Analog Electronic Circuits
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Lecture - 81
BJT Biasing and Basic Building Blocks

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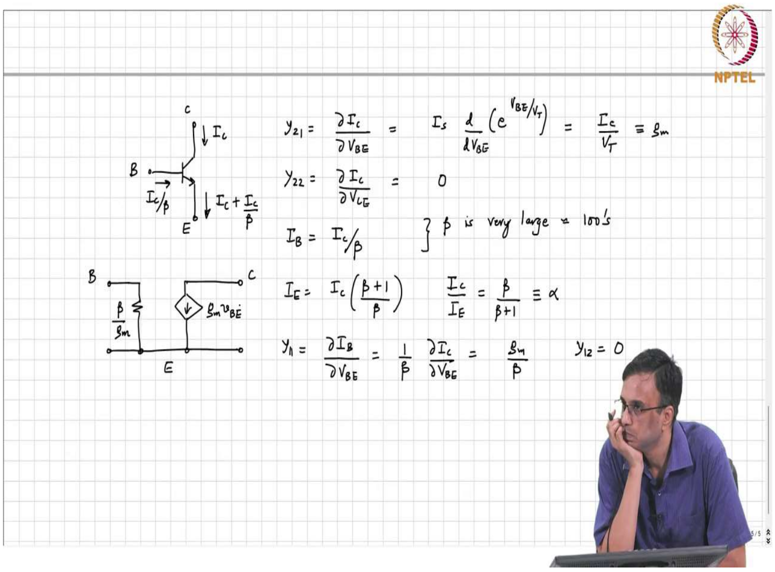

$$y_{21} = \frac{\partial I_c}{\partial V_{BE}} = I_s \frac{d}{dV_{BE}}\left(e^{V_{BE}/V_T}\right) = \frac{I_c}{V_T} \equiv g_m$$

$$y_{22} = \frac{\partial I_c}{\partial V_{CE}} = 0$$

$$I_B = I_c/\beta \quad \Big\} \ \beta \text{ is very large} \approx 100\text{'s}$$

$$I_E = I_c\left(\frac{\beta+1}{\beta}\right) \qquad \frac{I_c}{I_E} = \frac{\beta}{\beta+1} \equiv \alpha$$

$$y_{11} = \frac{\partial I_B}{\partial V_{BE}} = \frac{1}{\beta}\frac{\partial I_c}{\partial V_{BE}} = \frac{g_m}{\beta} \qquad y_{12} = 0$$

Does it make sense? Alright. So, now that we have this small signal model, do you know what the next thing we do is? What we did in the MOSFET was figure out how to bias the transistor.

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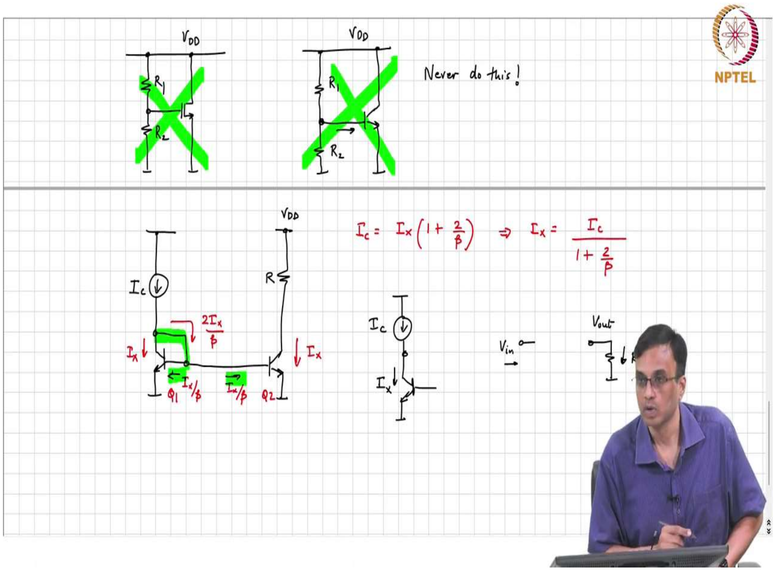

What is the first bias circuit that we used? And what is the problem with this? So, either you know changes in V_{DD} or changes in temperature will cause the drain current to vary very widely, right?

And that is because, I mean, the transconductance of the device is large, which basically means that a small change in the gate voltage will lead to a large change in the drain current. And that is the whole idea behind amplification, right?

So, you want a small change in gate voltage to result in a large change in current, which you can then push through a resistor to get a large voltage at the output.

