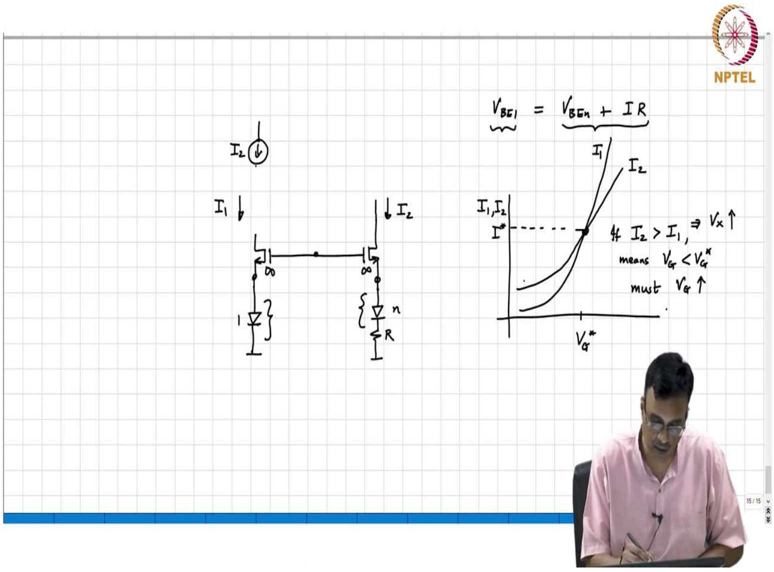
Analog Electronic Circuits
Prof. Shanthi Pavan
Department of Electrical Engineering
Indian Institute of Technology, Madras

Lecture - 60
The Bandgap Reference Part 2

(Refer Slide Time: 00:20)



If you want the current, if you want to generate a ptat current, right, what happens eventually as we saw V_{BE1} must be equal to V_{BEn} +IR, correct? So, one way of finding that magic current V_T ln(n)/R is to force the same current, ok. So, this is basically saying the voltage across this branch, remember that V_{BE1} is the voltage developed across the diode when the current is I.

When the current is I, the same current I is flowing through both branches, correct? So, if the voltage across both these branches is the same, when you pump the same current, the resulting current is P tat, correct? So, these two branches must have the same current flowing at the same voltage across them. So, one way of getting at that magic current is therefore, to pump some arbitrary current, right, and look at the two voltages and tweak the current in the right direction until the voltages are the same, because eventually the voltages are must be the same, the currents must be the same, ok. Now, can we think of an alternative way of getting at the same principle? We pumped the same current and we are looking at the voltages, what else can we do? What else can we do? So, basically the other obvious extension of this approach is to say, well I will apply the same voltage across both the branches, in general what comment can we make about the currents?

If I apply the same voltage across both these branches, in general for an arbitrary voltage what comment can we make about the 2 currents?

Student: They will be different.

They will be different, but for some magic value of the voltage that you apply. The currents will be the same, right, that is the, that current that results is, is I*Is that clear? Ok. So, this is the principle, now I mean we can cook up a circuit to do that. So, you want; so, you want to apply a voltage and measure the current; so, what kind of control source do you think we want? You want to apply a voltage and measure the current, what kind of controlled source does this take?

Voltage controlled current source. So, what is the simplest voltage controlled current source topology that you know? Single transistor voltage control current source. So, basically I have applied a voltage here. Ok, and what is the voltage? If I apply a V_G here, what is the voltage at this, what is the actual voltage across these two branches? What is the voltage here? What is it in terms of V_G man?

Student: V_G - V_T - Δ V.

That ΔV depends on the current flowing, if you want the ΔV to be independent of the current flowing, what should we do to the size of the transistors, make it infinite. So, then what comment can we make about the voltage at the source? It is V_G - V_T, where this V_T is not to be confused with the KT/Q, is this clear? Ok. So, do you agree that now the voltage across both the branches is? What comment can we make about the voltage across both the branches?

Student: Same.

It is the same, correct? So, in general, what comment can you make about I_1 versus I_2 ? In general, what comment can we make about I_1 and I_2?

Student: They will be different.

