Analog Electronic Circuits
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Lecture - 42
Fixed Transconductance Bias Circuits from First Principles

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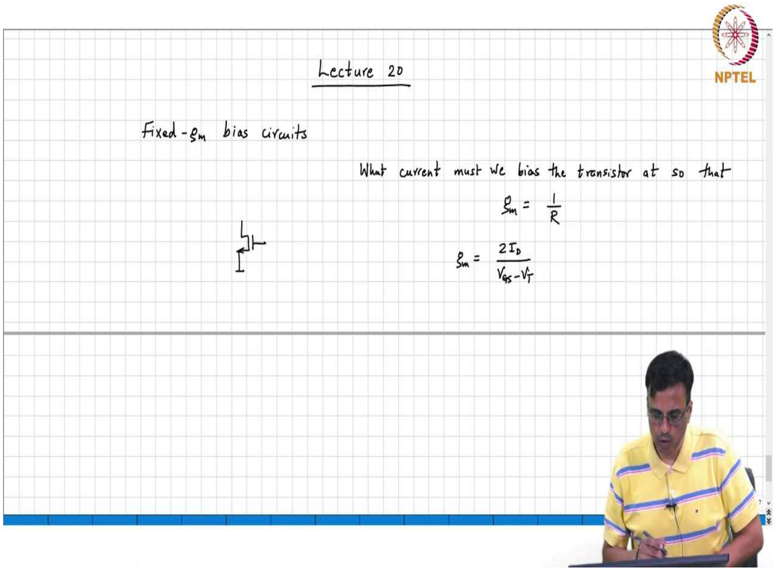

Lecture 20

Fixed - g_m bias circuits

What current must we bias the transistor at so that

$$g_m = \frac{1}{R}$$

$$g_m = \frac{2I_D}{V_{GS}-V_T}$$

In the last class, we looked at the PMOS transistor. We recognized how it came about. We saw it is the equations that govern it and recognized that this is basically a device which pretty much behaves like an NMOS device except that its characteristics are complementary to the NMOS transistor. And we also saw how, you know, whatever you can do with an NMOS device, you can also do with a PMOS device. In fact, if the if the μ_n C_{ox} W/L of the NMOS transistor and the PMOS and μ_p C_{ox} W/L for the PMOS transistor are the same and the threshold voltages are the same, then you can just take an NMOS circuit and convert it into a PMOS circuit.

It will have exactly the same behavior, small signal models have a properties gain input impedance, output impedance etcetera, right. But then the obvious question was, you know, why do we need the PMOS? If all you can do with the PMOS, you can also do with the NMOS and vice versa. The question is, why do you need a PMOS transistor in the first place? And the answer to that is that the behavior of the transistor is complementary. So, you can put NMOS and PMOS transistors together to do things that you could not have done with single type of transistor alone, right or maybe you could even try to do it with single transistor, single type of transistor, but you would have to jump through, you know, a lot of hoops, right. It is like having, it is like saying, well, my right hand looks like the left hand, right.

Why do I need both, correct? Isn't it? Is that I mean? The reason is that, you know, whatever you can do with the right hand, you can do with the right yeah, but you get the idea, right. But it is when you have both hands that you get. I mean, it is complementary. So, you can do things with, you know, both hands which you could not have done with just one, alright, ok. So, today we will, you know, try to see a simple example of a family of circuits, which basically, you know, I would say, is more of a fun class. We will try to build circuits from a scratch, basically trying to do something that we might want in practice.

So, as we have discussed, the performance of a circuit basically depends on the transconductance of a transistor. And the transconductance is basically μ_n C_{ox} W/L times. Some V_{GS} - V_T or $\sqrt{2k\,I}$, whatever you like to, whatever way you like to look at it, but the bottom line is that if you bias a transistor with a constant current, and that is what we have done so, far, right, the current is constant, and that is been established by the use of negative feedback, right, in one way or the other. If the current is constant, the transconductance of the transistor will vary with temperature due to a change in the mobility, right?

And, you know, this variation over, say, 120 degrees centigrade can be, you know, as large as maybe about plus minus maybe 25 percent or so. It might seem like a small change. It's only 25 percent variation of the transconductance over 125 degree centigrade. But, you know, commercial parts are basically designed so that they work well over this large range. Because you know, if you go to Ladakh, you do not want to go and, you know, buy another phone which only works, you know, at 0 degree centigrade. And if you go to Sub-Saharan in Africa, you want to make sure that the same phone still works there, right.

Now, it turns out that, you know, when we go forward with models for the transistor as far as I mean dynamic models for the transistor, where we are worried about parasitic capacitances and time constants with which these capacitances charge, it turns out that the speed of the transistor is dependent on not only on the gm, but also the parasitic capacitances that you see or any intentional capacitance that you might put, you know, to make the circuit work, right.

So, the g_m has got dimensions of 1/resistance. The capacitance, of course, is the dimensions of capacitance. So, all time constants will be of the form, you know, 1/RC which is the same as g_m/C. g_m of the transconductor of the transistor of some transistor in your network and C is some capacitance in your network, ok. Now, so, the bandwidth of a circuit is typically defined by a time constant of the form, g_m/C or g_m/C. Now, if g_m, I mean C largely remains constant because it is with temperature, because it is largely a geometry dependent, dependent parameter, right, some WL, you know, by area by distance and so on right.

