Analog Electronic Circuits
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Lecture - 58
The Bandgap Reference Principle

Now, the next thing that I would like to talk about. So, that is why, let us move on now to the next topic. Let us take, you know you looked at an opamp, let us see how we can put opamps to use, of course, you are familiar with many common applications, you know inverting amplifiers, non- inverting amplifiers.

Now, let us take a look at you know another application which you are most likely not familiar with, ok. And the motivation for designing or attempting to design such blocks is the following. So, it turns out that in a lot of electronic systems, you need to measure a voltage, with absolute accuracy.

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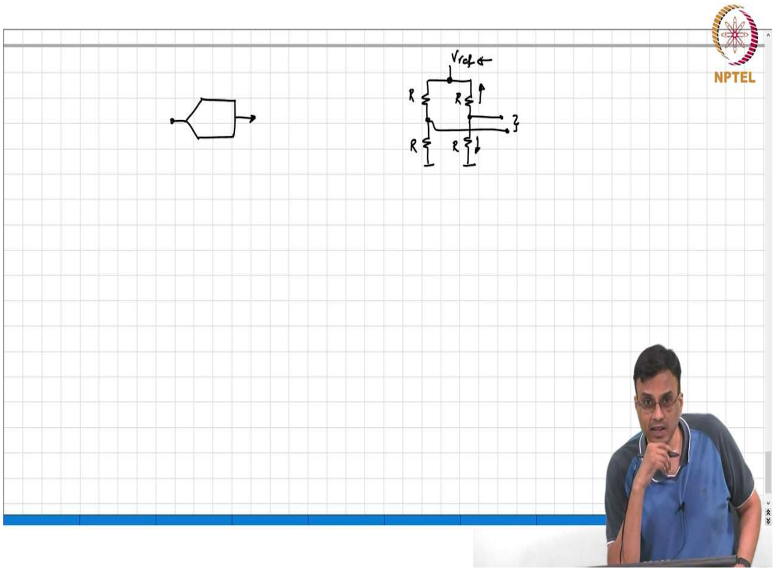

So, convert it into digital form, alright. So, in other words, for example, I do not know, maybe you are measuring, you have a multimeter and you want to measure voltage, or you want to measure weight and weight of an object and the weight of an object is usually measured by a sensor which is some kind of bridge.

And these are two identical resistors and this is connected to some voltage V_{ref}, alright. And you know you are standing on the weight scale and it turns out that the way the sensor is built is that if you stand on the way scale, this resistance increases with weight and this resistor decreases with weight, ok.

And so, if no weight is put then these two are exactly identical. If you put, if you stand on the weigh scale then one resistor goes up, one resistor goes down. So, the difference in voltage between those two leads basically represents the weight that you are putting on and you know clearly that difference is dependent on the reference. And so, if you want an accurate picture of the weight, if you want an accurate measure of the weight that reference better be absolutely accurate. You might think you know it well. How does it matter whether it shows me as weighing 50 kilos or 60 kilos. It's only maybe only a small difference. But imagine that you know you know you go to a jeweler shop and like you know you are buying diamonds, ok.

And you know now all of a sudden, even though in your exam paper you might not worry about a couple of decimal places here and there. Here you want to be absolutely sure that the weighing scale show is accurate to you know six decimal places, ok. So, there are a lot of applications where you know where you have to, it turns out that you have to measure a voltage where you need a very, very accurate reference voltage hm. Now, so the question and when I say accurately it basically must not vary with the Indian temperature.

I mean so, you do not want the weight to be different in an AC room, in the jeweler shop and then you come home and then you know in Chennai it's 50 degrees and then you suddenly find that oops you know I have been you know I have been conned. My gold only now weighs like you know you know 0.2 grams less. So, better I better go and fight. So, you want the reference voltage which is absolutely constant with temperature. Now, the question is, you know, of course, it must be constant with temperature, it must also be constant and it must not depend on supply voltage. So, it should also ideally not depend on you knowing variations of components inside whatever box you make. Your box is supposed to give you a constant voltage.

Now, you know maybe that is 1 volt 1 point whatever. But you want to make sure that this does not depend on temperature and it does not depend on some extraneous factors like supply voltage you know I do not know I mean how far your neighbor is from you and so on. So, it must be an absolute constant.

So, the first thing to attract, attack is basically the problem with temperature. I mean can you think of? I mean we have seen so many components, diodes , you know, MOS transistors, PMOS NMOS etcetera. Can you think of any voltage which will remain which can act like a I mean which seems reasonably you know constant Zener. I mean well he says a zener diode I do not know how many of you heard of a zener diode have you heard of this before?