So, what is our experience? What should we do in the lab? We should go on changing V_G. And keep comparing I_1 and I_2 and change V_G in the right direction. Does it make sense? Alright. So, to figure out what the right direction is, we know that for V_G is that magic, V_G* I_1

and I_2 will be identical. For V_G much smaller than the magic voltage, correct? Which current do you think will be larger? Let us say when V_G is much smaller than V_G*, what comment can you make about the currents I_1 and I mean what comment can you make about the magnitudes of the currents? If the currents are very small or the currents are very large?

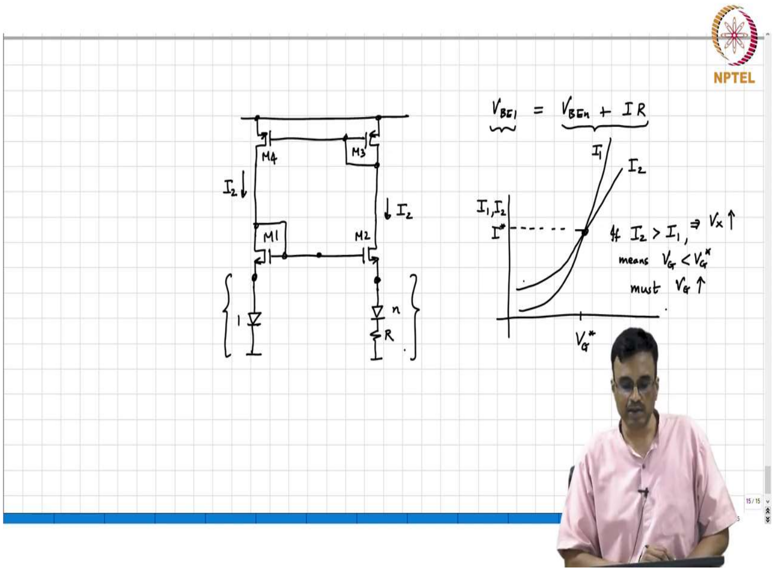
The currents are very small, ok? For very small current, what comment can you make about the drop of the across the resistor versus the drop across the diode? The diode? What, which one can we neglect? We can neglect the drop across R, ok? So, for very small V_G, right? The entire voltage that you apply is appearing in this case across a diode of size n, whereas, here it is applying, it is appearing across a diode of size 1. So, which will have more current? It will have n times larger current, correct? So, if V_G less than V_G*, I_2 will be greater than I_1, it will be n times larger and because of the exponential characteristic of the diode, it, the for small V_G, both of them will have, both of them will have an exponential characteristic, correct? And the ratio of the 2 will be I_1 to I_2 will be n, right? Now, as I, as the voltage V_G keeps increasing, what comment can you make about I_2 which, which voltage drop can you neglect as I become more and more?

The diode drop will change very little, because you know the voltage is logarithmic, whereas the voltage drop across R is linear, right? So, eventually this will, which is something which is going exponentially will only go, linearly like that, I mean I think I am a bad artist but, ok. It will go linearly, whereas, oh sorry, this is the I_2 must basically do this and eventually go only linearly, what about I_1?

I_1 will basically keep going exponentially for all values of V_G, right? So, this is I_1, correct? So, for the magic value of V_G*, both the currents will be the same, let me call that I* and what is. So, special about I*? I* is a PTAT, alright? So, basically it's saying that if I_2 is greater than I_1. Means V_G is less than V_G*. So, must I increase V_G, alright? So, how do you make it? So, you have to compare I_2 and I_1 and change the direction of V_G in the right, in the right way. How do you compare what physical principle will be used to compare 2 currents? KCL. So, I must, I mean comparison with difference.

So, I basically need to compare. So, if I somehow make a copy of I_2, alright? Ok. If I_2 is greater than I_1, what comment can we make about node X? So, if I_2 is greater than I_1, which means V_x goes up, alright? So, if V_x goes up, V_G must, V_G must go up, ok? So, basically what must we do? Connect it this way, ok, fine.