On the other hand, the transistor is a much more complicated device. So, the way it varies, varies with temperature is a lot more complicated as you can imagine, right. And therefore, you know, if g_m varies over, you know, 100 degrees by about 25 percent, right, what comment can we make about the bandwidth of an amplifier? The bandwidth depends on some g_m/C, C remains largely fixed with temperature, g_m varies by 25 percent over temperature and therefore. Bandwidth will change over temperature, alright. Now, if you want the, if you want to have a minimum bandwidth for your amplifier, right, and you want to bias your transistor with a constant current, which is what we have done so far, right. How do you think we can make an amplifier whose bandwidth is guaranteed to be greater than a certain minimum over all operating temperatures? Do you understand the problem?

So, let us say you are, you know, you want a bandwidth of at least, I do not know, 100 MHz, ok, which is some g_m/C, right, ok. And then, you are trying to bias your transistor with a constant current so that g_m is some, you know, a temperature dependent quantity. And by the way, as temperature increases, do you think the trans conductance will increase or decrease? Increases or decreases with temperature? I mean, as things get hotter, you know, basically the, the physical reason is that the atoms in the lattice are jumping around a lot more, right. And carriers are going to get, trying to get through from, from source to drain.

So, if in the middle, you know, people are, you know, if the lattice atoms are jumping around, then; obviously, there are a lot more collisions and it takes, you know, effective mobility of the carriers. And therefore, as temperature increases, you should expect that the trans conduct mobility will decrease and so, the g_m, will not increase. Do you understand, ok. So, now coming back to our situation. So, let us say we bias the transistor with a constant current and we want to guarantee a minimum bandwidth of say, just for argument, say, some 100 MHz, right. What do you think we should design for?

So, basically, we say, ok, well, we know that the g_m is going to be the lowest at the highest operating temperature. So, I will design my amplifier to have the minimum required bandwidth at the highest temperature, ok. And so, by design at lower temperature, it will be guaranteed to have a bandwidth greater than the minimum required, right, ok. But so, what is the problem with this approach? So, you are designed for the worst case, right, ok. But that basically means under the nominal temperature, which is you are most of the time you are likely to operate. If you design for the worst case, then you are wasting power simply because, you know, you have a bandwidth which is much larger than necessary, ok.

And you could have in fact, if you had designed it only for the required bandwidth at room temperature, you could have burnt a lot less, lot less current which basically translates to a longer battery life. Does it make sense? Ok, alright. I mean to drive home the point, I mean well, a lot of our energy is nuclear energy, right. And we have plants, you know, not very far away, right. So, I mean, you know, at any time anything can happen, right.

So, one way to de-risk yourself is to say, well, you know, there could be a nuclear explosion any time. So, let me, you know, cover myself with, you know, 3 inches of lead and walk around, right, ok. Well, I mean, you know, it is true that it could happen, but I mean that is, it seems like such a rare occurrence that it does not seem to make any sense to design for the worst case, right. And then you will say I will leave underground, so that, you know, nothing will happen, ok. Somebody may bomb me, right?

So, let me sit underground. So, this I mean so, this kind of designing for the absolute worst case basically means that you will be, you know, of course, you know, even under the nominal case nobody can bomb you at that time, right. But the point is that you are terribly inefficient under normal circumstances. So, what is the smart thing to do? So, yeah so, basically you want the problem to be that the trans conductance is changing with temperature, right. And because we are biasing it with a constant current, right. So, if we could, if we know that we are operating at room temperature, you could, if you had somehow a way of figuring out, you know, what the temperature is, for argument's sake, then you, if I know that I am operating at room temperature, I could go and reduce my bias current so, that basically if you want a minimum bandwidth, I want to make sure that the trans conductance is at least this much, right.

And this means that if I somehow are able to figure out what current to bias the transistor at. So, that the trans conductance will remain constant with temperature, correct. Then under all temperatures, I am never over designed. So, you know, at low temperature when the room is cold, then, you know, I have less current flowing in the transistor and therefore, because the mobility is high, the trans conductance will be what I want. If the temperature is very high.

Student: (Refer Time: 11:57).

Well, you know, we should increase the current. So, that we compensate for the fallen mobility so that under all circumstances at all temperatures, we should always, we will always have a constant g_m. So, in other words, rather than bias with a constant current, we would like to bias it with such a current. So, that the trans conductance of the transistor is constant, right. And this is commonly used in a lot of, a lot of circuits, right, for this, for this very reason, alright. So, such circuits are called fixed g_m bias circuits and, you know, are an example of how one can use NMOS and PMOS transistors together to do things which were kind of difficult to do with only a single transistor, alright. So, the statement of the problem is here is a; here is a transistor, right. And the transistor is operating in saturation, right.

What current must I bias or must we bias the transistor at. So, that g_m is a constant which is I let us call this sum 1/R. And remember in principle what will we do? What is trans conductance? Ok. So, g_m remember is nothing, but there are many multiple ways of doing this $\mu_n C_{ox} W/L (V_{GS} - V_T)$.

Student: $2 I_D/(V_{GS} - V_T)$.

So, if you are given a transistor in the lab and if you would like to find its trans conductance, right, when you bias it at a certain current, ok, which one is most convenient?

Student: Bias $2 I_D/(V_{GS} - V_T)$.

