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

Lecture - 29
The Incremental Current-Controlled Voltage Source Transimpedance Amplifier

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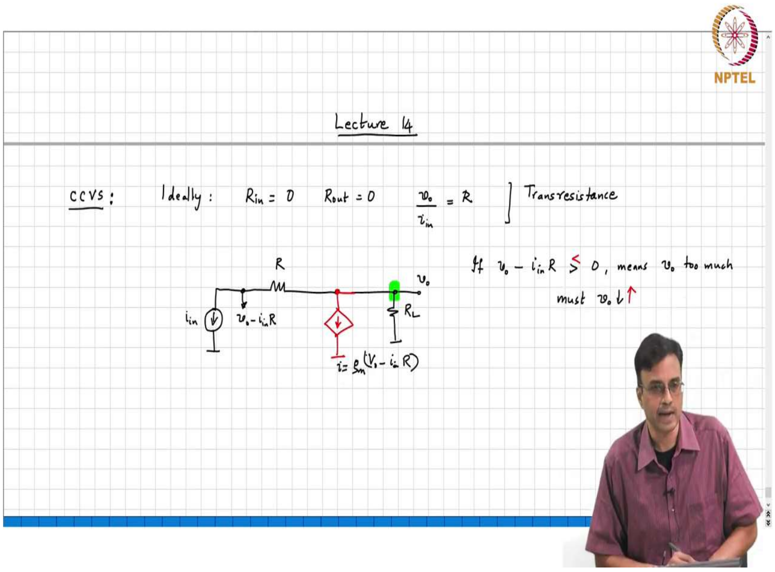

So, in the last class we were looking at how to realize the current control voltage source. Ideally of course, the input resistance must be 0, the output resistance must be 0 and the ratio of the output voltage to the input current must be some resistance R which is either called the transimpedance or the trans resistance. And the idea is very straightforward, we have an output voltage across load R_L and we want that to be equal to i_{in} R.

So, the basic idea as we discussed yesterday was to compare this quantity v_o - i_{in} R with 0 and use negative feedback to go and kick v_o in the right direction. Earlier in the context of using an op-amp we used a volt variable voltage source at v_o.

But, now we recognize that it is also possible to do it with a variable current source, because if you want to increase the potential of a node you pump in current, if you want to reduce the potential of a node you drain out current from that node. So, in other words, basically if v_o - i_{in} R that quantity there is greater than 0, it means that the output voltage is too much or too little?

Student: Too much.

It is too much; so, its voltage must be?

Student: Reduced.

Reduced; so, current must be pulled out of the node v_o. So, in other words this current here must be proportional to v_o - i_{in} R ok. And the constant of proportionality must have a dimension of conductance some g_m and what is the sign of the g_m?

Student: Positive.

Positive right and what is the value of g_m you would want ideally?

Student: Infinite.

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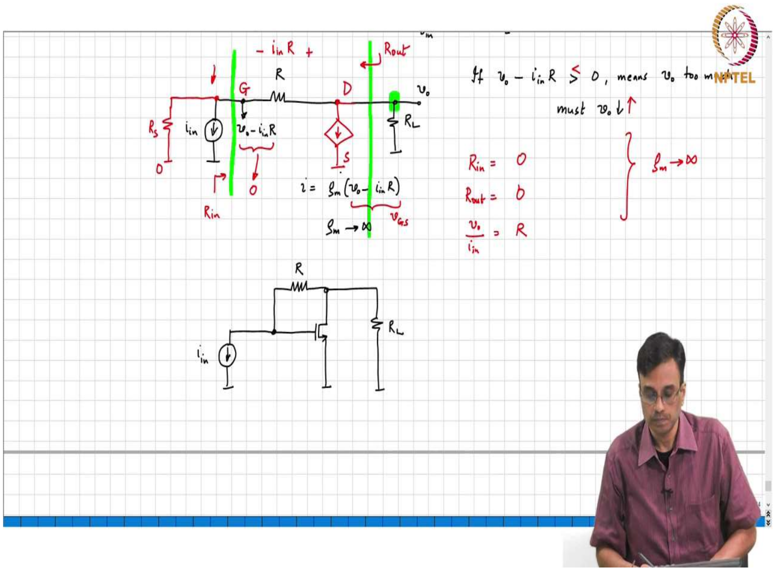

Infinite right. So, basically this current i = g_m (v_o - i_{in} R) and ideally g_m must tend to infinity alright. So, now can you identify the transistor?

Student: Yes.

So, this is the drain ok; so, if that is the drain then this must be the source gate great then where is the gate; so, basically this must be the gate right. So, this is basically g_m times incremental V_{GS}, the gate voltage is v_o -i_{in} R, source voltage is 0 and therefore, this is the transistor and we draw it this is i_{in} that is R_L that is R ok.

