Analog Electronic Circuits
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Lecture - 50
The Different Amplifier with Active Load Part 1

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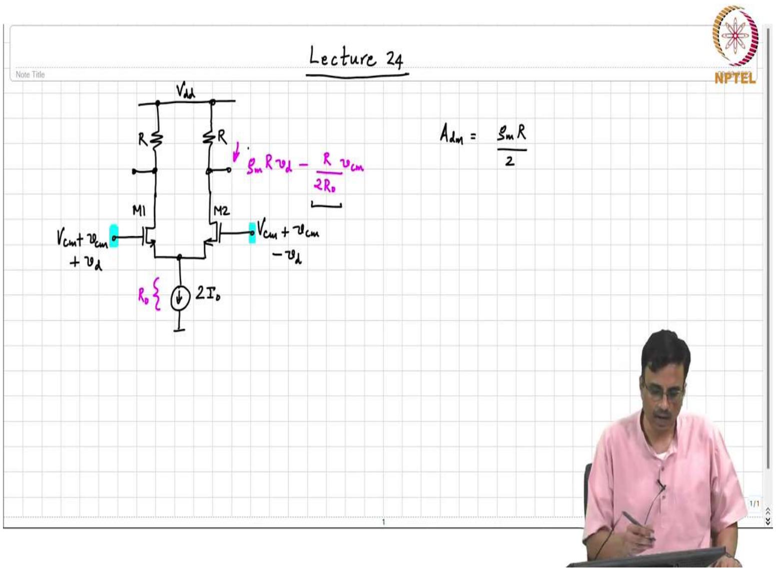

In the last class, we looked at the differential pair and let us do a quick recap. So, in the last class, we discussed the differential pair and why we needed a circuit like this. Right and the motivation was that when you have, when you are building an operational amplifier, the two inputs, the operational amplifier as you know is a voltage controlled voltage source where it amplifies only the difference between the two input voltages. And you know that there is a negative feedback loop that goes and makes, tries to drive that difference to 0 ideally and in practice to some very small quantity.

So, as far as the negative feedback loop is concerned, you know, a job is not to worry about whether you know what the two voltages are V_{in} and V_{out}. If so, the job is only to look at the difference between the two, I mean which is V_{out} F and V_{in} and then go and do whatever it needs or whatever it takes to keep that difference equal to 0.

So, the first step in the whole process is therefore, to design a gain stage where it only amplifies the difference and all the gain stages, we have seen so far basically the common, for example, the common source amplifier where we have amplified only a single voltage and. So, using the intuition behind the common source amplifier, we eventually came up with the differential amplifier.

We have done it with NMOS transistors; there is no reason why the same thing cannot be repeated with PMOS transistors. And the key points behind the differential pair are that of the two inputs, we know that they are going to be somewhat close to each other or very close to each other.

So, rather than talk of two inputs which are you know which are almost the same, we talk of them as being the sum of the average plus half the difference and average minus half the difference, the average you know of course, it does not look very, it does not look very scientific when you say average it basically you say what is common to both the signals. So, that is the common mode part of the input signals and then you have the differential mode.

And so, to represent the change in the common mode we have a small v_{cm} and to represent a change in the differential mode we have I mean the differential mode is represented by v_d. And we exploited symmetry to analyze this circuit the last time around and what will be the incremental voltage at this terminal here? What will it be? It is plus $g_mRv_d – R\ v_{cm}/2R_o$. If the current source in the tail becomes ideal then true to what we see that the output of the differential path does not depend on the common mode right.

So, once I mean So, in principle once you have let say we can make, we have already figured out how to make a very good current source. I mean we can always use cascoding and things like that to make this gain as small as possible or make it really small. So, that does not bother us in which case this incremental voltage is simply g_m R v_d ok. And as you can see in the incremental picture this voltage here is referred to ground with respect to ground it is g_m R v_d.

Where v_d is the difference between these two, I mean or g_m R/2 and 2 v_d is taken to floating voltages in principle and converted into a larger take in that difference converted into a larger voltage and that resulting voltage is referred to ground ok. And then once you want to amplify that you can put in another common source amplifier or if you know if that gain is not enough another common source amplifier and so on to get as large gain as you want right.

So, as you can imagine the differential amplifier is a key building block in the design of analog integrated circuits and analog circuits in general. And it is because it is it in one form or the other it forms the input stage of every operational amplifier, which is the workhorse of analog engineering alright. Now, there is only a small problem with the differential pair. What is that problem?

Like in a common source amplifier the gain is not as large as it would like it to be because it is only the output, I mean if the common mode gain is assumed to be negligible. We see that the gain for differential signals is basically A_{dm} is what we called it is g_m R/2 correct?

And the only way to increase the differential mode gain is to increase the load resistance R which will basically cause the output I mean quiescent voltage to become lower and lower eventually pushing the two transistors M1 and M2 into the triode region right.