Very good, why? This is basically, this gives you an easy way of measuring I_D through ammeter. $(V_{GS} - V_T)$ can also be formed and dividing one by the other we can get the trans conductance, correct, alright. So, and so, if you are in a lab and you want to make sure that you want to find the trans conductance of a transistor, I mean what is the process? We will find the trans conductance of the transistor, it's either less than what we want equal to what we want or higher than what we want. If it is less than what we want, what will we do? What does it mean? I mean, remember the trans conductance, you know this is our trans conductance, correct, ok alright. So, if we find that we measure the trans conductance, if we find that the trans conductance is too small, what does it mean?

If g_m is greater than 1/R, what does it mean? You have a transistor guys, there is some current flowing through it, right. It is much easier to think about it in terms of current rather than you know I and (V_{GS} -V_T), right. So, if the trans conductance is smaller than what you want, what does it mean for the bias current flowing through the transistor? It is smaller than what should be there. So, what will you do? Increase current flowing through the transistor, do you understand this?

Student: Yes sir.

So, we measure that this is common sense, there is nothing rocket science here about it, right. We have some trans conductance of the transistor, right. It is smaller than what we want, how will we increase the trans conductance? We increase the current flowing through the transistor. On the other hand, if the trans conductance is too much, we decrease the current. So, this is what kind of system is this, this is negative feedback all over again, right, ok alright. So, now the question is, ok. So, if you are in the lab and you want to measure V_{GS} minus V_T, what will you do? You want to bias the transistor with a current I_D, a current I_D must flow in the transistor, right. Our first job is to find what the trans conductance is, then we compare it with 1/R and then go and change the current in the right direction, do you understand? Ok so, the question is how do we find? Yeah, you are in the lab, how would we find g_m, what do you suggest? A current I_D must flow through the drain and we would like to measure (V_{GS} -V_T). So, what experiment will you suggest?

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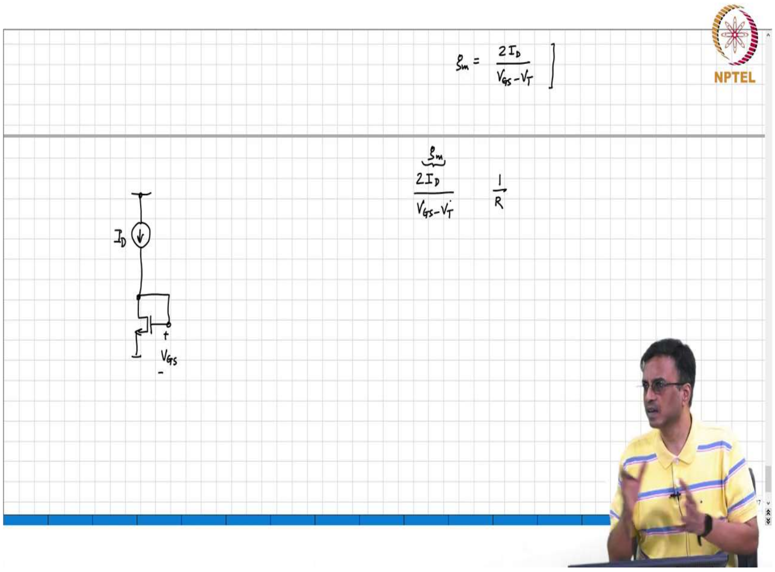

Please tell me exactly what I need to do here is the transistor, alright. What do I do with it? We need to, we need to, I mean, we want to make sure that the current flowing through the transistor is some I_D, correct, and we want to calculate the g_m when a current I_D is flowing through the transistor and the transistor is operating in saturation. What do you think we can do? So, the suggestion is, well, you take the transistor, you short the gate in the drain, ok then what?

So, you put I_D here, correct. So, what will be the voltage there? That will be V_{GS}, right, but what do we want?

Student: $(V_{GS} - V_T)$.

So, basically g_m, remember, we want to compare $2 I_D/(V_{GS} - V_T)$, which is the g_m. We want to compare it with 1/R, right, which is equivalent to comparing, remember, the easiest things to compare are either voltage or current. Because you can use KCL and KVL, ok.

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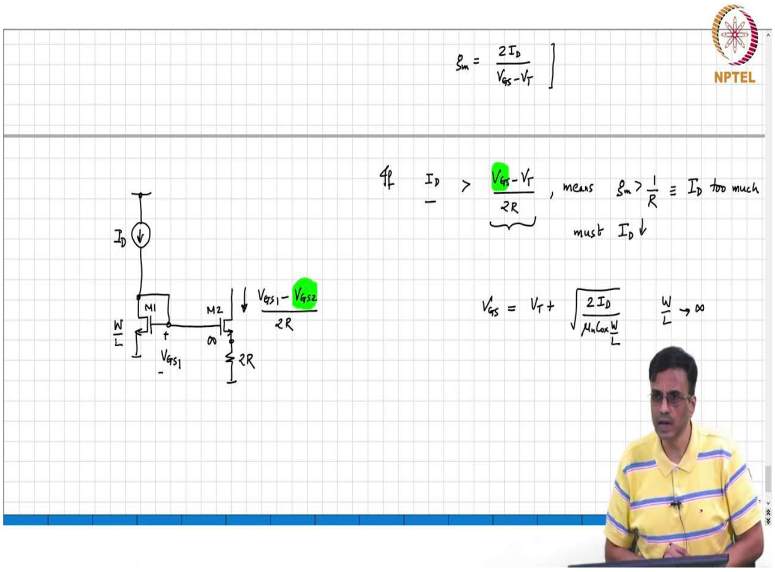