(Refer Slide Time: 11:02)

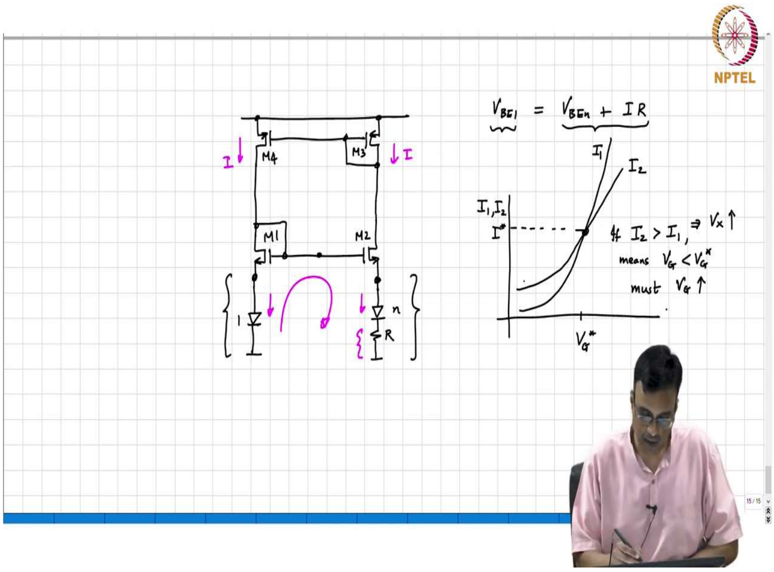


Now, the question is the only, you know, the only problem now is how do I generate? A copy of, how do I make, I have I_2 here on the right side, how do I make a copy?

Student: PMOS current.

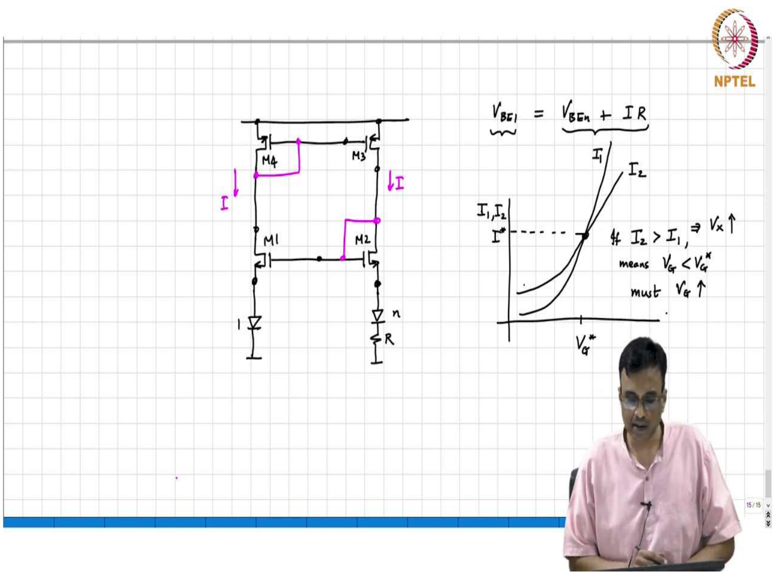
Which of the devices on top will be diode connected. Because I am copying I_2 and making it, alright? So, what is the only problematic part in this circuit, the infinite transistor? So, is it really a problem now a problem, what is the current flowing through both these transistors? Let us call them M1, M2, M3 and M4. M1 and M2, both the transistors carry the same current. So, should we be? So, is it necessary that the voltage, the size be infinite? Why? The overdrive is the same, right? So, basically you do not need the infinite size after all, right? Even with the finite size you will basically end up with the same voltage, if you apply a voltage at the gate, you must get the same voltage at both sources on both sides and you know, once the circuit is stabilized that is what happens anyway, both currents are the same. So, the voltages across this branch and this branch are the same, does it make sense? Ok, deceptively, looking I mean and of course, if you have never seen the circuit before, the analysis is pretty straightforward.

(Refer Slide Time: 13:21)