So, what comment can we make about the output resistance? I mean as g_m tends to infinity what comment can you make about the input resistance. As g_m tends to infinity this potential will be 0 and clearly you can see that is in the I mean regardless of the value of i_{in} the voltage at the input of the voltage I mean current control voltage source is 0 right. So, regardless how much current you pull in or push into the CCVS, the voltage is 0. What does that mean? So, it looks like a short circuit; so, what is R in?

Student: 0.

What comment can we make about R_{out}, what comment can we make about R_{out}? So, there is no point, there is no need to do the math right, remember in all our discussion we said that if g_m tends to infinity v_o - $i_{in}R = 0$ which means where is all the current flowing that i_{in} current where is it flowing through R; so, what is the voltage across R, what is that voltage? I_{in} R alright, what is the voltage at the left end of the resistor?

Student: 0.

0; so, what is the voltage at the output? The voltage at the output is $i_{in}R$ and is that dependent on R_L? It is not dependent on R_L. So, basically this is telling you that here is a voltage source even if you change the load resistance the voltage remains the same. So, what comment can you make about the output resistance?

Student: 0.

Output resistance is 0 and v_o/i_{in} is R and as you can see as g_m becomes tends to infinity. We indeed get the properties of an ideal current controlled voltage source where the input resistance is 0, the output resistance is 0. And the trans-impedance is R which is again independent of the properties of the transistor itself alright. And the reason for this is that we use negative feedback to go and to provide us this trans conductance, alright.

So, the next step is to find out you know what it means to have a high g_m and before that I would like to add a small extension. So, by the way if you have a poor current source, let us say this current source is not ideal, then it's equivalent to having a parallel resistance R_S in series in shunt with the current source alright.

And now, what comment can we make about the output voltage? The fact that you have finite output resistance for the current source does not change anything as long as g_m is infinite and why is that? This potential is 0, what comment can you make about that potential?

Student: 0.

0 ok, and therefore, what is the current flowing through R_S? 0. So, R_S does not affect the operation of the circuit at all. So, all the i_{in} flows into R and the output voltage will remain i_n R ok. Now, that basically means that I can now represent this by a Thevenin equivalent.

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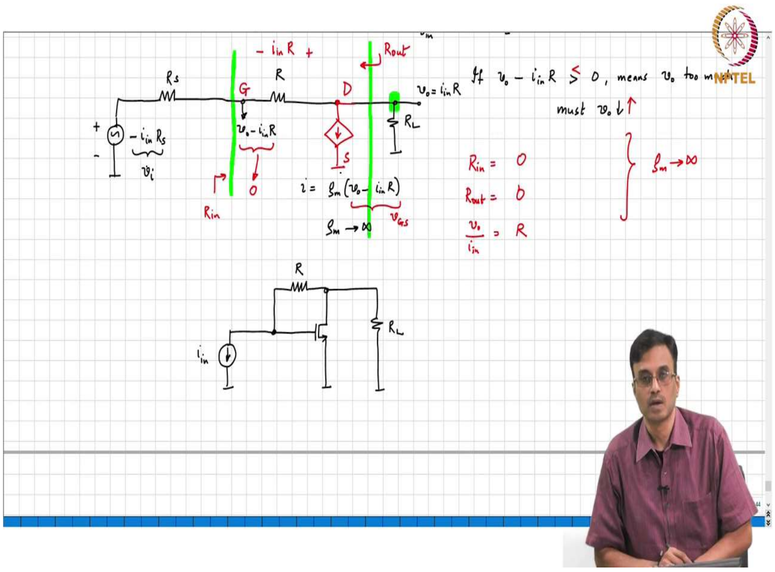

So, that is R_S. What will that be?

Student: $i_{in}R_S$.

$i_{in}R_S$ alright, and v_o as we saw is nothing but $i_{in}R$, ok.

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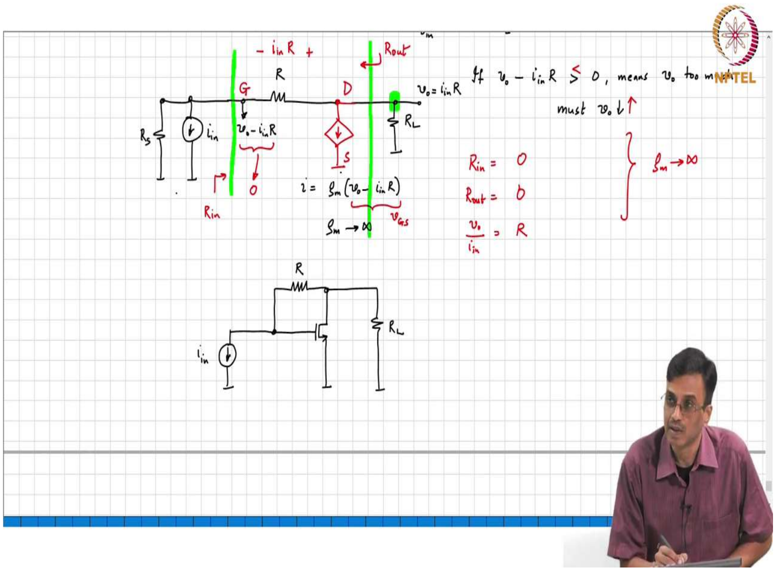