$$g_m = \frac{2I_D}{V_{GS}-V_T}$$

$$\text{If} \quad I_D > \underbrace{\frac{V_{GS}-V_T}{2R}}, \text{ means } g_m > \frac{1}{R} \equiv I_D \text{ too much}$$

must $I_D \downarrow$

$$V_{GS} = V_T + \sqrt{\frac{2I_D}{\mu_n C_{ox}\frac{W}{L}}} \qquad \frac{W}{L} \to \infty$$

So, basically one way of doing this is to basically say, I can, which is equivalent to comparing? $(V_{GS} - V_T)/2$ R right. So, if I_D is greater than $(V_{GS} - V_T)/2$ R, what does it mean? Does it mean trans conductance is too little or too much? Means, g_m is greater than 1/R, which is equivalent to saying I_D is too much or too little?

Student: I_D is too much.

What must I do?

Student: Reduce.

Reduce I_D, correct. So, what we do, what we need therefore, is to compare this current I_D with $(V_{GS} - V_T)/2$ R, alright, ok. So, let us call this, yeah, ok, $(V_{GS} - V_T)/2$ R. Now, given a voltage V_{GS}, we are trying to generate a current, which is $(V_{GS} - V_T)/2$ R. So, what kind of control source is this? Given a voltage, you are generating a current. So, Voltage controlled the current source. What is the simplest voltage controlled current source you know with a transistor? Voltage controlled current source. We want to generate $(V_{GS} - V_T)/2$ R. How will you generate it? So, basically the voltage controlled current source that you know is something like this. Does it make sense?

Student: Yes, sir.

If let us call this V_{GS1}, let us call this M1 and let us call this M2. So, what is that voltage there? If this M2. And let us call this, I am talking about the absolute current, not the incremental current. So, this is V_{GS2}. What is the current flowing in this transistor? Assume that the drain is connected to a sufficiently large potential so that M2 is operating in saturation. So, this is M1, this is M2. So, the gate voltage is at V_{GS1}. This is nothing but $(V_{GS1} - V_{GS2})/2$ R. Is this clear people? Alright. I mean this is so far we have just basically you know we are playing around with all blocks that we know so far. Nothing is new. Ok. But what do we want? What are we looking for to generate $(V_{GS1} - V_T)/2$ R, but what we have is V_S-$V_{GS1} - V_{GS2}/2$ R. Ok.

So, how will we solve this? I mean. So, ideally therefore, our problem would be solved if V_{GS2} was equal to V_T. Ok. So, any suggestions on what I how can I make V_{GS2} equal to V_T. If you have a transistor and you want it's V_{GS} to be equal to V_T, what can we do? What is the formula for the V_{GS} of a transistor?

I mean I_D equal to 0 basically you know does not help because we want some current right to be flowing. What else can we do? You cannot change two, you cannot change the square root. So, if you choose W/L tending to infinity right in other words you choose a huge device which is equivalent to saying current must go to 0 correct. Ok. But either for a fixed for a small transistor current must go to 0 or for an infinitely large transistor you have some finite current flow correct. So, in other words if the size of M2 is chosen to be infinity.

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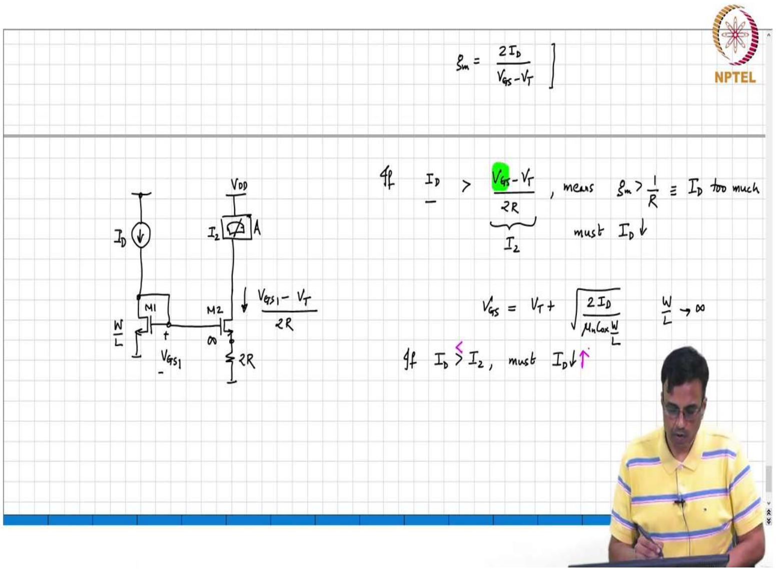

$g_m = \frac{2I_D}{V_{GS} - V_T}$

If $\underline{I_D} > \underbrace{\frac{V_{GS} - V_T}{2R}}_{I_2}$, means $g_m > \frac{1}{R} \equiv I_D$ too much

must $I_D \downarrow$

$V_{GS} = V_T + \sqrt{\frac{2I_D}{\mu_n C_{ox} \frac{W}{L}}}$ $\frac{W}{L} \to \infty$

If $I_D \overset{<}{>} I_2$, must $I_D \downarrow \uparrow$

So, this is W/L, if the size of the transistor is chosen to be infinite what will be the current flowing? (V_{GS1} - V_T)/2 R. Alright. Ok. So, now in principle what must we do? Ok. So, I mean in principle therefore, we this is V_{DD} let us say we can put an ammeter here let us say this reads I_2 right. So, if I_D is greater than I_2 what does it mean?