Now, if this was remembered, and then we said this is a bad idea, In a bipolar transistor, if it was a bad idea in the case of a MOS transistor, what comment can we make about the bipolar transistor? So, if it was a bad idea in a MOS transistor where the transconductance in a MOS transistor is proportional to when it is operating in saturation, let us say you have a drain current flowing in the transistor, the transconductance is proportional to $\sqrt{I}$, ok. In a bipolar transistor it is proportional to I, right.

So, basically, as you can see, the transconductance of a MOS in a bipolar transistor is much stronger than that in a MOS device. And that basically means that if it is a bad idea in the MOS case, it is a terrible idea in the case of a bipolar transistor. So, you should never do this.

Alright, because tiny changes in the base emitter voltage can cause a large change in the current.

Another point is that another source of problems with the bipolar case is that the base is also now drawing current. So, apart from the you know variation of V_{DD} and variation of R_1 and R_2 also have to worry about the base current because, if you draw base current out from here, what comment can you make about that potential? And ideally, it is supposed to be V_{DD} $R_2/(R_1 + R_2)$. Now you start pulling base current out of that node the voltage will drop, right. So, it turns out that β is not very well controlled.

So, you know, the same transistor can exhibit different β 's on different days, depending on temperature and all this stuff. Those of you who have done a device class know that you probably all know about this already; but the point is that. So, you should never rely on; whenever you are doing circuit design you should never rely on the fact that your transistor has got a β of 98, ok. And if β is 99, if your whole circuit falls apart, that basically means that this is a bad design. You understand, alright.

So, what did we do to fix this problem of bias in the MOS case? Well, we use negative feedback, ok? And the first thing that we did was use a current mirror, which is something that we can do here too.

And just like in the MOSFET, there are four fundamental ways of establishing the quiescent operating point: through negative feedback. You can measure the collector current; you can measure the emitter current, and I mean, we go with the notion that the collector current and emitter current are almost the same, ok?

So, you can measure the current in the transistor and the quiescent current of the transistor in two different ways, and you can adjust the base emitter voltage in two different ways. You can either keep the base fixed and vary the emitter voltage or keep the emitter fixed and vary the base voltage.

And you know you basically go and that is basically what causes the feedback action to occur. So, you can think of at least four ways in which you can stabilize the bias of the bipolar transistor, just like we did in the MOS case, right? So, all these circuits are pretty much the same. So, there is no point in beating a dead horse.

So, basically, let me only point out the differences. So, here is the bipolar transistor current mirror, ok? And there is a small catch here. In the MOS case, the gates were not drawing any current, so the reflective current in the mirror would be exactly the same as what was pushed in. Now, there is a slight difference, and that has to do with the base current.

So, let us call this I_x, ok. So, what is the current in, what is this current? What is that current there? It is going to be exactly I_x because both transistors Q1 and Q2 have the same base emitter voltage. So, they will have the same collector current. So, what is the base current of Q1? What is I_c? The collector current of Q1 is I_x. So, this current is going to be I_x/β, this is also going to be I_x/β, so this current is going to be 2 I_x/β. So, how is I_x now related to I_c, therefore? I_c must therefore be equal to $I_x + 2/\beta$ which therefore, $I_x = I_c/(1 + 2/\beta)$, alright. So, basically you can see that there will be some small error in the current in Q2. Collector current in Q2, it will not be exactly I_c, it will be slightly smaller because some of the current I_c is gone into the to support the base current.

So, in a MOS transistor based current mirror you could just simply copy, you know you could have 100 transistors sensing the same voltage and all the 100 transistors would at least ideally give you the same current without any. Now, what do we do; what comment can we make about when you have let us say you know 10 transistors mirroring off of this Q1?

The error will go on increasing because, basically, if you have 100 transistors feeding off that single node, you will have 100 base currents that you have to support, and so the accuracy of the mirror will become, you know, very poor. So, what do we do to fix this problem? Any suggestions? I mean, well, you cannot avoid these base currents; these base currents cannot be avoided, right? But the problem is that base current is getting subtracted out of I_c, that is the problem, correct. So, what is this short doing actually; his base emitter I mean collector base short what is that doing? I mean what is its job?

How did we get the current mirror? We compare the collector current with the reference current and kick the base voltage in the right direction. So, basically, if this goes up, this voltage must go up. The easiest thing to do in the MOS case was simply to shorten these two, right? And shorting did not affect any; we want the voltage of the base to be the same as that of the collector, right? In the MOS case, that was very easy; we just created a short circuit, and because the gate did not draw any current, we were okay. But now the gate actually draws current, so what do you think? We want the base voltage to be the same as the collector voltage, but we do not want the base current to come from I_c.

