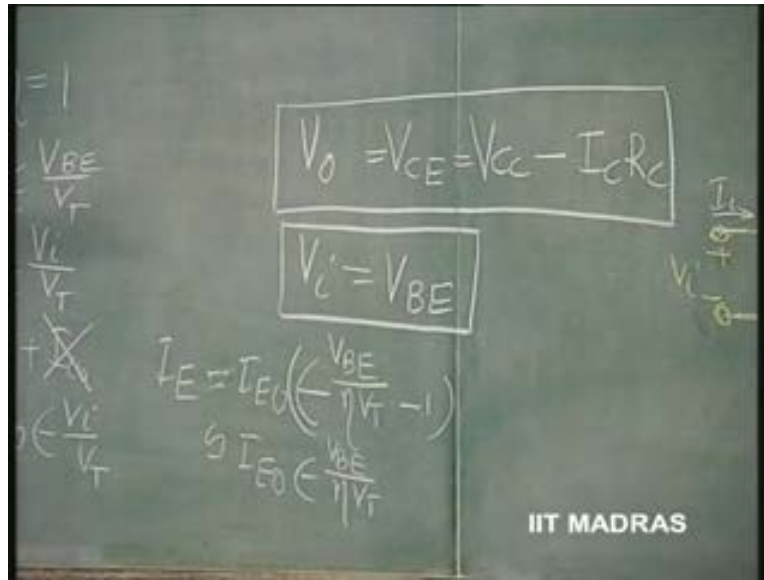
$$I_C = \alpha I_E + I_{C0}$$

$$= \alpha I_{E0} \left( e^{\frac{V_i}{V_T}} \right)$$

There is also a partially visible equation on the right side of the board:  $I_E = I_{E0} \left( e^{\frac{V_{BE}}{V_T}} \right)$ . The IIT MADRAS logo is visible in the bottom right corner of the chalkboard image.

Or now,  $V_{BE}$  is going to be equal to  $V_{CC}$  minus, already we have now  $I_C$  in terms of  $V_i$ ; so, Alpha times  $I_E$  naught; that into  $R_C$  exponent  $V_i$  by  $V_T$ . This is the non-linear relationship between  $V_{BE}$  and  $V_i$  without making any approximation whatsoever; except that,  $I_E$  has been made equal to  $I_E$  naught exponent  $V_{BE}$  by  $V_T$ , ignoring that 1.

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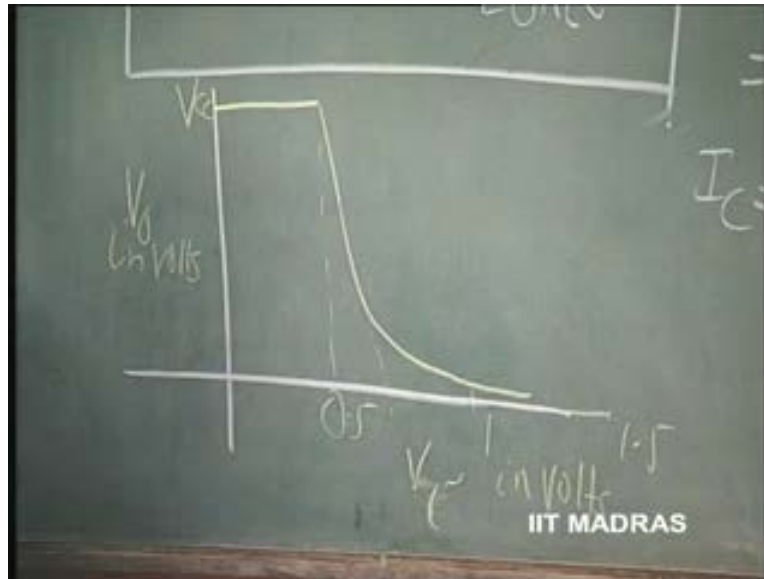
Because emitter base junction is always forward biased, this approximation can always be made. So, this approximation, in future, will always be made, and I will not repeat it again. We will take it for granted that  $I_E$  is equal to  $I_{E0} \exp(V_{BE}/V_T)$ , in the case of transistors. And also,  $\eta$  equal to 1, we will take; unless otherwise mentioned. And, in all future situations, we will take  $I_C$  as  $\alpha$  times  $I_E$   $\exp(V_i/V_T)$ . And, if you plot this... Let us plot this. This will give you  $V_{CE}$  versus  $V_i$  characteristics, transfer characteristics for the amplifier.

This is the common emitter amplifier. So, NPN transistor, inverter we will call it. We will see why it is called inverter, presently. So, when this  $V_i$  is zero, when  $V_i$  is zero, this exponent is going to be,  $I_E$  to power zero, which is 1; and  $\alpha I_E R_C$  is the only drop.  $I_E$  being of the order of nanoamperes, this voltage  $R_C$  may be of the order of Kilo ohms; this voltage may not be much. So, this can be ignored; or, it is slightly less than  $V_{CC}$ .