Student: Yes.

Well if you mean even easier than a zener diode.

Student: Normal diode.

Normal diode and what about the normal diode?

Student: 0.6.

Yeah. So, well in all our problems we said the voltage across the voltage drop across a forward bias diode is 0.7 volts. That seems like a reasonable place to start.

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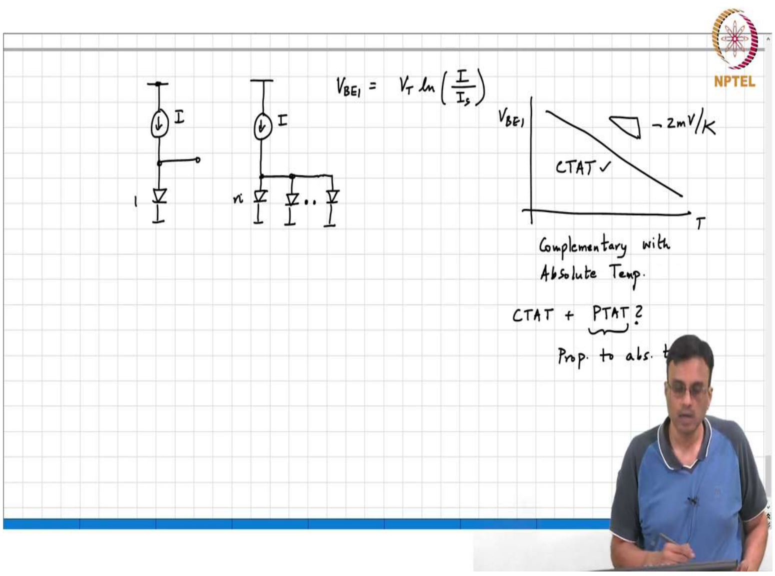

So, you take our diode and then you know bias it, push some current through it and to first order we say that the voltage is about 0.65 to 0.7 volts. In reality it is V_{BE1}, which is basically

V_T ln (I/I_S). I mean we should be I think particularly naive to assume that this will remain this point. I mean this 0.65, 0.7 volts is merely an approximation. We would be silly to believe that you know that is valid across all temperatures especially when you look at the formula that V_T is of course, you know KT/Q and is varying with temperature. More importantly for those of you who have done a device's class what is that I_S? How does that happen with the saturation current as a function of temperature?

It basically is exponential I believe. So, the, So, I_S increases with temperature and therefore, and that is in the denominator. So, what comment can you make about V_{BE} for a given I? If I_S increases exponentially with temperature. What comment can you make about V_{BE1}? It decreases with temperature. So, actually if you go and measure it turns out that if you plot V_{BE} there is a reason why I am calling it V_{BE1}, but with absolute temperature. It turns out that you know it's reasonably well approximated by a straight line with a slope of is somebody know, no we either you know it or you do not it is just information its not some big insight.

Ok. So, it just turns out that it has a negative temperature coefficient of 2 millivolts per kelvin but what we want is something which does not change with temperature. So, if you have something which is following with temperature how do you get a quantity which does not change with temperature? Common sense tells us that if you found some other quantity which increases with temperature then if you add that and this in the proportion you will probably get something which does not change with temperature. So, this kind of characteristic which reduces with temperature is what is called CTAT or short for complementary with absolute temperature, alright, ok Now, the question is now, we have a CAT to this we need to add something with positive slope. So, that basically is what is called a PTAT which is something which stands for proportional to absolute temperature. So, what temperature I mean we need to add therefore, to this V_{BE1} a voltage with a positive temperature coefficient of 2 mV/K. If you add that to this the result will be something which is flat over temperature, does it make sense?

Student: Yes, sir.

Alright. So, now that I mean this characteristic we have now the question is how do we generate something with a positive temperature coefficient, correct and some clever guy basically I recognized that basically if you take the same current and put n diodes in parallel, ok.