So, what do you in principle do? You want the voltage there to be the same as the voltage here, but you do not want that load current to be supplied from here. What will you put between the two nodes? Let me call this is V_{in}, this is V_o. We want V_{out} to be the same as V_{in}, but we do not want this current through R_L to be drawn from the input. What will you put? We will put a voltage controlled voltage source.

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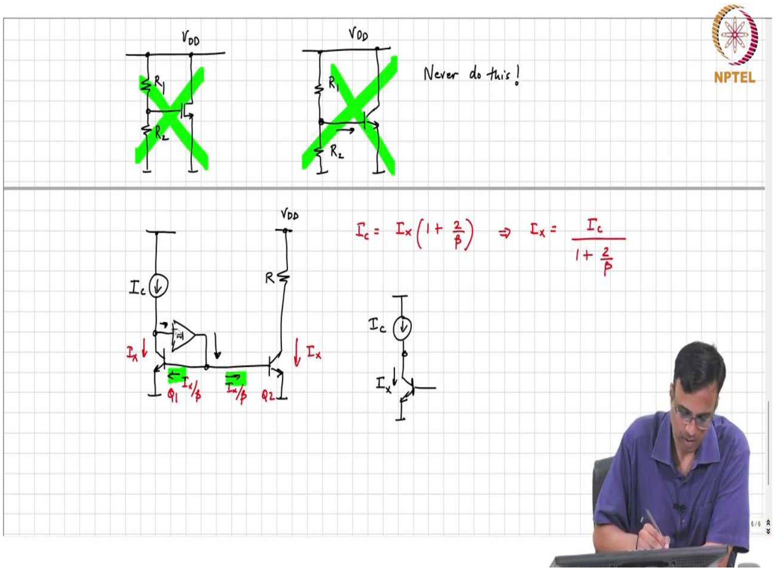

So, basically, the principle is that if you put a voltage-controlled voltage source here, then all this current will be supplied by VCVS, and you know this current will be very small. Now, how do we realise the voltage-controlled voltage source? Well, you know if; I mean, if you realise a voltage-controlled voltage source with MOS transistors, what is the simplest VCVS that you know?

Student: Common drain.

So, here the analog will be a common collector, right?

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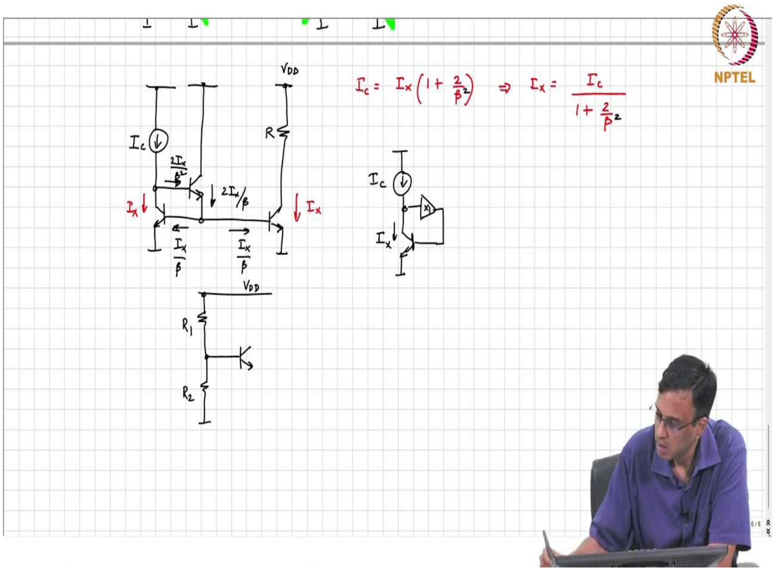

So, basically, ok. And now all this current—you know, if you have 100 transistors here, all the base current will be supplied by the common collector stage, right? And so, for this current to be, what will this current be? It will be smaller by a factor of β. So, in this case, let us call this I_x/β, this is also I_x/β, so this is $2\,I_x/\beta$. What is the base current, therefore $2\,I_x/\beta^2$. But actually, there will be another factor of $\beta/(\beta + 1)$, which I am neglecting, ok. So, you can see therefore, that instead of the new $I_x = I_c/(1 + 2\,\beta^2)$, ok.

So, now you have the error reduced by an order of 9. So, that was one way of biassing the transistor; the other way of biassing the transistor is to keep the base voltage fixed. And vary the emitter.