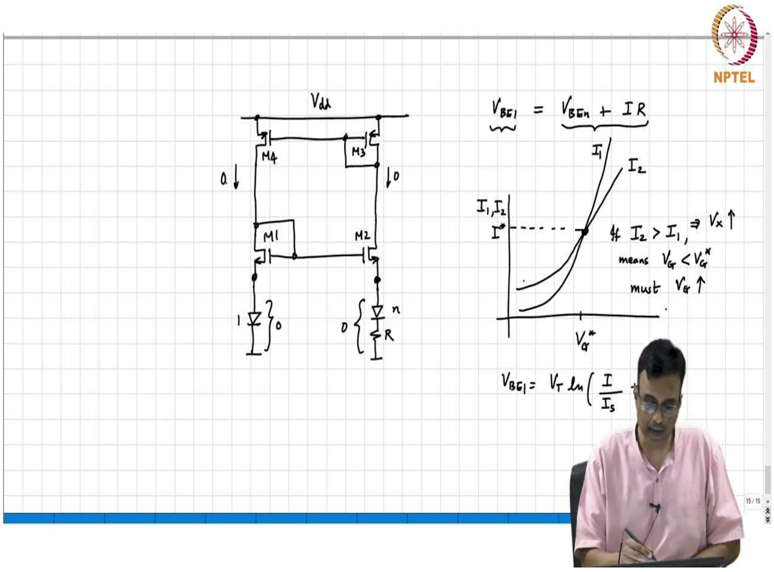
I mean in other words, I mean all I am saying is that instead of wasting so much time, you know, deriving the circuit from scratch, you can as well show the final circuit and say, well, if you look at the circuit, how do you analyze it? Well, this is easy, oh well, this is I, this is I, right? Or the same current must flow here; So, this is I, this is I and therefore the voltage drops there, you write KCL in this loop and then V_{BE1} - V_{BEn} = IR. So, I mean it is obvious that, it is obvious that the current I = V_T ln(n)/R, ok.

(Refer Slide Time: 14:10)



But the problem comes, if you do not understand carefully, now let us say I gave you this circuit like this, ok. And if you did not know anything, you would just still complete this, again you would go through the, say I mean the equations are still the same, the same current flows, if I mean you assume this is I and this is I and you apply KVL, across the same loop. So, it appears as if it makes no difference whether it was the whether you mirror this way or you mirror that way, it will turn out that this way of doing it is basically positive feedback, right?

(Refer Slide Time: 14:54)



It is like saying if you did not know anything about negative feedback and you thought always that the virtual ground of an op-amp is a short no matter what, then what would you wonder, now why is all this fuss about this + and - and so on, the signs, I mean anyway it is virtual ground. So, what happens if I flip the signs at the input of the op-amp, you would think that, you know, if you just mug up the rules for the op-amp, I mean you would wonder whether, you know, why are we, you know, why are doing. So, fussy about the signs of the op-amp, right? So, this is basically the same thing, here right?

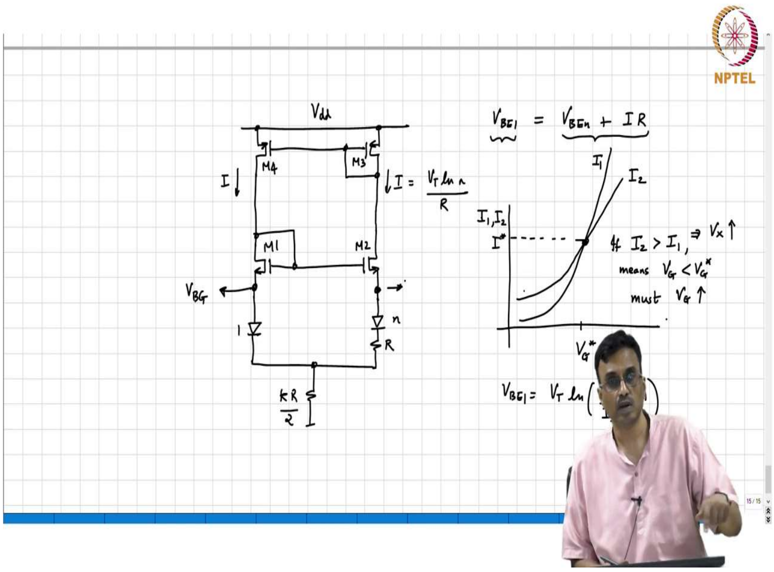
So, the correct signs are, this way, ok? Now, all these circuits that we have seen so far, you know, this is one equilibrium point, right? Now, the 0 current state is also an equilibrium, is a potential operating point, ok? Remember that the voltage V_{BE1} is V_T ln (I/I_s) only. If I am much larger than I am, right? So, the two equations are ln $((1 + I)/I_s)$.

So, for example, in this circuit, if the currents were 0, what is the voltage drop across this diode is 0, what is the voltage drop across that branch?

Student: 0.

So, the voltage across this branch of both branches is the same, the currents through both branches are also the same. So, it, you know, evidently it is, that is a possible operating point, right? Fortunately, it turns out that it is an unstable operating point and you know, if you actually slightly kick one side, it will come to, it will come to the desired operating point.