Student: g_m is large.

It means that g_m is larger than 1/R, what must we do?

Student: So, I_D should be reduced.

We should reduce I_D and vice versa. So, in other words if I_D is greater than I_2 reduce I_D and if I_D is less than I_2 you must increase it. Does it make sense to people? Alright. So, how will we compare two currents?

Student: KCL.

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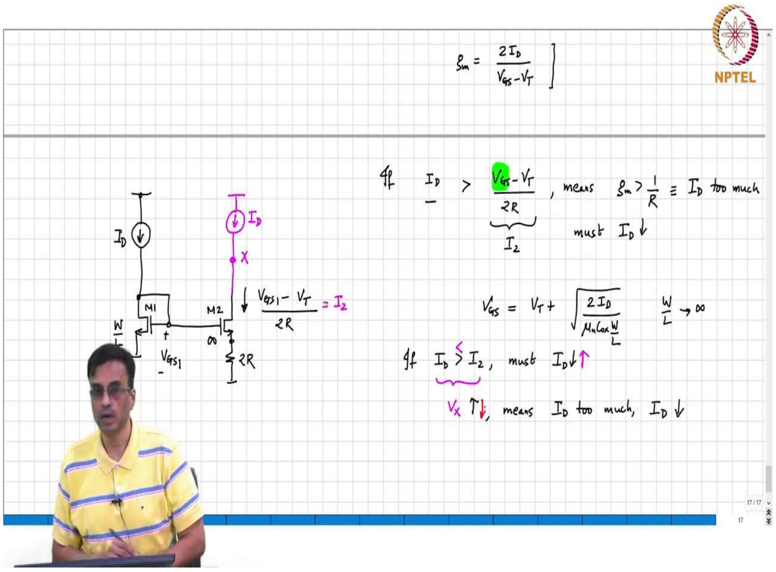
$$g_m = \frac{2I_D}{V_{GS}-V_T}$$

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$$V_{GS} = V_T + \sqrt{\frac{2I_D}{\mu_n C_{ox}\frac{W}{L}}} \qquad \frac{W}{L} \to \infty$$

If $\underbrace{I_D \overset{<}{>} I_2}$, must $I_D \downarrow\uparrow$

$V_X \uparrow\downarrow$, means I_D too much, $I_D \downarrow$

So, any suggestions? This is I_2. I must compare it with I_D. Alright. So, what do you think we could do? Ok let us say you had another current source I_D. What will you do? Let us say you had a copy of this I_D. What will you do? So, basically you say ok well if I had another copy of I_D what I would do? Would be to connect I_D to that 2 I_2 correct and what will be the potential of node X? So, if I_D is greater than I_2, what comment can you make about the potential of node X?

That basically means that if V_X is going up it means that means I_D too much and therefore, I_D must be reduced and if V_X is going down alright. Ok. Now, we have a current we need. So, therefore, we basically need two variable current sources I_D because we are going to vary I_D. So, you need two identical current sources which are electronically controlled. So, any suggestions on what you can have for two we need two current sources which push current down?

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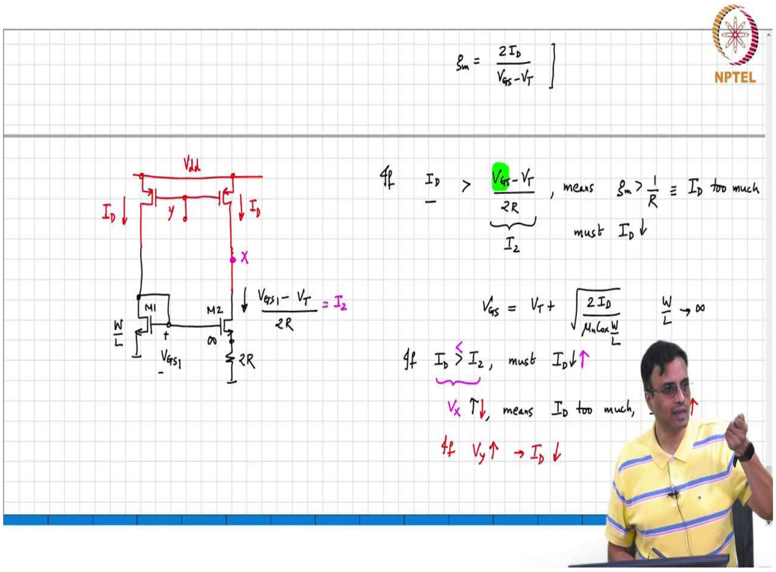

$g_m = \frac{2I_D}{V_{GS}-V_T}$]

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If $\underbrace{I_D \overset{<}{>} I_2}$, must $I_D \downarrow \uparrow$

$V_X \uparrow\downarrow$, means I_D too much,

If $V_y \uparrow \rightarrow I_D \downarrow$

And must be variable. So, what do you think we can do? So, this is nothing, but that is V_T correct. Let us call that V_Y. That is our control voltage. So, if V_Y goes, so, this I_D this is an identical copy I_D alright. So, if V_Y goes up what happens to I_D? I_D decreases because the V_{SG} of the transistor is reducing. What should we do? If V_X goes up I_D must go down. If I_D must go down what should we do to V_Y? Yes, what should we do? Connect nodes. Remember that if V_X goes up it means that I_D is too much and I_D must be reduced. How do you reduce I_D? You must increase V_Y.