And the only way to fix this problem is to keep increasing the supply voltage and as we have seen in the case of a common source amplifier with a resistive load that is not a particularly efficient way of doing things because to increase the gain by a factor of 100 you would have to increase the supply voltage by the same factor almost right. And that is a terribly inefficient way of spending power right.

So, in the common source amplifier what did we do, well we said well you know we after a lot of discussion we decided that the best thing to do would be to use an active load right. And so, not surprisingly well, we have the same problem. So, the logical place to start is to work with the same solution right.

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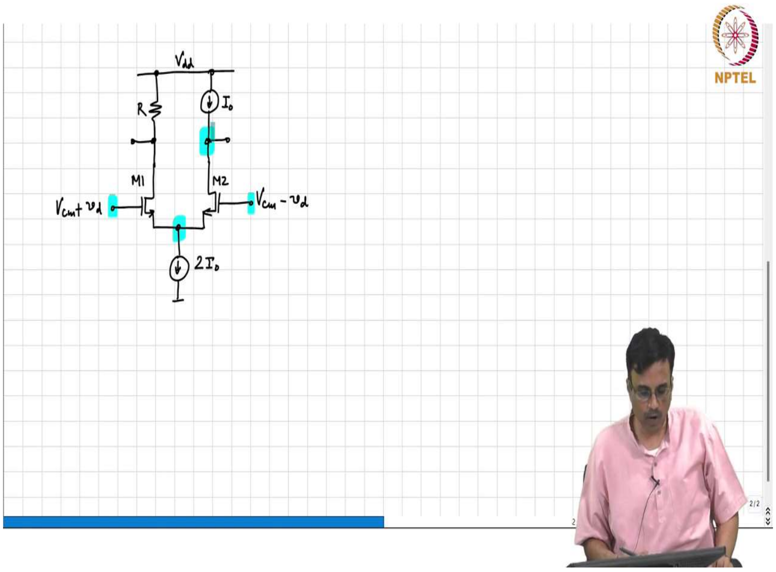

So, that is what we will do now and the basic idea is to solve this problem of and let us assume for the time being that we are you know we are not going to be worried about the output let us assume an ideal current source. So, if this is v_d and this is $-v_d$ we do not care about the incremental common mode change right. We will worry about that later.

So, we have to increase the gain of the output. So, what do you think we should do? What would we do, what would we do in the common source amplifier case, what did we choose for the load? There we had a PMOS input device and therefore, we chose a load which was an NMOS current source. Now what should we do?

Well, we have an NMOS input device and therefore, it seems logical to use a PMOS current source. So, in principle what we would like to do is to put in here a current source and what should be the value of the current source?

Student: I_o.

I_o, alright. So, basically when v_d is 0 well the current in M2 is exactly the same as the current in current being pushed into the drain right. And if v_d is infinitesimally greater than 0 then what comment can you make which transistor M1 or M2 which will have a larger current? I mean if v_d is greater than 0, if v_d is infinitesimally positive remember that M1 and M2 have the same source potential. So, if the gate potential of M1 is slightly higher than the gate potential of M2 and M1 has got a larger overdrive than M2 and, but the sum total of both the currents is constrained to be $2I_o$.

So, this $2I_o$ has to go either this way or that way if M1 has got a larger gate potential more of it will go through M1 less of it will go through M2. So, basically if less of the current goes through M2 therefore, the drain current of M2 will be smaller than I_o. And as a consequence what comment can you make about the potential of that node current pushing into that node is I_o. Current being pulled out of that node is less than I_o. So, that node potential will go up right and you know if M2 and M1 have infinite output resistance then the incremental gain is going to be infinite correct ok. This is exactly similar to what you would see with the common source amplifier with an active load. Is that clear?

So, now, how do we implement this current source?

Student: PMOS current transistor.

We connect a PMOS transistor very well.

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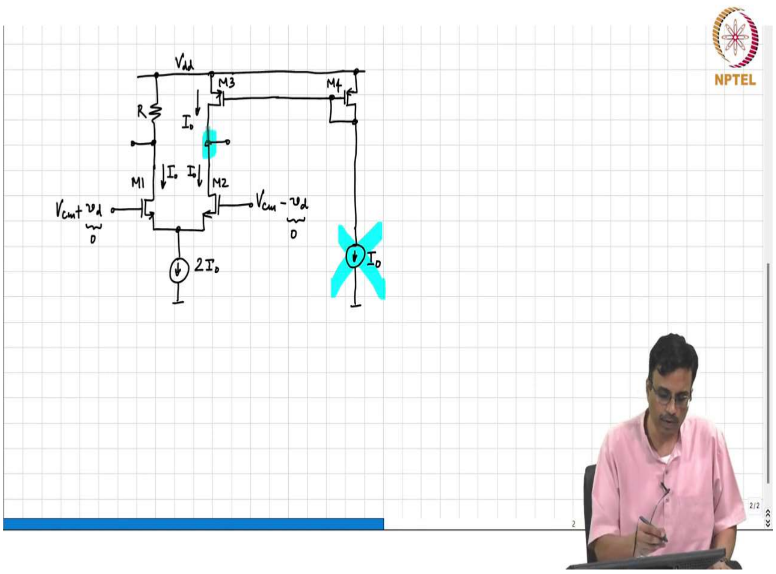

So, somebody suggested a current mirror, ok fine let us do that. If all the transistors are identical, what comment can I make about it? If all the transistors M1, M2, M3 and M4 are identical what comment I mean does it make sense or should I do this or basically what I meant to ask was are we ok with this current or is this is not correct?