(Refer Slide Time: 17:30)



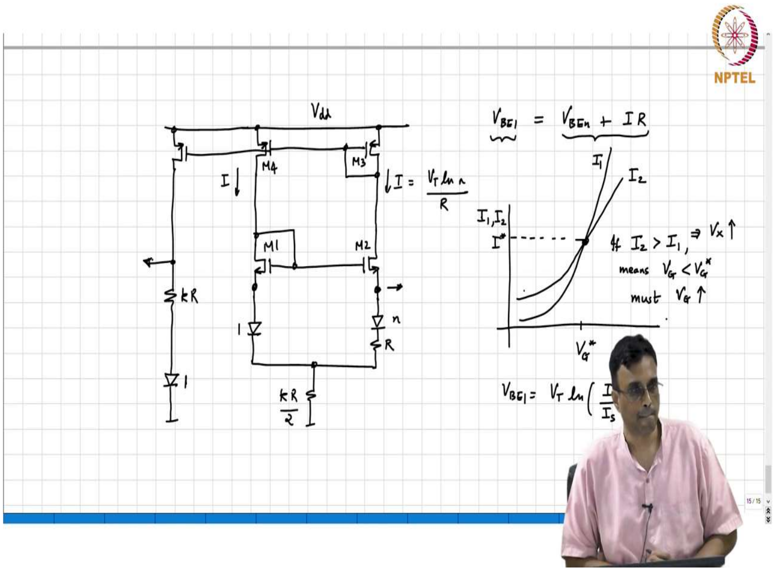
But when you are trying to make a product, you know, you are not, I mean, you should not be praying that something happens, ok. So, usually, I mean; so, basically there is, a straightforward to basically, if you know that the current flowing through any of these transistors is 0, right?

You know that, there is, the circuit is stuck at that, all 0 state. So, it is a simple straightforward matter to simply detect if no current is flowing, and go and kick any one of those nodes to, and push it out of that unstable operating point. So, these are all called*tup circuits. I am not going to cover it in this course. You will see it in analog IC design when you do it next semester.

So, likewise for this also, here also. The 0 current state is, is a stable operating point, right? And likewise, here, ok? So, I mean, and you can see that the basic principles are, I mean, after all, the basic principle is still, you know, generate a PTAT, and then use that PTAT to add what do you call, to the PTAT, you, I mean, you are amplified by an appropriate amount and add. So, here how do we generate the PTAT volt? I mean how do you generate the band gap voltage? This is PTAT. Now, how do we generate the band gap voltage? There are many ways of doing this, obviously. You can use one way of doing it. I mean, you can, you know, use any of those things that we have used in the past.

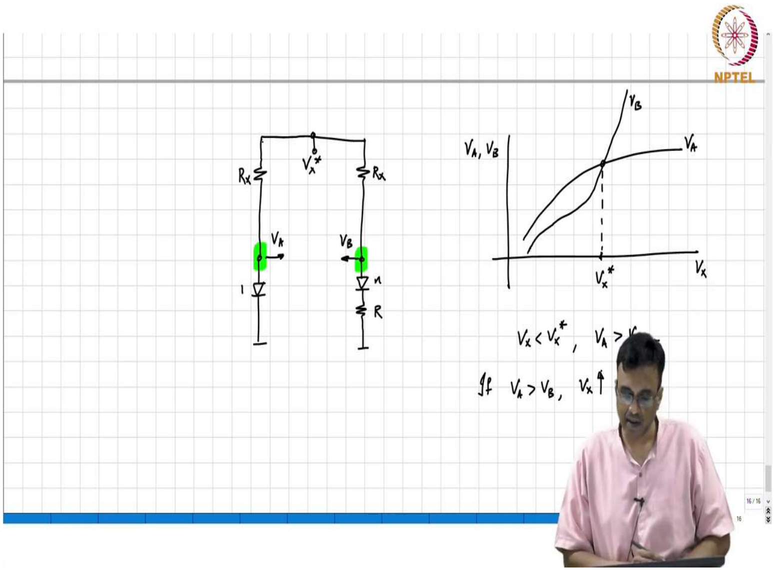
So, let us say, one way of doing this is to connect KR/2 here, ok, and take the band gap output voltage there, right? So, that is one way of doing it, right. Or you can take the band gap output voltage here. Another way of doing it is to take this.