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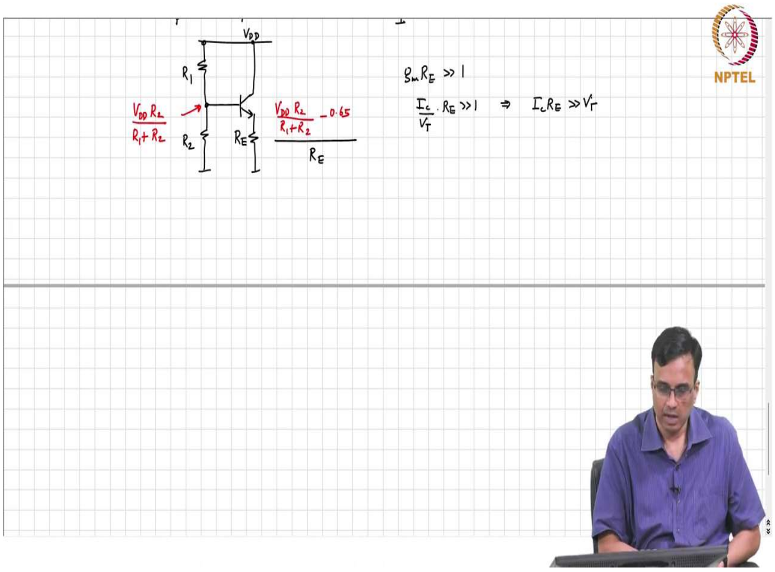

$g_m R_E \gg 1$

$\frac{I_c}{V_T} \cdot R_E \gg 1 \Rightarrow I_c R_E \gg V_T$

By "emitter voltage," I mean compare the measured current in the emitter and vary the emitter voltage so that the emitter current is the same as the reference current. So, again, I will not go through the math all over again or the intuition all over again. You just stick the current source I_{ref} in the emitter, and you are good to go, alright? So, assuming the β is very large; what is the potential here?

So, this is nothing but V_{DD} R_2/(R_1 + R_2). And therefore, this potential will be V_B. V_B nominal for a forward bias for an active transistor operating in the active region is 0.65 volts. So, this is going to be you know V_{DD} R_2/(R_1 + R_2)- 0.65 volts, ok. Alright, now you know if you cannot afford a current source what will you do?

Put a resistor there, ok. So, this is a, let us call this R_E. So, what is the current collector current? So, this divided by R_E is the collector current ok. And again, you know what constitutes a large. So, ideally R_E must be infinity, you cannot make R_E infinity. So, it has to be large. What is the meaning of large? So, g_m R_E must be much much greater than 1, ok. And what is g_m?

Student: I_c/V_T.

So, this R_E must be much much greater than 1, which basically means that I_c R_E must be much much larger than V_T, alright.And then the other two ways of stabilising the bias, you know, you can figure it out yourself; there is really nothing very much there, right? And likewise, I mean, this covers the biassing of NPN transistors.

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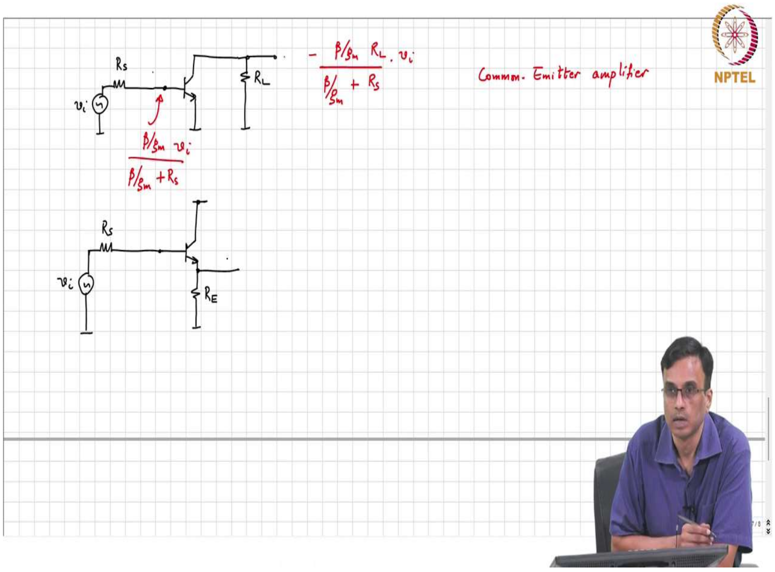

And as usual, you know, we went on to bias a transistor, and then, you know, look at the four basic amplifiers. So, this is the small signal equivalent of the common source amplifier, okay? Now, the fact that the transistor has a non-zero Y_{11}. That means that what is the voltage at the base now—the incremental voltage at the base? $I_s = (\beta/g_m\ )\ R_L\ v_i/(\beta/g_m + R_S)$. So, the voltage at the output is nothing but $-\ (\beta/g_m\ )\ R_L\ v_i/(\beta/g_m + R_S)$. This is the common emitter amplifier, ok. And in principle the g_m of these transistors, I mean that the transistor can be made very large by pumping by biasing it with a sufficiently large quiescent current.