Yes, ok? Ok alright. So, M4 M3 is a 1 is to 1 current mirror and therefore, I_o will get reflected here and you know we are all good to go right. Now, can somebody stare at this and say well I can do something smarter.

Ok, well, basically one suggestion is that well you know these current sources have all have to be realized using NMOS transistors that is a given correct. So, basically eventually there is going to be one master you know I_o from which you can generate both $2I_o$ and I_o that is not what I ask, that is not what I am getting at this is can you see some redundancy here and see if we can do better. In other words, can we get rid of that current source I_o and use something that is already there?

Student: Remove that.

Ok. So, the suggestion is well you remove this guy here and the principle what is the principle? So, basically what he intends to say is that when v_d is 0 right. That is at the point when the differential input voltage is 0, what is the current flowing through M1?

Student: I_o.

I_o right. So, you know what is that I_o doing, what is the drain current of I_o of M1? What is it doing? Is it useful in other words?

Student: Drain of M2.

So, do we need the resistor in the drain of M1 at all? If we do not need the drain or if we do not need this R we might as well connect to it?

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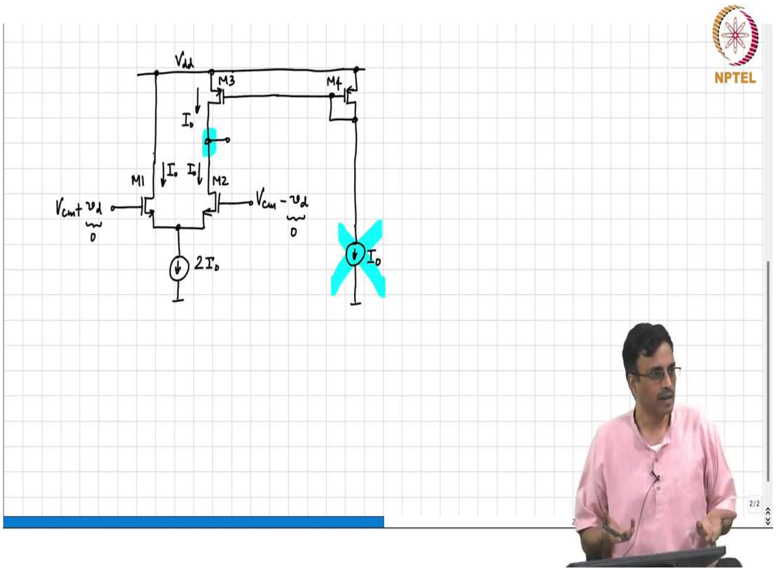

V_{dd} alright. So, now, you can see that M1s drain current is just simply doing nothing; it is just simply connected to V_{dd} you might as well put it to work right. What does M4 need? And what is M1s drain current?

Student: I_o.

And what is M1s drain current doing? Nothing. So, what do you think we can do? What can you do? Let us say you are sitting at home doing nothing man right ok, alright. And you know you want to order a Swiggy from your neighbourhood Pizza Hut ok. What is your mother going to do this fellow is sitting at home doing nothing right.

Why waste somebody else somebody else's time like bringing pizza from Pizza Hut to our house let us send this fellow instead right. Isn't it? Ok. That is why you should get a job quickly, you understand. So, that is all. So, M1 is sitting idle doing nothing correct. Why get one more current source and then put it through M4, M4 needs a current I_o anyway right and this M1s drain current is just doing nothing. So, the smart thing to do is to say get rid of that extra I_o break this character here and connect that guy there, does that make sense right?

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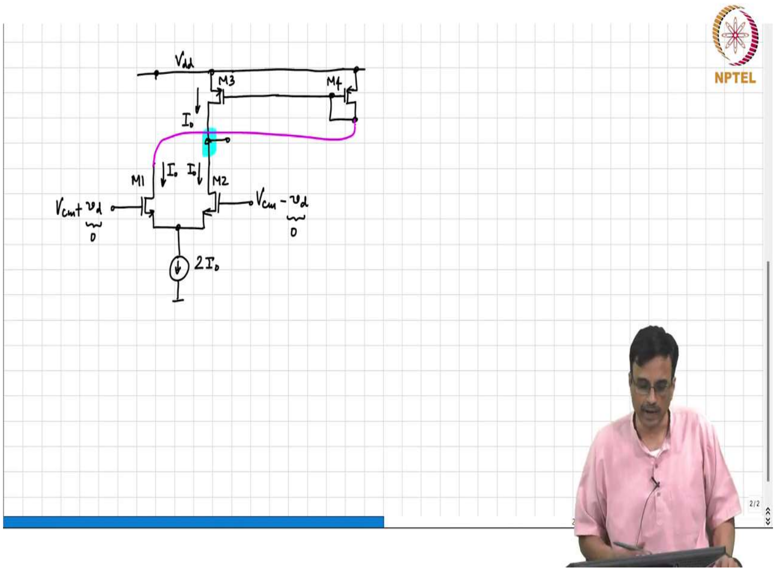

I mean this is not rocket science right. So, alright. So, now, of course, you know this diagram looks terribly terrible. So, I am going to redraw it in a slightly different way. So, I am going to move.