(Refer Slide Time: 20:00)



Alright? You know, put KR there and V_{BE1} there. So, this will be your, put in that is one way of doing the band, alright.

(Refer Slide Time: 20:22)



So, one more variant, again using the same basic idea is to say, well, this is V_{BE1}, this is V_{BEn}, this is R, alright? And what is magic, what is the golden principle? To find the PTAT, the voltage across these two branches must be the same and the current must be the same. So, at the equilibrium point, at the, you know, at the magic point, the voltage across, both these branches is going to be the same anyway, correct? So, rather than use current sources, one mode could as well use resistors. So, let us say, let us call this R_x and I can go on. This is my, I mean, to push a current into these 2 nodes, I can use, remember that a large resistor is the same as a current source, right?

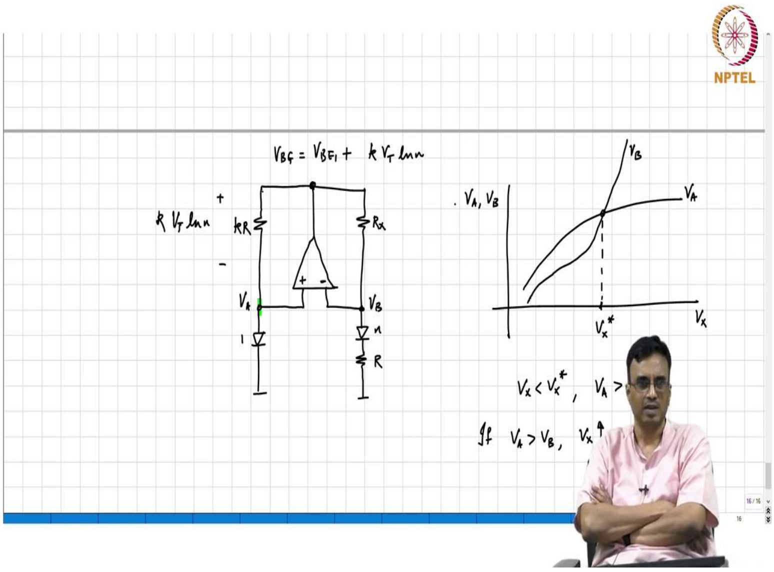
The only problem is that the current typically will depend on this, this potential. You want, remember, both the currents must be exactly the same, alright? But then the argument you make is, well, when the circuit works, these 2 potentials are going to be the same anyway, alright? So, I will keep yank you know, varying this voltage, right? And keep looking for that magic voltage V, I do not know, I am going to call this V_x*, where V_A equals V_B, alright? Ok? And at the magic voltage, when V_A equals V_B, this current is going to be exactly the same as this current, because the top terminals of the resistors are the same.

And I am telling you that $V_A = V_B$, alright? Ok? So, what will we do here now? Now, you tell us, now, I want you guys to help me figure out what I am going to do. What are we going to do? What will be what plot will be, draw V_x on the horizontal axis, very good, ok? We will draw V_A and V_B, ok? So, for V_x very small compared to V_x*What comment can we make about, V_A? So, when V_x is very small, what comment can you make about the current?

The current will be very small. So, in this branch, which voltage drop can you neglect? You can neglect the voltage drop across R. So, for V_x very small compared to V_x*, which will be larger V_A or V_B. So, the same current is flowing through a diode, which is size 1, whereas, on the right side, it is flowing through a diode with size n. So, for V_A, will be exponential, one logarithmic like that, ok? And for V,. So, V_x much smaller than V_x*, V_B will be smaller, right? And as V_x, I mean as V_x keeps increasing, what will happen?

Then it is logarithmic, then it will become, do something like that, ok? So, for V_x less than V_x*, $V_A > V_B$. So, what must you do? So, in other words, if V_A is greater than V_B, what must you do? $V_A > V_B$, it means that $V_x < V_x$*. So, V_x must be increased and vice versa. So, therefore, V_x is a voltage which is controlled by the difference between V_A and V_B.

(Refer Slide Time: 26:00)



So, it is a voltage controlled voltage source. And what must be the gain?

Student: Infinite.

Ok. Now, so, what is this voltage, therefore? What is the current flowing? Is it always the same? V_T ln(n)/R. So, what is the voltage across this resistor?