So, then we said let us make the 4 controlled sources. When we were talking about the MOS case, we said let us talk about the 4 controlled sources. So, that is basically this is v_i and this is R_S, right. This is R_L. And this is common.

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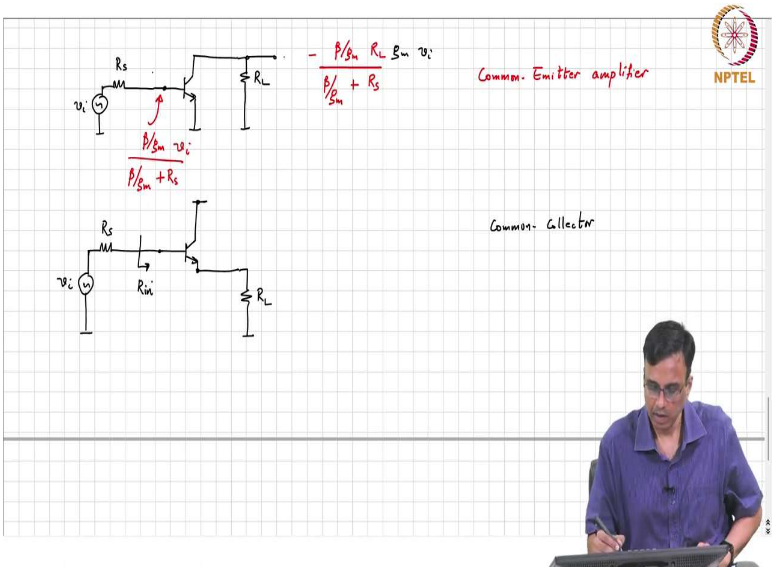

$$-\frac{\beta/g_m\, R_L\, g_m\, v_i}{\beta/g_m + R_s}$$

$$\frac{\beta/g_m\, v_i}{\beta/g_m + R_s}$$

So, this is the common collector amplifier, which is analogous to the common drain amplifier. It gives you an incremental voltage-controlled item to give an incremental voltage-controlled voltage source with unity gain. And so, the incremental; to find there is one more departure from the MOS transistor is basically that the gate current there was 0, so the input impedance was infinite as seen by the source, now it is no longer, so let us try and find what the input impedance is.

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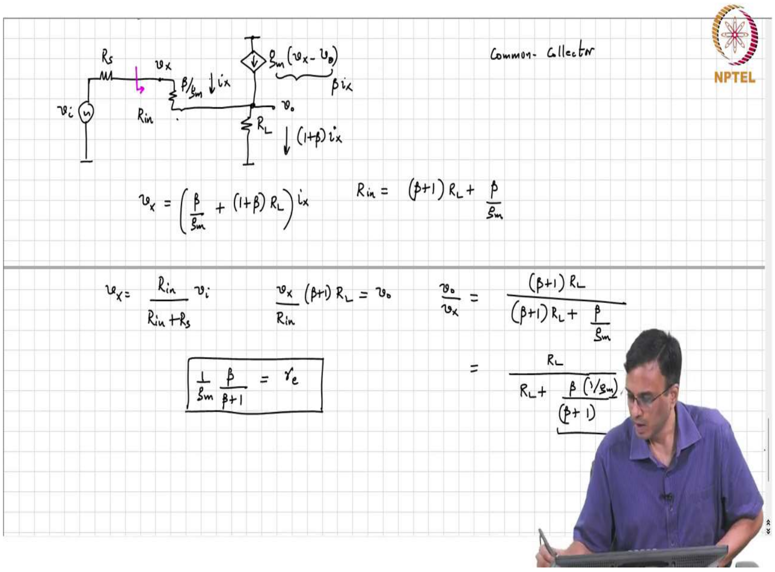

$$v_x = \left(\frac{\beta}{g_m} + (1+\beta) R_L\right) i_x \qquad R_{in} = (\beta+1) R_L + \frac{\beta}{g_m}$$

$$v_x = \frac{R_{in}}{R_{in}+R_s} v_i \qquad \frac{v_x}{R_{in}} (\beta+1) R_L = v_o \qquad \frac{v_o}{v_x} = \frac{(\beta+1) R_L}{(\beta+1) R_L + \frac{\beta}{g_m}}$$

$$= \frac{R_L}{R_L + \underbrace{\frac{\beta (1/g_m)}{(\beta+1)}}}$$

$$\boxed{\frac{1}{g_m} \frac{\beta}{\beta+1} = r_e}$$

So, R_{in} as you can see we have β/g_m. This is g_m v_x - v_o, alright, ok. Or another way of thinking about it is if this is I_x, what is this current?