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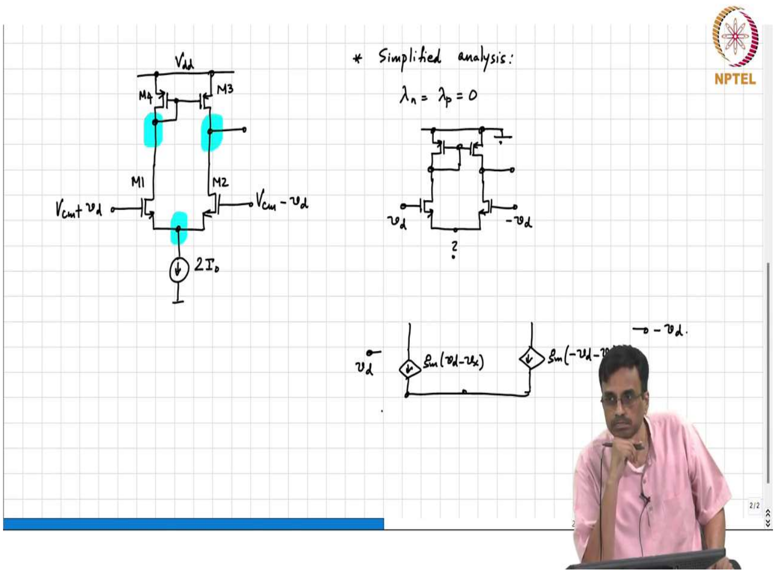

Alright so, this is M3 this is M4 alright ok. Now let us so, when v_d is 0 of course, there is no difference between the earlier scheme and this one right, when v_d is not 0 we have to sit and analyze what is happening alright. So, you know simplified analysis when λ_n equal to λ_p equal to 0 when the transistors are all where the current in the transistors is independent of the drain source voltage right.

So, clearly so, if λ_n and λ_p are 0 basically in English what it means is that the potential at the drains, I mean by the way, is the circuit symmetric now. Clearly does not look symmetric; however, if λ_n and λ_p are 0 then what comment can we make? Well, if λ_n and λ_p are 0 that basically means that the incremental drain source resistances of both transistors M1 and M2 are infinite and in English what; that means is that their drain potentials have no bearing on the drain current correct. So, under those circumstances what comment can you make about the incremental voltage at the common source node? Yes, what is the incremental equivalent? How does it look like the current source becomes?

Student: Open.

Open. So, this is v_d this is - v_d alright. So, the question is what is that incremental voltage?

Ok, there are multiple ways of looking at it. I mean you know if λ_n and λ_p are 0, you know as far as the network here is concerned, so, what happens at the drain end is irrelevant right. Because the λ is anyway 0, this is v_d. So, this is $g_m(v_d - v_x)$. And on the other side it is I do not know guys if you guys are following or not the other side it is $g_m(v_d - v_x)$ and that is - v_d right. And basically, this is v_x alright. So, clearly, I mean what is happening at the drains is no influence and what happens below therefore, well even though the circuit does not look symmetric as far as calculation of v_x is concerned. This node joining these two halves is concerned . The simplest thing to do is to write Kirchhoff's current law at that node. What does KCL say?

The sum of those two currents must be?

Student: 0.

So, the only way the currents can be the sum of the currents can be 0 is v_x equal to 0. So, this incremental current is this incremental voltage is 0.

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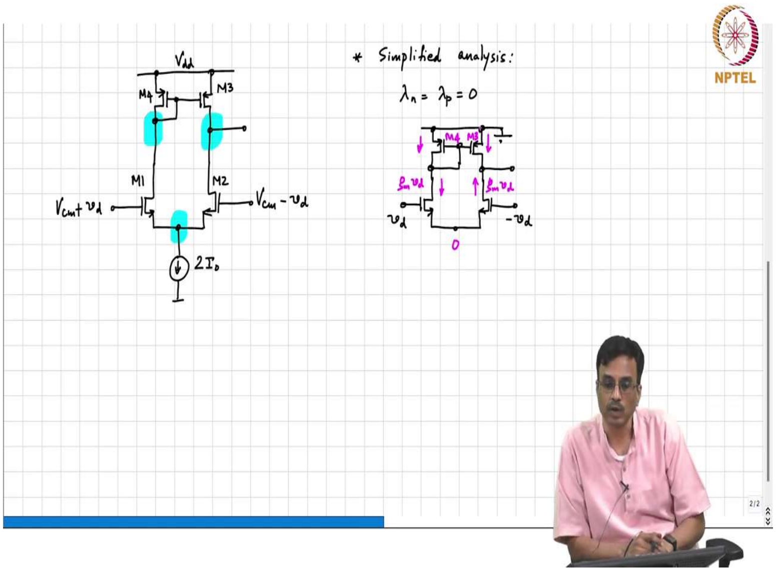

So, what is this incremental current?