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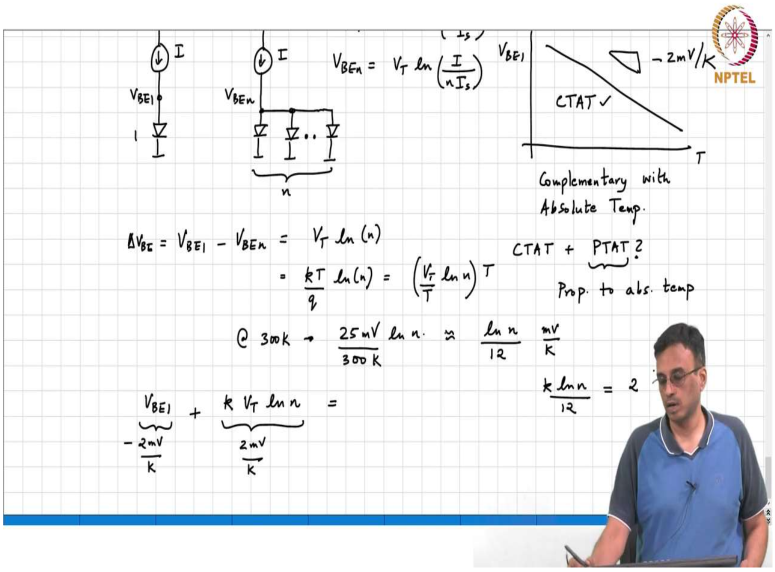

So, this is V_{BE1}. So, what is V_{BEn}? All the diodes are identical. I take you know this is just nothing but n such diodes in parallel. V_T/n I_S, correct, alright. So, what is V_{BE1} - V_{BEn}?

Student: V_T ln(n).

Does n change with temperature?

Student: No just numbers.

No, it's just the number fortunately *ln* does not change with temperature the only thing that changes with temperature is pt which is kT/q, where k is Boltzmann's constant, q is charge in an electron and so, this is ln(n), and therefore, what is the temperature coefficient of V_T of this ΔV_{BE}?

Student: k ln(n).

Which is basically nothing but V_T/T ln(n) T, correct. So, the temperature coefficient is V_T ln(n)/T, ok this is just easier to calculate instead of doing k/q which I am sure most of you have forgotten what k is and what q is. What is Boltzmann's constant? At 300 K temperature, I mean basically it's easy to calculate the temperature coefficient at some known temperature. We know that at 300 k V_T is about 25 millivolts. I mean I like to round things of 25 millivolts by T is 300. So, this is ln(n), ok which is approximately ln(n)/12 is it 12, yeah 12 millivolt per kelvin or I made a mistake? It's final, alright. So, we need this to be equal to we need this to be equal to 2 millivolts.

So, V_{BE1} is - 2 mV/K, to this we must add some, I mean this obviously, you know ln(n)/12 if this has to be + 2mV/K, then ln(n) has to be e^{12} that is you have to cover all of Chennai with diodes and then only then you will get the required thing. So, the smarter thing to do is you generate whatever you can with a practical end and you multiply it by with some gain k, is this clear? I mean nothing, I mean by the way nothing prevents you from making that n very large, but that does not seem practical.

You know a practical idea given real estate prices in Chennai, ok alright. So, k V_T ln(n) must be chosen so that this has plus 2 millivolts per kelvin which basically means that k ln(n)/12 must be equal to 2 left side is mV/K. So, which basically means that this k ln(n) must be equal to 24, ok.

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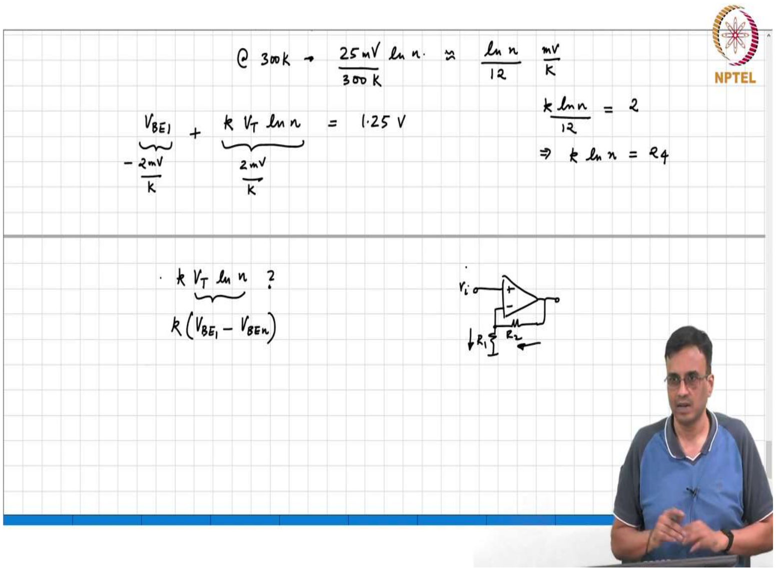