Student: β i_x.

So, what is the current flowing through R_L?

Student: $1 + \beta$ i_x.

so, what is v_x in terms of i_x? v_x is nothing but (β/g_m) i_x $+(1 + \beta)R_L$ i_x. So, the input resistance $R_{in} = (\beta + 1)R_L + \beta/g_m$. So, sanity check of course as β tends to infinity input impedance it tends to infinity. But you know, if you know in practice that is not really the case. With finite β you will have some you have a large impedance, but you know but it is not infinite.

What is the, what comment can we make about the gain. We know R_{in}. So, v_x is basically $R_{in}/(R_{in} + R_S\ v_i)$. And current flowing in I_x is nothing but v_x/R_{in}, ok. That current will get multiplied by $(\beta + 1)$ and that is the current flowing in the emitter. The emitter current into R_L is the output, right.

So, this $(v_x/R_{in})(\beta + 1)$ R_L is v_o. So, $v_o/v_x = (\beta + 1)R_L/R_{in}$ which is $(\beta + 1)$ $R_L + \beta/g_m$, which is written as $R_L/(R_L + \beta\ (1/g_m)/(\ \beta + 1))$. So, this quantity turns out that if you keep working out these problems you keep getting this quantity all the time $(1/g_m)(\beta/(\beta + 1))$, ok. And this is often called small r_e, ok.

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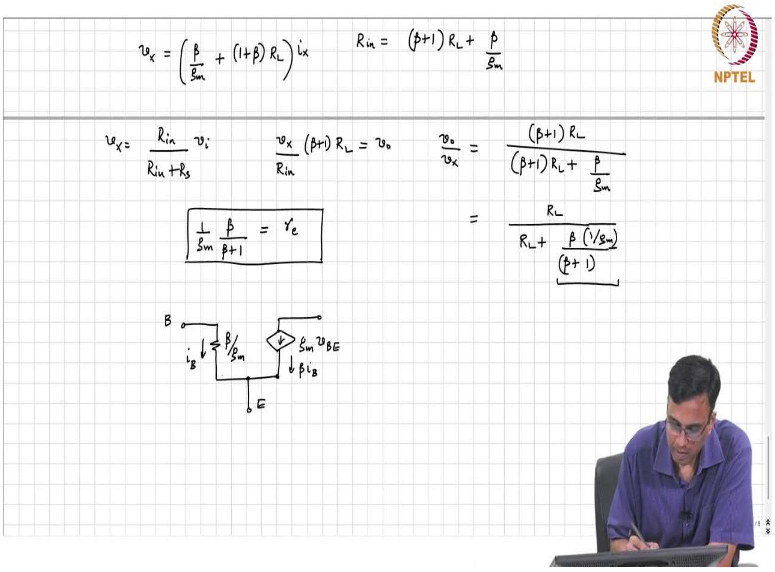

$$v_x = \left(\frac{\beta}{g_m} + (1+\beta)R_L\right) i_x \qquad R_{in} = (\beta+1)R_L + \frac{\beta}{g_m}$$

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$$= \frac{R_L}{R_L + \underbrace{\frac{\beta\,(1/g_m)}{(\beta+1)}}}$$

$$\boxed{\frac{1}{g_m}\frac{\beta}{\beta+1} = r_e}$$

And the motivation why this comes about, I think it should be is quite simple to see. Remember that this is β/g_m and this is $g_m v_{BE}$, alright. And this is βi_B, alright. So, one could alternatively push this resistor through this node.

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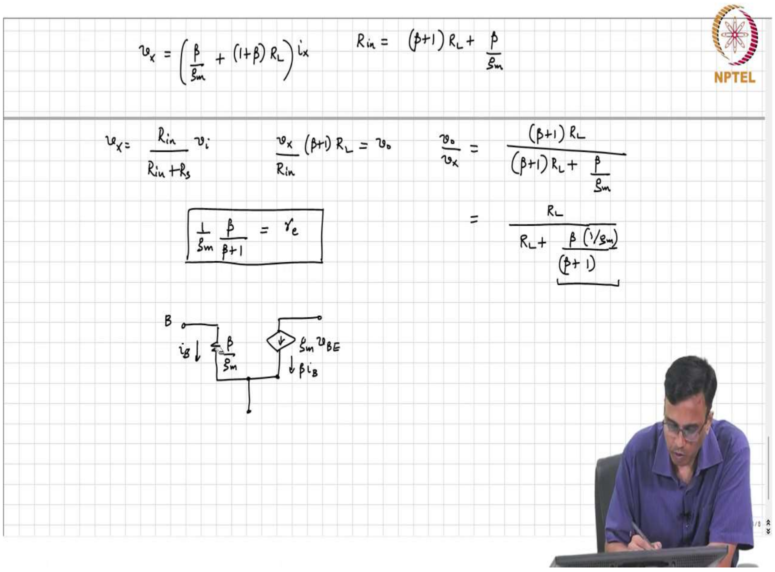

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$$\boxed{\frac{1}{g_m}\frac{\beta}{\beta+1} = r_e}$$

So, this is β/g_m. So, what is the drop between the base and emitter? It is $i_B \, \beta/g_m$.