Student: V_T ln(n)/R.

So, what is the output voltage? $V_{BE1} + R_x/R\ V_T \ln(n)$. Supply voltage, where is it coming? I mean, not this circuit, any circuit that we have seen with the op-amp, we have not connected, we have not drawn the supply and ground for the op amp. That is understood right? Same thing here. I mean, remember, please remember that whenever everybody draws, anybody draws an op amp, it is understood that there is a V_{dd} and a ground, right? Without it, nothing will work. So, if you want K $V_T\ln(n)$, what will you make R, R_x?

Make it K R. So, Then this will become K V_T ln(n) and the output will be K V_T ln(n) and this is V_{BG}. Alright. Ok. And the advantage of this is that what might be the advantage of this? I mean, ok, well, there is a, that is a very small thing, right? Now, you have no two extra transistors, but well, in the op amp, we have like half a billion of them. So, it really does not matter alright. The nice thing here is that you are taking the output at the output of the op amp, which is a? So, if you connect a load here.

You put R_L here, what comment can you make about the output voltage? Will it change? The output impedance is, the op amp is 0 anyway, ideally at least. So, this can tolerate, I mean, you can load it and the output voltage will not change. Whereas, for example, here, if you go and put a resistive load, what will happen?

Current will be drawn from there and you will get messed up. So, I mean, this will need a buffer here, right, in order to draw, drive you know, some other thing alright. So, that advantage is, that disadvantage is gone. Right so, you know, they said there are any number of ways of coming up with, I mean, the principle, of course, of the band gap is the same, alright, and is, has been the same for a very long time, right.

But you can see that the circuits look, I mean, we have seen, I do not know, at least what, 1, 2, I mean, we have seen 2 ways of looking at the same circuit, right. And once you figure out the principle, you can, I mean, you can see that, you know, this variant looks, this variant looks very different from the op-amp based variant, right.

But the basic principle is the, is the same. So, you pump the same current, I mean, you can think of it as, you pump the same current through a branch of, you know, size 1 and size, and you know, size n plus a resistor and find when the voltage becomes the same or apply the same voltage and measure the current and keep varying the voltage where the currents become the same, alright.

And in either case, you will eventually end up with the circuits that, that you see, right. And these circuits are actually, you know, very deceptive, right? So, it is very easy to make a mistake, correct. If you do not understand, you will simply, I mean, you know, if you write the equations that, that, the other circuit where, you know, you flip the mirror on the PMOS side and flip the mirror on the, NMOS side looks, I mean, if you write the equations, they all are the same.

So, you would get, you know, tricked into believing that, that circuit works when it, in reality, when it does not alright. And you have seen a similar situation earlier, what is that? Fixed GM bias also had the same problem, right. I mean, if you did not know how the circuit came about, it is very easy to, to flip the, the other 2, I mean the, the mirror orientation and then end up with the circuit, that does not, that does not work. So, yeah, that is all I had to say about band gaps, band gap references. And this is just a way of, I mean, this is just to give you a flavour of how op-amps can be used to design lots of nifty little circuits.

And it is not for nothing that the op-amps are called the workhorse of analog engineering, right. So, negative feedback is, is something that is an underlying, if you want to make anything work robustly, right, negative feedback is an absolute must, ok. And negative feedback is predicated, I mean, working properly is predicated on the fact that you have a high gain forward amplifier, right. And the high gain forward amplifier is basically an op-op-amp.

And now we not only know how to design the internals of an op-amp, we know what those transistors inside are doing, but we have also seen a use case of, you know, of, of an op-amp in a circuits that generate useful, you know, bias quantities, ok, alright. So, with this pretty much, I think all the within-quoted memoryless parts of the course are over, alright.

So, the bottom line, therefore, is that, you know, however small the transistor gets, it still has inertia, right, electrical inertia if you. So, if you want to think about it that way. And we need to now examine all the circuits that we have seen in this new line, right.

So, what happens to our standard, you know, op-amps and, you know, transistors and stuff, if, I mean, our op-amps or common source amplifier, common drain amplifier, etcetera.

What happens to all these circuits when the speed, finite speed of the transistors is, is accounted for. So, first we need to model the transistor when memory effects are concerned.

And then, you know, replace the old small signal model we had with, with this modified one end, basically reanalyse all our circuits that we have done. And from where we go. Alright, ok.