Student: g_m v_d.

What is this incremental current? You write that as - g_m v_d going down or g_m v_d going up alright. What is this current and what is the current in M4?

Student: g_m v_d.

Same current has to flow through that diode-connected transistor. So, what comment can you make about this current M3? This is M4 this is M3 ok what is the current in M3 in the direction shown? So, current is flowing up in M4 in M3 sorry maybe it is too small is it visible.

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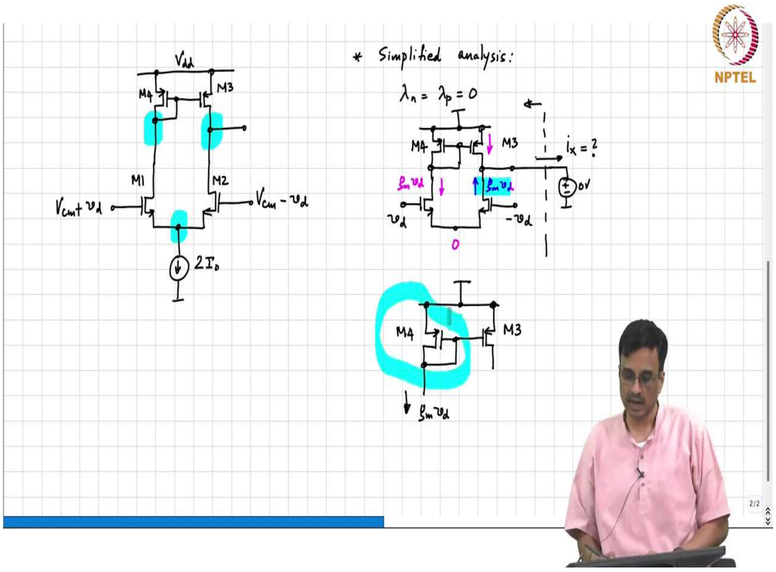

Actually, I think not, that is M4 and that is M3 what we are trying to do is find this current. What is that current alright? So, I guess this could be confusing ok. Let us try and I mean let us try and find the not an equivalent of the output the not an equivalent looking in here.

So, what will we; what will we do? We will find the short circuit current flowing into this voltage source right ok. What is i_x that is what I want to find eventually. So, we i_x clearly consist of two components one is g_m v_d that is this character here alright. There is also the current flowing through M3 ok. Now can you tell me what the current through M3 will be? How will you find the ok? How will we find the current through M3 ok. What do you need to find the current of M3? The gate voltage. How will we find the gate voltage?

So, let us take a more careful look at. So, what is the current flowing here, this is M4 this is ground this is M3. So, what is the current flowing incremental current flowing down?

Student: g_m v_d.

g_m v_d ok. So, incrementally by now you should know what the incremental equivalent of this character is. It is a resistor of value $1/g_m$.

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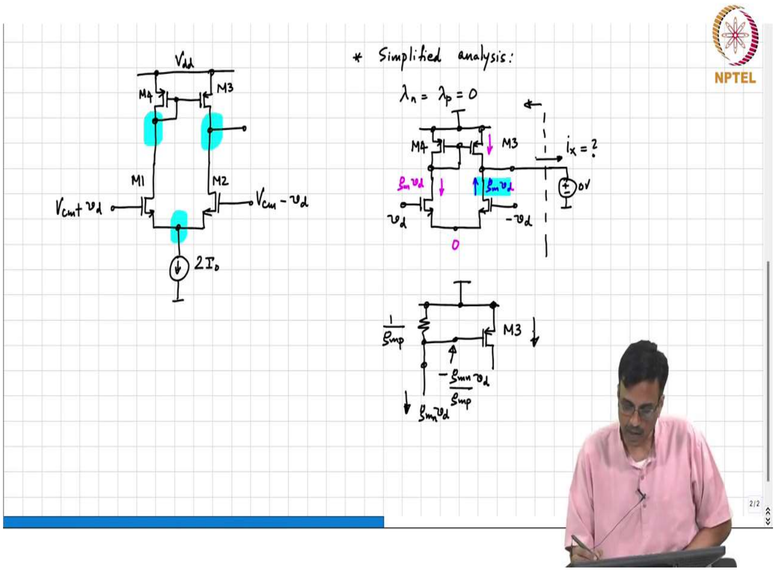

So, this is $1/g_{mp}$ alright and let us call this g_{mn}. So, we separate the two alright and this voltage is connected there ok. So, what is this voltage therefore $-g_{mn}/g_{mp}\ v_d$ ok. So, what is M3 current through M3, what is the model for the PMOS transistor?