So, it is going to start at very nearly  $V_{CC}$  because of the fact that for  $R_C$  of the order of Kilo ohms,  $I_E$  of the order of nanoamperes, this voltage is going to be extremely small.  $V_{CC}$  of the order of volts, let us say, here. So, it is slightly less than  $V_{CC}$ .

And, it will start with  $V_i$  becoming substantial. What is substantial?  $V_i$  is substantial when there is substantial current flow. That will happen only when  $V_{BE}$  is of the order of point 5 to point 6; so, when this voltage is of the order of point 5 to point 6. So, this is therefore  $V_{BE}$ , sorry,  $V_i$ . This is of course  $V_{BE}$ . So,  $V_{BE}$  will start with  $V_{CC}$ ; and when it is point 5 to point 6; let us say this is about 1 volt, this is 1 point 5 volts. So, by about point 6 or so, it will fall off exponentially. Current is going to increase exponentially with input voltage. So, the voltage will drop; because, this drop will increase. This will keep on increasing very drastically; keep on increasing...

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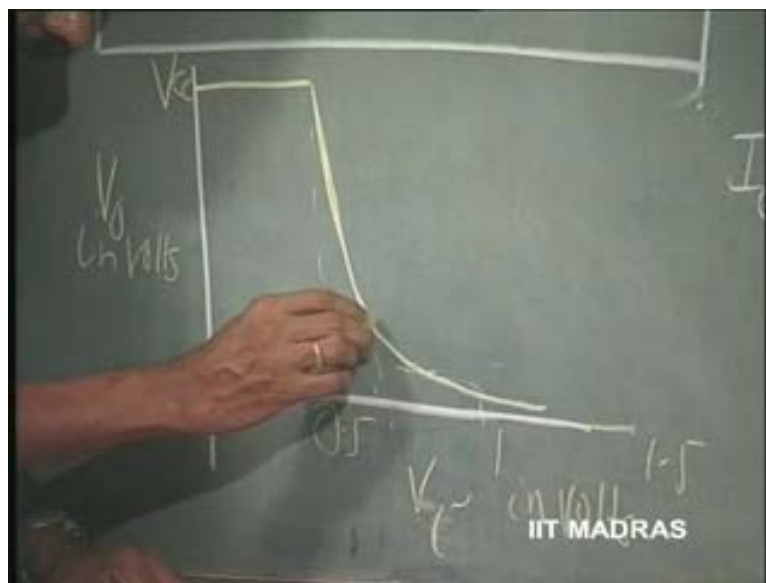
After a certain point, when this voltage keeps on decreasing, a point will be reached, when, if this is point 5 to point 6, let us say, and this is zero, it has reached saturation; because,  $V_{CB}$  equal to zero; we said, the transistor has reached saturation.

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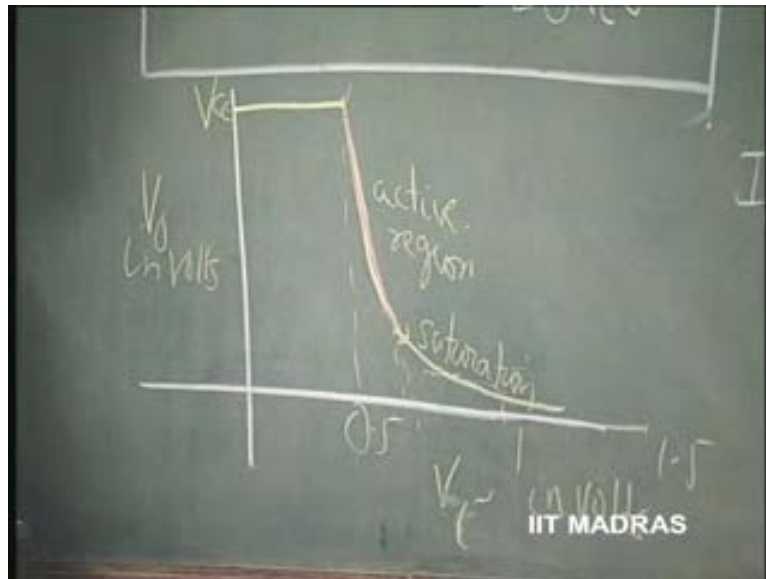
That means, when  $V_{CE}$  becomes about point 5 to point 6, it has just entered saturation. So, any voltage which is less than, let us say, point 6 or so, will make it go to saturation. This voltage is going to be extremely small. So, up to this, it is going to be... the transistor will enter saturation, somewhere here.