So, if k ln(n) = 24 which is equivalent to saying that if you take a V_{BE} of a transistor I mean. So, I am sorry, a diode and most of the time it turns out that the diode is realized as a transistor with base and emitter, base and collector shot. So, that is why I am calling it V_{BE}, ok, but it's actually basically a diode drop. So, basically what is the moral of the story? It is telling you that if you take a diode voltage to it you somehow add k ln(n) V_T and that k ln(n) must be as per our math 24. If you add 24 V_T to it the temperature coefficient of the result will be 0. Temperature coefficient will be 0. So, the voltage will be constant. So, V_{BE} roughly

0.65, 0.65, 650 millivolts roughly 24 V_T and is how much? 600 millivolts. So, 650 + 600 is how much? It is about roughly about one point, you know, 1.25 volts, ok. So, you will get a reference voltage which is 1.25 volts you know is constant with temperature. This is the principle, alright, ok and this is very similar to you know the principle is not I mean it's as you can see this is not rocket science. Long ago I mean you know when I do not know how many of you actually saw a pendulum clock, how many of you saw a pendulum clock? Ok good.

You know that the time period of oscillation of pendulum is about $2\pi \sqrt{L/G}$ and you know in the good old days you know they have made that pendulum in some kind of metal and of course, the metal will expand with you know in summer and contract in winter and therefore, the pendulum will run you know faster in winter and I mean the clock will run faster in winter and slower in summer. So, which of course, is no good I mean for most people its ok I suppose, but you know if you are on a ship and like you know you thought you will get to island day after so, many hours then and you find that you are you know then you see only red Indians suddenly then you know big problem. So, thermal expansion is a problem because of the positive temperature coefficient of the metal. So, you know once people figure that out what would they do?

You either make an alloy which you know you know combines metals with in the proportion so, that the net temperature coefficient is 0, that alloy is called in var, ok it stands for invariant and or you know otherwise what they would do is they make a you know hollow tube of one metal inside they will pour mercury. So, what would happen? The hollow tube will expand downwards inside this mercury in the hot weather the mercury column expands in the opposite direction and with the amount of mercury you can basically you know make sure that the center of gravity of the pendulum remains at fault. So, I mean basically you know as you can see that the principle is not is not rocket science, correct. So, now you know the principle well there is one thing you know the principle is one thing, but actually realizing it is something else. V_{BE1} is straight forward you take some current plop it into a diode and you are all set, correct.

But what we need to do now is how do I do this? You know kV_T ln(n) because how do I take some V_T ln(n) which is the voltage difference between this and this simply is nothing, but $(V_{BE1} - V_{BE})$n. And I need to multiply this by k, alright. There are so many ways in which you can think of you know doing this which explains why there are so many band gaps topologies around. We will just do a couple of them just so that you know we get intuition as to how circuits are designed, ok.

I mean of course, if you open the textbook, you will have the final circuit and you analyze it and sure enough it will all work. But it is always important to understand how the circuit came about in the first place. So, remember whenever we want to amplify a voltage. So, for example, I do not know if I mean your for example, say your familiar $(R_1 + R_2)/R_1$ circuit, what is happening? This current is v_i/R_1. You basically convert the input voltage into a current, making that or pushing that current into a large resistor and therefore, getting a large output voltage. So, the principle of amplification I mean the same thing with the common source amplifier, what are you doing? You are applying voltage between the gate and the source generating a current which is $g_m v_e$.

The input voltage passes it through a large resistor in the drain. So, the basic principle of amplification is always: you convert voltage into current, take that current, push it into a large resistor and therefore, get a large voltage at the output. So, if you want to therefore, amplify this V you know $V_T \ln(n)$ which is basically $(V_{BE1} - V_{BEn})$n k. the first step is to convert $V_{BE1} - V_{BEn}$ into a current and push that current into a large resistor so, that you get a large multiple of V_{BE}, $V_{BE1} - V_{BEn}$, is this clear? Alright. So, I mean let us do things, simple things first rather than you know try to amplify $V_{BE1} - V_{BEn}$. The first step lets us try and figure out how to convert V_{BE1}, let us try and amplify V_{BE1} first and from that intuition hopefully we will be able to figure out $V_{BE1} - V_{BEn}$.