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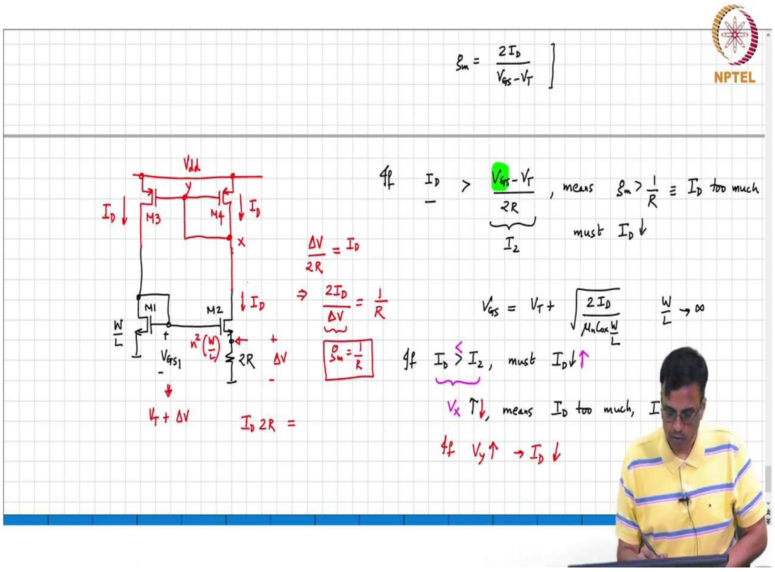

So, basically you can do what we need to do therefore, is to short X and Y alright ok. Now, yeah how do we know this works? Well, if you are looking at this circuit for the very first time alright. I mean there is no nothing to be worried about. Well, we know that the current in the 2 PMOS transistors M3 and M4 are exactly the same. So, let us call that current I_D the same I_D is flowing through M1 and M2. So, V_{GS1} must be equal to let us call this V_T plus some gate overdrive alright. So, what is the voltage there? The gate V_{GS1} is $V_T + \Delta V$ which is the voltage across 2 R. The 2 ways in which you can write it. One is I_D times 2 R. What is the other way you can write it as the voltage across 2 R is nothing, but V_{GS1} -V_{GS2}? So, the voltage across 2 R is ΔV right. So, $\Delta V/2$ R must be equal to I_D which is equivalent to saying which means what? 2 $I_D/\Delta V$ =1/R which is equal to saying that g_m equals 1/R.

But it is one thing to basically you know I mean we could have finished this in 5 minutes by simply showing you the circuit and saying look it works and then move on right. But now we actually know how the circuit came out in the first place right. So, what is the only problem with the circuit which is impractical? W/L equal to infinite right. So, basically instead of making it you know infinity let us say I will call this n square times W/L ok.

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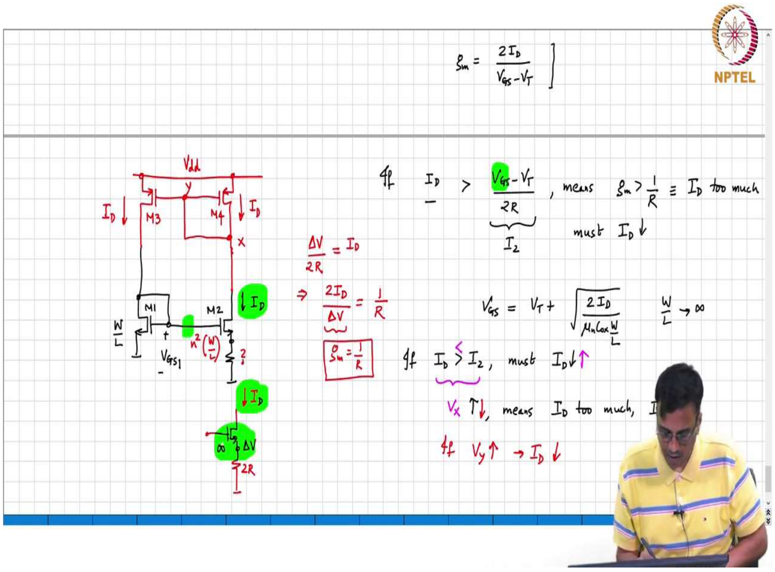

$g_m = \frac{2I_D}{V_{GS}-V_T}$

If $I_D > \underbrace{\frac{V_{GS}-V_T}{2R}}_{I_2}$, means $g_m > \frac{1}{R} \equiv I_D$ too much

must $I_D \downarrow$

$\frac{\Delta V}{2R} = I_D$

$\Rightarrow \frac{2I_D}{\Delta V} = \frac{1}{R}$

$\boxed{g_m = \frac{1}{R}}$

$V_{GS} = V_T + \sqrt{\frac{2I_D}{\mu_n C_{ox}\frac{W}{L}}}$ $\quad \frac{W}{L} \to \infty$