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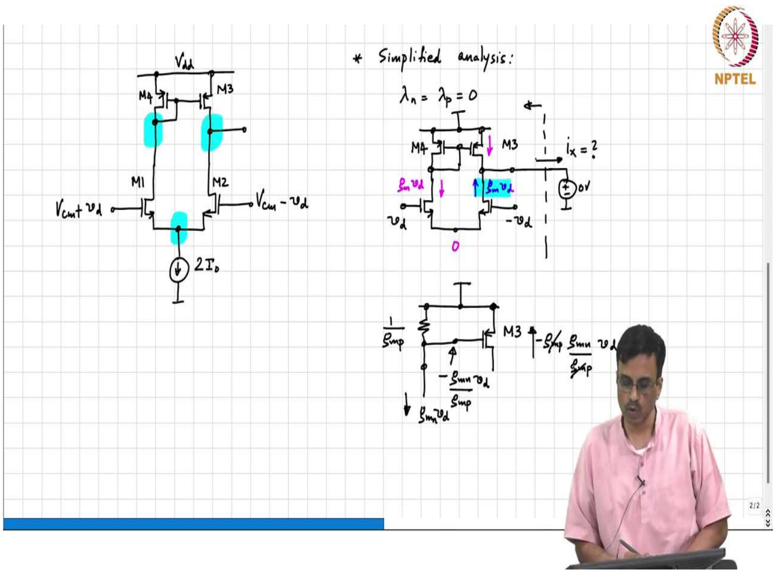

From that direction $g_{mp}v_{gs}$ will flow. What is v_g? $-g_{mn}/g_{mp}\ v_d$. So, this and this goes away. So, what is happening?

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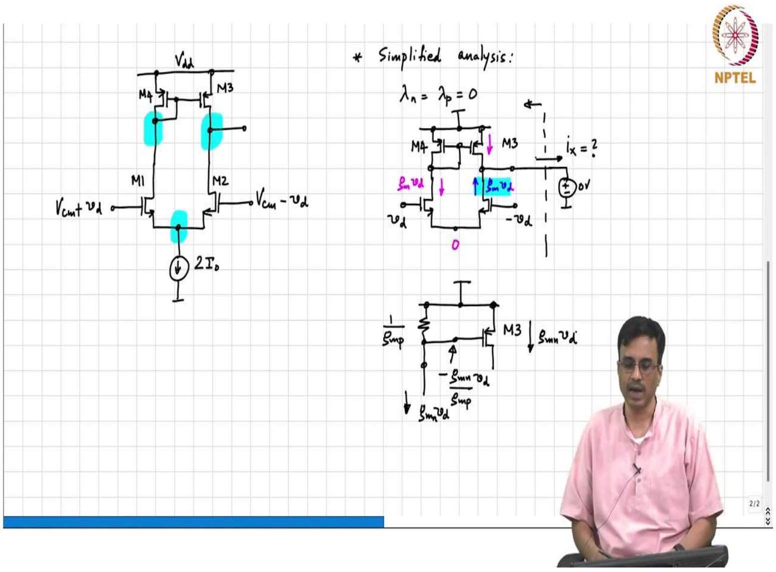

The current Is flowing downwards and that current is exactly the same as g_{mn} v_d alright ok all this comes out of the math is there some way of simply staring at the circuit and saying this obvious.

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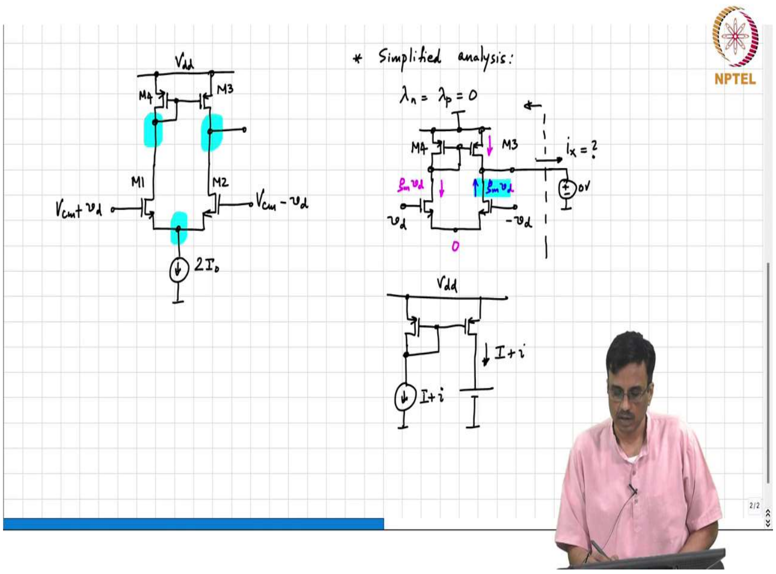

So, it is a current mirror after all, remember that in the let us say in the large signal picture in the if this current is I and this transistor is in saturation and λ is 0 what comment can you make about this current? If this changed by a small amount what comment can you make about the current in the mirror transistor?