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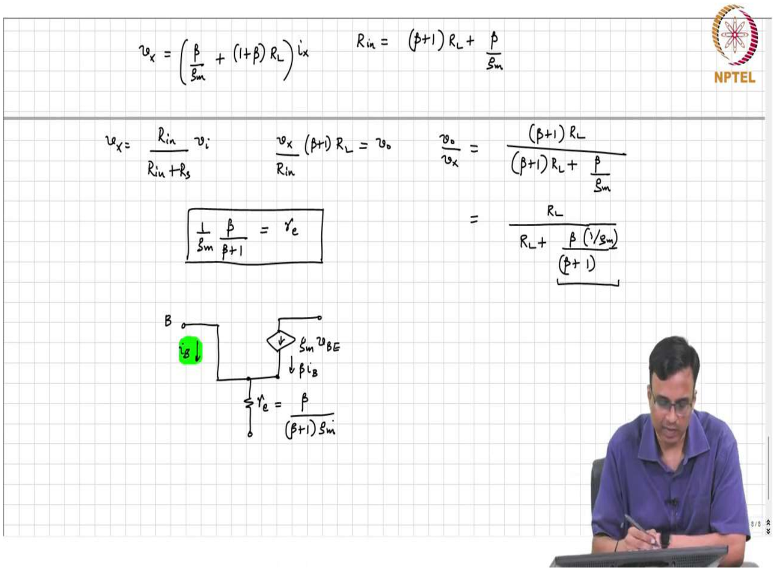

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$$\boxed{\frac{1}{g_m}\frac{\beta}{\beta+1} = r_e}$$

So, one could in principle move this resistance here, okay? I mean, what is the difference between, you know, that branch and this branch? The current flowing here is i_B, and the current flowing here is (β + 1) i_B. So, if you want the same drop between the base and emitter as you had earlier, what should you choose for R_E? The current flowing in R_E is (β + 1) higher, so the resistance must be β/g_m. So, this must be $\beta/(\beta + 1)\,g_m$. I mean this is just simply circuit manipulation, there is nothing only about this.

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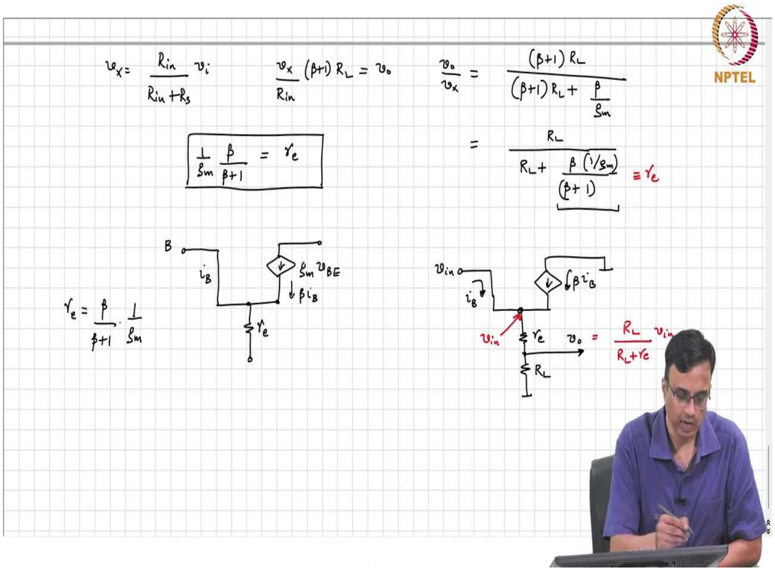

$$v_x = \frac{R_{in}}{R_{in}+R_s} v_i \qquad \frac{v_x}{R_{in}}(\beta+1)R_L = v_o \qquad \frac{v_o}{v_x} = \frac{(\beta+1)R_L}{(\beta+1)R_L + \frac{\beta}{g_m}}$$

$$= \frac{R_L}{R_L + \underbrace{\frac{\beta(1/g_m)}{(\beta+1)}}} = r_e$$

$$\boxed{\frac{1}{g_m}\frac{\beta}{\beta+1} = r_e}$$

$$r_e = \frac{\beta}{\beta+1}\cdot\frac{1}{g_m}$$

$$v_o = \frac{R_L}{R_L + r_e} v_{in}$$

But in many cases, this will let you know it might result in mildly simplified circuit schematic, I mean circuit analysis. A case in point is the circuit that we have been seeing. So, for the common, for the common collector amplifier, this is the transistor. So, this is i_B, this is β i_B. And what is the output voltage v_o?