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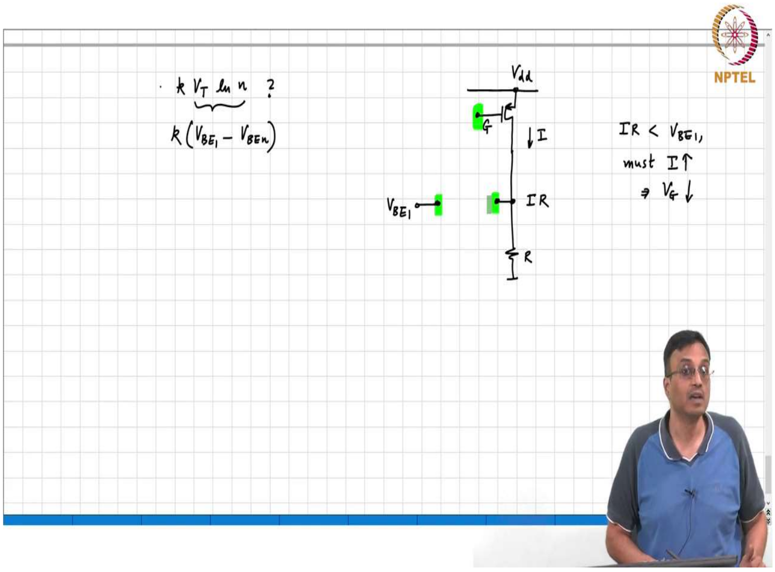

So, if you want to convert you know this V_{BE} we have some V_{BE1}, we want to convert it into a current, what do you think we can do? Let us say if you want to convert it into a current, say V_{BE1}/R and if you are in a lab and you have a variable current source and you want that variable current source to be equal to V_{BE1}/R what do you think you will do?

Student: Pass the current.

Very good. So, if you have some variable current source, you will pass it through R. So, you will put this voltage, therefore, is going to be I_R.

So, you will put a voltmeter and go and kick. Go and turn the knob on I such that V_{BE1} equals I_R, but now you are all experts at this. So, now so, if IR < V_{BE1} what does it mean? I is very low. You must increase I and vice versa, correct, ok. So, in other words you need a volt, this is you basically need to control that current I is controlled by the difference between V_{BE1} and IR, that to voltage, ok. So, now I mean you know of course, you cannot keep sending a technician every time you want to convert a voltage into a current, whatever you can do the moment you describe it clearly you can get an electronic circuit to do it, correct. So, this current source, this current is pushing down and its variable. So, can you think of some component that you already have, some device that you already are aware of which can push, push current and you have control over that current?

You need a current to be pushed down PMOS, alright, ok. Now, this is the knob. And you must compare V_{BE1} with that node IR and go and kick the gate of the transistor in the direction. So, alright. So, if IR is less than V_{BE1}, we must increase I which means that V_G must V_{BE1}.

We are basically looking at V_{BE1} IR, then controlling V_G. So, if $IR < V_{BE1}$, it means that the current is too small which means that V_G is too high and I must therefore reduce V_G. So, V_G must reduce, ok and vice versa, ok, alright. So, this is a voltage controlled voltage source. So, V_G is a voltage, which must be controlled by the difference between these two, and what must be the gain of that voltage controlled voltage source?

Student: Output.

Even if I see an infinitesimally small difference between V_{BE1} and IR. I must go and kick the gate so hard that the difference becomes 0. So, what should be the gain of that voltage controlled voltage source?

Student: Infinite very high.

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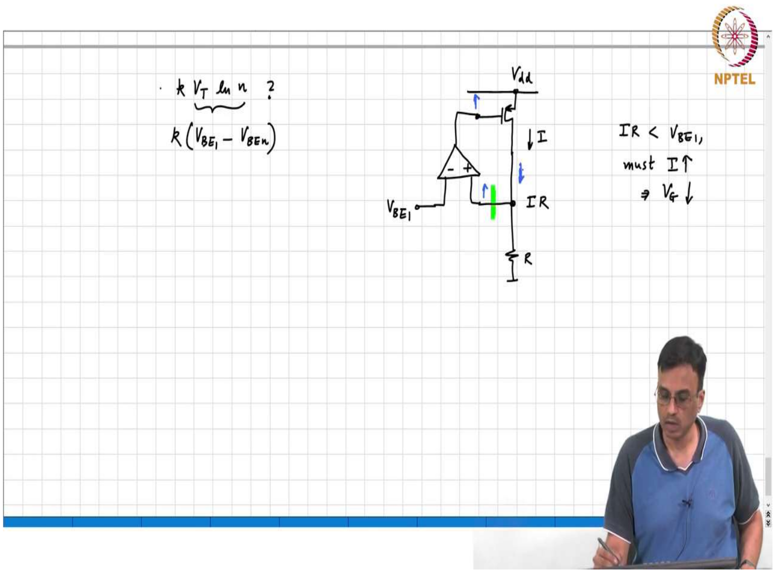

So, what is that which has an infinite voltage? What is the voltage controlled voltage source with infinite gain op amp alright? Alright, and what are the signs on the op-amp, if IR is less than V_{BE1}. The gate must be pulled down, so is IR positive or negative?