It will be the same thing correct. So, what comment I mean now are you able to make sense of the final result without doing any analysis at all, what is that? It is a current mirror. The incremental current being pulled into the M into the gate of M4 is g_m v_d, so it is just reflected in M3 alright ok. So, basically this is this current therefore, is what is the current row M3 therefore g_m v_d flowing downwards.

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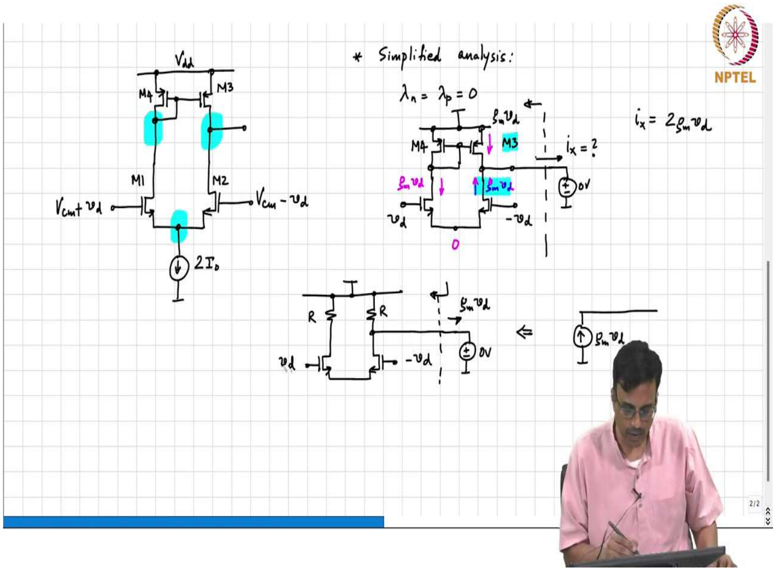

So, what is the short circuit current i_x? 2 g_m v_d ok. Now how does this compare with the Norton I mean if we did the same thing with our regular differential pair where we had resistors. This is v_d this is minus v_d this is R this is R in the incremental picture this is grounded. If we found the Norton equivalent short circuit current of this guy. What would be the short circuit current?

Student: g_m v_d.

If that current is 0, why are we doing all this man? It is g_m v_d, is that clear? Alright. So, what is the difference between the active load and the active load that we have now and just having a resistive load, as far as the short circuit current i_x is concerned. We are getting twice the current intuitively. That is because the current through M1 is decreasing. Sorry, the current through M1 is increasing while the current through M2 is decreasing, correct. In the circuit on the left if small v_d is positive then the current through M1 increases, the current through M2 decreases. That increased current is getting reflected through the current mirror right and you are getting an and; whereas, what is being pulled out by M2 is actually smaller correct. So, that difference you are getting as the Norton short circuit current alright.

So, you can see that M4 that uses the drain current of M1 is actually earlier. We were just simply throwing away that incremental current into the; we are not doing anything to the incremental current of M1 earlier. If you had resistors correct, we were just throwing that away into the drain right.

Now, actually using that incremental current to actually give us twice the short circuit current that you would otherwise get alright, now ok. So, to find the gain we need the short circuit current as well as.

Yeah. So, basically, I mean let us go back to the earlier one. The short circuit current as you can see is g_m v_d we already saw this before, but I want to see it in another way. What is the Norton resistance looking in here to find the Norton resistance looking in there what would we do?

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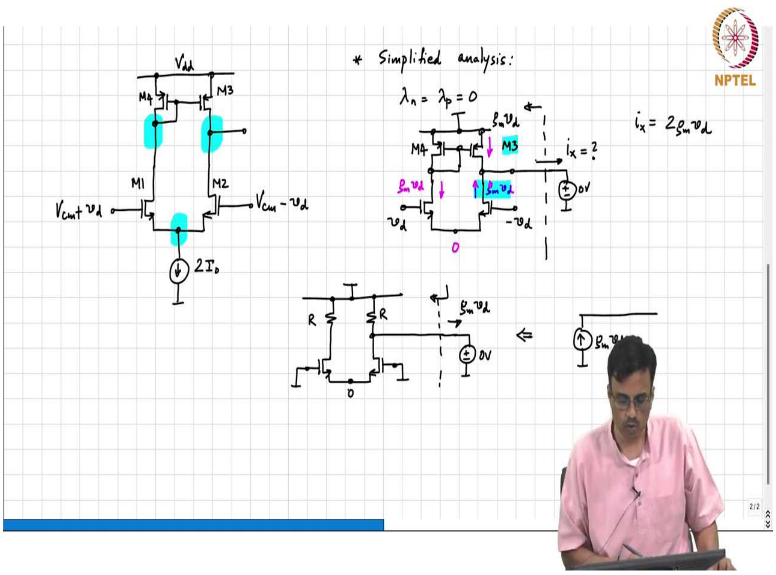

Deactivate the sources. So, if v_d goes to 0 this v_d also goes to 0, what is this voltage incremental voltage?