If $\underbrace{I_D \overset{<}{>} I_2}$, must $I_D \downarrow \uparrow$

$V_X \uparrow \downarrow$, means I_D too much, I

If $V_y \uparrow \rightarrow I_D \downarrow$

So, what must you do about this? Let us say I mean when earlier when this was infinite this voltage was ΔV and this was 2 R. And the current was I_D right. Now, let us say we want to change this transistor size to something finite alright, but we want to maintain the same current. See as long as this current remains, I mean as long as this voltage remains the same and this current remains the same. You do not care what you have inside that box. So, if you put V_{GS1} I must get $(V_{GS1} - V_T)/2$ R. That is what I want internally. You could have an elephant, it does not matter, correct ok. So, rather than make it infinite let us say we make it finite alright. What comment can we make about this R here in other words what should R_X be?

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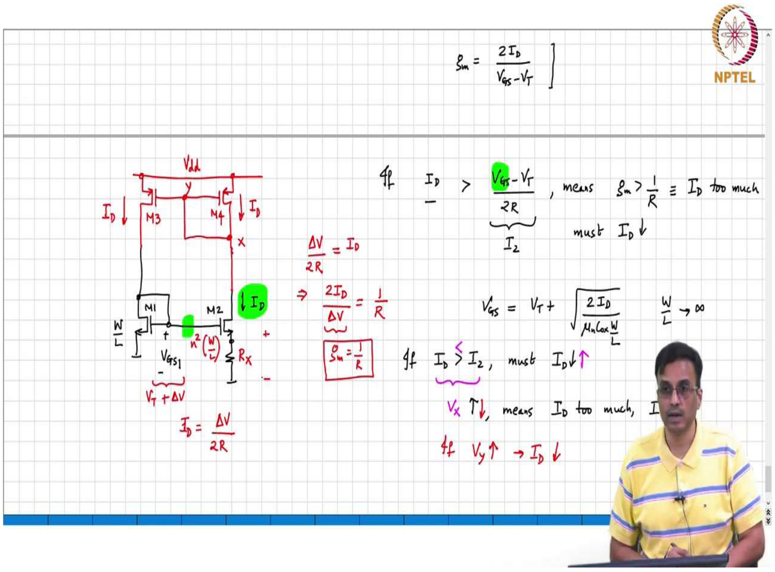

So, that I_D is nothing, but $\Delta V/2$ R right. So, this is V_{GS1} is what $V_T + \Delta V$. The same current I_D is flowing through M2. So, what will its overdrive be? If you have the same current in a transistor which is n square times larger what comment can we make about the overdrive?

Student: $1/n$ ΔV.

Does it make sense?

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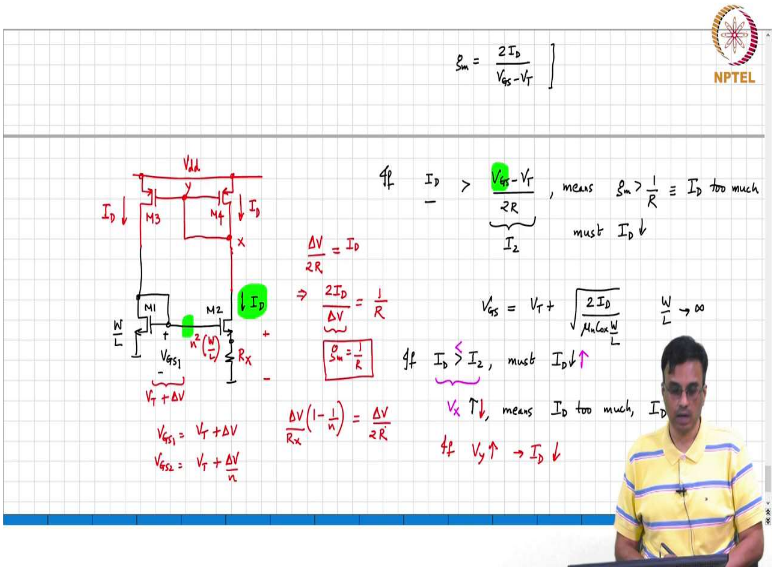

So, what will be the voltage drop across R_X then? V_{GS1} is $V_T + \Delta V$. $V_{GS2} = V_T + \Delta V/n$. What is the voltage across R_X, this is ΔV (1- 1/n) and so, what will be the current. $1/R_X$ must be equal to $\Delta V/2$ R, correct.