Student: Positive.

Positive, is this clear? If you are not, if you are not convinced, if I break the loop here and yank this voltage up, what comment can you make about that node voltage going up? If that goes up, what comment can you make about that voltage?

Student: Goes down.

Goes down. So, there is negative feedback.

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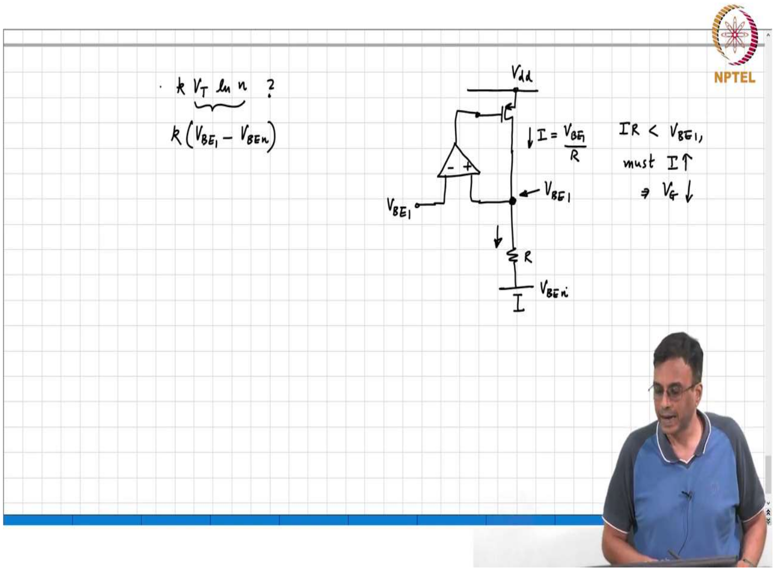

So, basically therefore, what happens to I, therefore?

Student: V_{BE1}/R.

But what we want is not V_{BE1}/R, V_B we want V_{BE1} - V_{BEn}.

So, any suggestions? Why is this current V_{BE1}, this voltage therefore, is because the op-amp has infinite gain, what is the voltage on the hand side?

Student: V_{BE1}.

V_{BE1}, correct. So, this current is V_{BE1}/R, if I want (V_{BE1} - V_{BEn})/R, what do I do?

Student: V_{BEn}.

So, if you add a battery of value V_{BEn}, you will get the current that will flow is $(V_{BE1} - V_{BEn})/R$.

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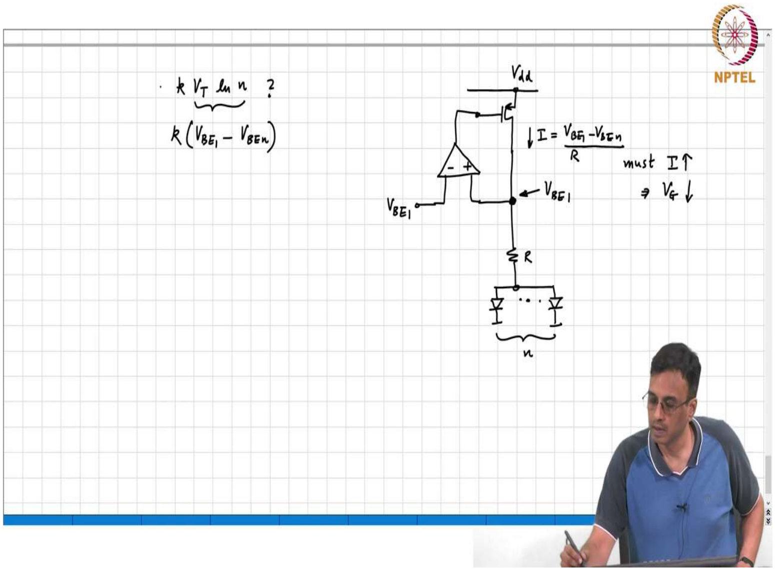

So, V_{BEn} is nothing but N diodes in value, ok. So, this will give us $(V_{BE1} - V_{BEn})/R$, ok. So, we will continue in the next class.