Student: 0.

0. So, what happens to the true transistors? They are just not there.

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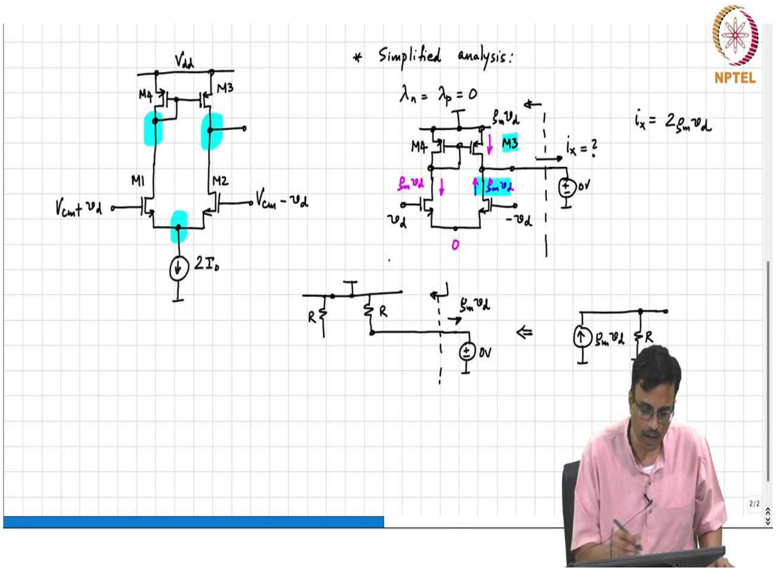

Now, what is the Norton resistance?

Student: R.

So, what is the gain? g_m R v_d is the output voltage. So, the gain is g_m R in the earlier case when we had resistive loads. Is that clear folks? So, now, what comment can we make? Now we will do the same thing here, what is the short circuit current?

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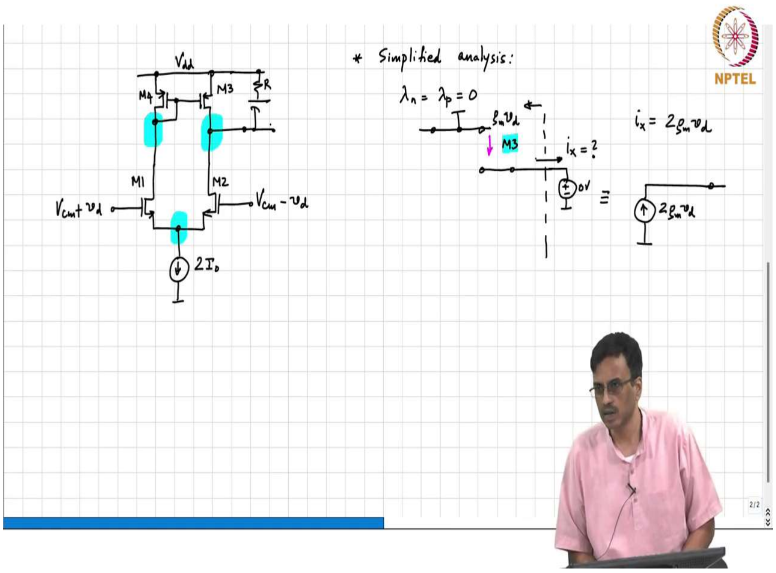

So, this is nothing but a current i_x. What is i_x? 2 g_m v_d and to find the Norton resistance what will we do? Deactivate all the independent sources. So, that becomes 0 this becomes 0. So, again the two transistors become no longer there in the incremental equivalent ok. So, what is the current through M4?

Student: 0.

0. So, what is the current through M3 therefore, what is it? That potential is 0. So, current through M3 is 0, that also goes away. So, what is the Norton resistance? Infinite. So, what is the gain?

Student: Infinite.

I mean is this a surprise or was this something that you are expecting anyway. So, basically just like how we had in the common source is an amplifier with an active load if the λ if the output impedance of the transistors was infinite then we got an incremental gain which was infinitely correct. Same thing happens here ok alright. So, that I mean this is the bottom line is that that M4 transistor is useful after all right. Because it gives you twice the short circuit current. So, I mean for example, if it turned out that the Norton resistance here was also R correct ok. So, somehow let us say I deliberately put in an incremental resistance of R with an infinite capacitor here. How much gain will I get now here?

Student: It is a 2 $g_m v_d$ R.

Whereas, with the regular resistive loads I have got only g_m. So, that M4 is useful after all, just like when your mother sends anyway you are sitting at home doing nothing right of course, for her gate preparation all does not count right. Say anyway you know, get pizza along the way you get from here and then you get some vegetables from there and you know and so on right, alright.

So, like that, this M4 is basically it turned out to be useful after all right whereas, if you order on Swiggy you cannot do all that right. You only bring pizza, nothing else. Isn't it? So, that is the. So, the basic operation is understood.