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So thereafter, both the junctions are going to be forward biased and the transistor is deep in saturation. So, this characteristic is that of the transistor inverter characteristics. Why it is called inverter? We can now see that this is the active region. This point; it might enter saturation. Beyond this point, this is in cut-off; almost. So, this is the active region. This is the active region.

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Now, in this region, you have to operate in order to make the transistor, amplifier. The transistor should not enter saturation. That transistor should not be in the cut-off. This should be in the active region. If it is in the active region, it can work as an amplifier. And, it will be linear, only for small signal changes; because, basically it is non-linear; it is an exponential relationship.  $e^{V_i/V_T}$  can be expanded as  $1 + x + \frac{x^2}{2!} + \frac{x^3}{3!}$ . That way.

So basically, this is equal to  $V_{CC} - \alpha I_E R_C$  into, exponent  $x$ , which is actually speaking, exponent; let us call it as  $V_{iQ}$ , some voltage, which is constant, plus  $\Delta V_i$ . That is, I am changing the voltage by a small amount around a quiescent voltage.

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A chalkboard with a handwritten equation in red:  $v_{ce} = V_{CC} - \alpha I_{E0} R_C e^{\frac{v_{be} + \Delta v_i}{V_T}}$ . The text "IIT MADRAS" is visible in the bottom right corner.

Why is this being done? Because, this voltage can be increased or decreased. So, I can apply an AC input, by maintaining, basically, the emitter base junction at a quiescent voltage of  $V_{iQ}$ . This effective voltage should always be of the order of point 5 to point 6. So, this is going to be  $V_{CC} - \alpha I_{E0} R_C e^{\frac{V_{iQ}}{V_T}}$ ,  $V_{iQ}$  by  $V_T$ , into exponent  $\Delta V_i$  by  $V_T$ .

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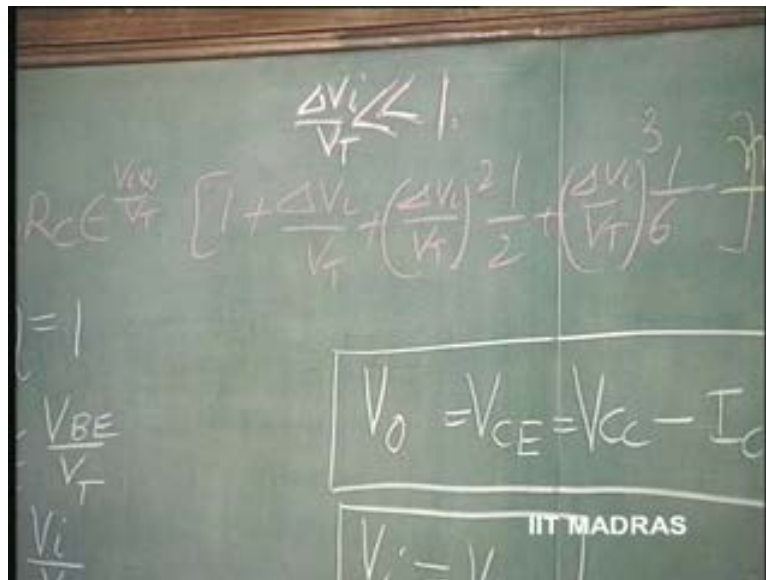
A chalkboard with handwritten equations in red and white. The top equation is  $v_{ce} = V_{CC} - \alpha I_{E0} R_C e^{\frac{V_{iQ}}{V_T}} e^{\frac{\Delta v_i}{V_T}}$ . Below it, the relationship  $I_E = I_{E0} e^{\frac{V_{BE}}{V_T}}$  is written. The text "IIT MADRAS" is visible in the bottom right corner.



What is small signal? A small signal is that signal at which I can consider this relationship between input and output, linear. So, when the input voltage is changing by a small amount, then, I can consider it as small signal. That small amount is comparable to  $V_T$ .  $V_T$  is of the order of 25 millivolts. That means, if this  $\Delta V_i$  is of the order of a few millivolts, then, it can be considered as small signal. Then, we can expand this as  $1 + \Delta V_i / V_T + (\Delta V_i / V_T)^2 / 2 + (\Delta V_i / V_T)^3 / 6 + \dots$ .  $\Delta V_i / V_T$  whole cubed by factorial 3, which is 6.

So, this is the nature of variation of output. These are, I have told you earlier in our general discussion about amplifier, this is the linear term; this is the offset; this is the offset, DC offset; this is the linear term; this is the non-linearity; these are the nonlinearities. We have to have these non-linear terms made as small as possible for reducing distortion. That means  $\Delta V_i / V_T$  should be much less than 1.

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This is an important ... for making this common emitter transistor, a good amplifier. We will discuss further in the next class.