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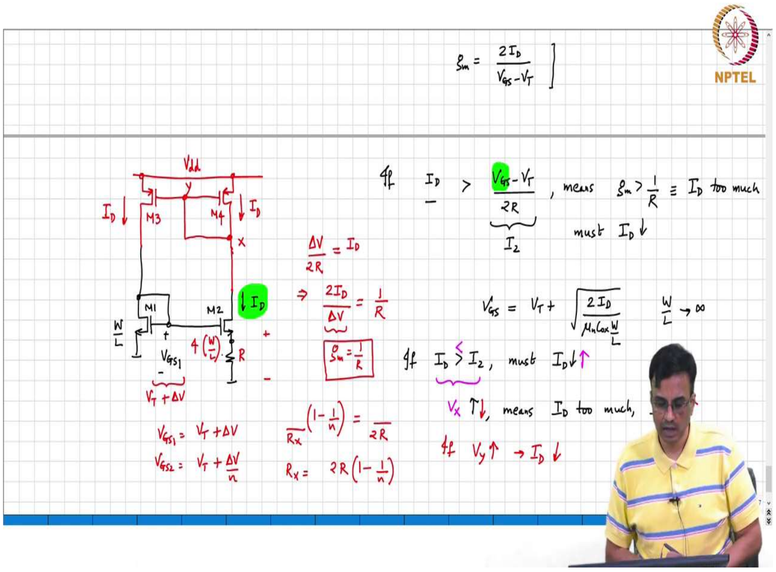

So, what should you do? So, R_X must be chosen to be 2 R (1-1/n) ok. Now, can you make a simple choice of you can we choose anything for n what is the good choice you think? n = 2 will make this simply R_X equal to R. So, and this will become what will be the size of M2? 4 W/n alright and this becomes R ok. So, this is an example of a practical circuit.

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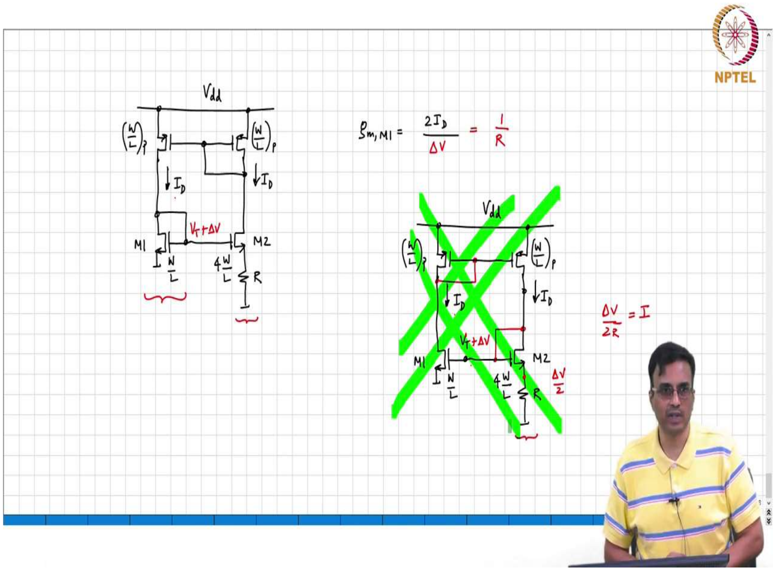

So, so, g_m = 1/R regardless of. This is W/L this is 4 W/L and these are W/L of this PMOS and W/L of the PMOS alright and this is and the current in both arms will be exactly the same and will be always such that g_m of which transistor? Which transistor g_m are we stabilizing folks?

Student: M1.

M1 right. So, the g_m of M1 which is 2 $I_D/(V_{GS1}-V_T + \Delta V)$. 2 $I_D/\Delta V$ is equal to 1/R. Does it make sense? And this does not depend on it does not depend on temperature it does not see you know depend on supply right as long as all the transistors are in saturation. The current will automatically stabilize in such a way that the g_m of M1 is 1/R ok. So, but now if R changes with temperature then you have this you know a similar problem. So, what people do is you know it turns out that in many processes you have what are called 0 temperature coefficient resistors alternatively people make this external to the put in so that the resistor can be external right.

And therefore, and it is a very easy to get you know 0 temperature coefficient you know resistors you know as discrete components you put that there and even if the temperature operating temperature of the of the chip changes right because this resistor is constant you will find that you will find that the current always adjusts itself so, that the trans conductance of the of the transistor is 1/R ok and now if you want to bias other transistors what will you do? If you want I mean this goes and ensures that trans conductance is 1/R, but I have an amplifier where it needs to be biased too. So, what should I do? Basically you know you can make as many copies of this I_D that you want how will you do that current mirror right. So, you can mirror this current you know how many hour times you want ok and make it you use it for a whole bunch of circuits right. So, that the g_m of all the transistors remains constant with temperature ok. Now, you know how the circuit comes about alright.

Now, if you did not know how the circuit comes about and you are looking at this for the first time. If you looked at that circuit and if you did the I mean well the same equations hold right the top is a mirror. So, the same current flows in both legs right.

So, this so, the same current flows in both M1 and M2 and therefore, again the voltage V I mean you know between the gate of M2 if this if this overdrive is if this is $V_T + \Delta V$, this voltage will be $\Delta v/2$, because same current flows in M1 and M2. M2 is 4 times larger and therefore, $\Delta V/2$ R equal to I, which then seems to indicate that g_m of M1 is still equal to 1/R.

So, it seems like it does not matter whether you use the circuit on the left or the circuit on the right just from the point of when you write equations. But it turns out that if you analyse this carefully you will find that this is positive feedback and you will find that this works on the principle of if the trans conductance is less than 1 over R you reduce the current ok. If you go and analyse this carefully that is what you will find and even though the circuit looks deceptively similar to the circuit on the left the circuit will not work in practice ok.

So, that is why it always makes sense to understand why a circuit works and how it comes about in the first place rather than simply opening the textbook and mug up a circuit and then start using it you understand alright ok alright. I will stop, we will continue.