What is this voltage? That is v_{in}. So, the output voltage is nothing but simply $R_L\, v_{in}/(R_L + r_e)$, right. So, people, I mean, you know, keep interchangeably using this equivalent or the other depending on convenience. And it is, I mean, good to know both of these things, but the final answer that you get will be the same or should be the same in both cases.

So, the common collector amplifier is analogous to the common drain; it behaves like a volt incremental voltage control voltage source with a gain of 1. Does it make sense, folks? Ok, then, so that is the voltage control voltage source. The voltage-control current source is very similar.

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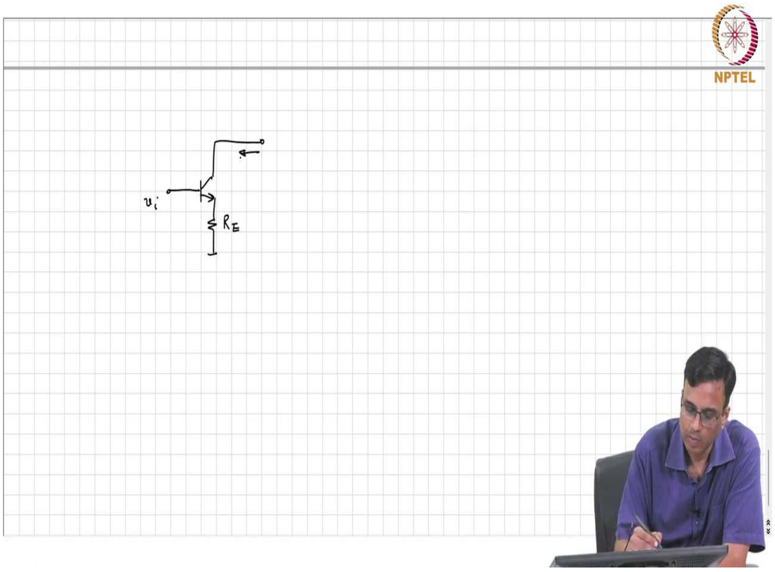

So, this is v_i, ok. Now, what is the incremental current flowing here?

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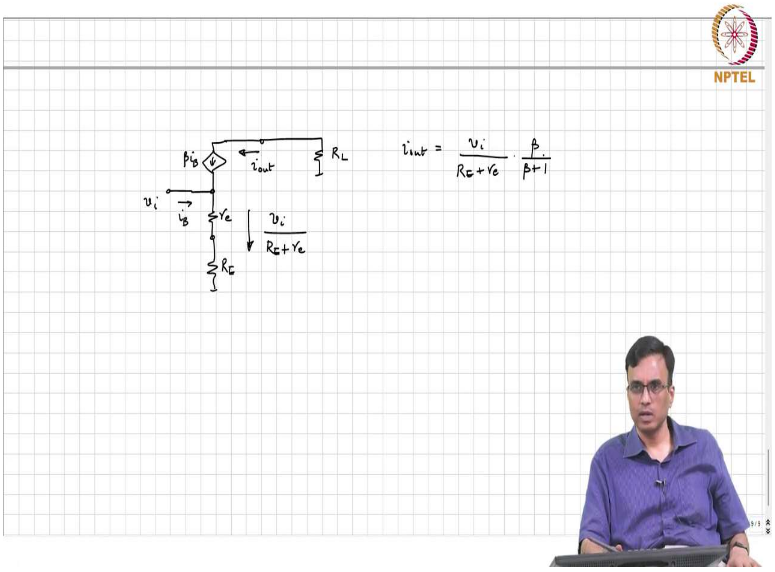

So basically, remember that we replace the transistor; just now we replace the transistor with this equivalent. So, if this is i_B, this is β i_B and there is small r_e in the model, right. This is what we just did just now and this is i_{out}, ok, alright. So now, stare at it and tell me what is this current. $v_i/R_E + r_e$. How much will i_{out} be? How much of it will flow through i_{out}?

Basically you can see that the collector current is β the base current. So, the current i_{out} will be $v_i/(R_E + r_e)$ $(\beta/\beta + 1)$. So, you know if you want to split accurately you do this, but for all practical purposes this is simply $v_i/(R_E + r_e)$. And if R_E is much larger than r_e then it is pretty much the same as v_i/R_E. So, this is the voltage controlled current source.