So, if I now call this v_i, what will be o, b? Ok, what is the output voltage? Because, what is the voltage across R_S.

Student: 0.

So, no current flows through this we discussed already alright and we are going through the same arguments all over again ok alright. Now, if I convert this into a Thevenin equivalent, what will it look like?

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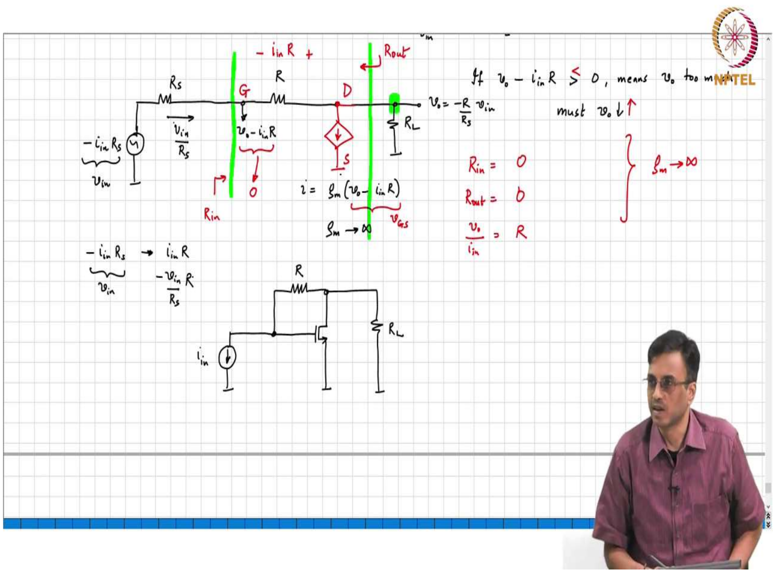

This is $-i_{in}R_S$, if I call this v_i what will this be? It is not because the voltage the current through the through R_S is v_{in}/R_S, do you understand. There is a difference between the two, one is the cause and one is the effect, which is the cause? So, g_m tends to infinity; so, the gate voltage is?

Student: 0.

So, what is the current flowing in? $- R/R_S\ v_{in}$. And you do not have to do any of this stuff, because if $- i_{in}R_S$ gives you an output voltage of $i_{in}R$.

Now if this is v_{in} what will be the output voltage v_{in} instead of i_{in}? You have to put in.

Student: $- v_{in}/R_S$.

So, now the next thing to do is to figure out what happens to the properties of the network.

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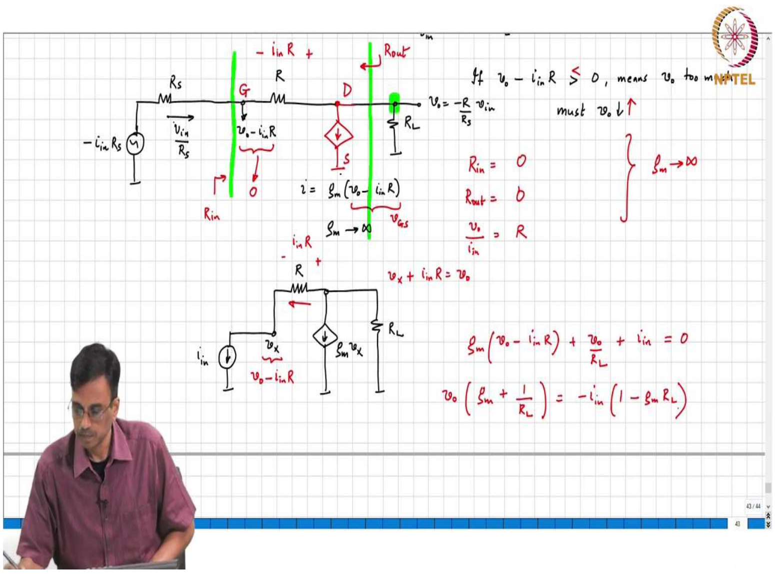

When the trans conductance is finite; so, let us call this v_x as $g_m\ v_x$; so, what is the current flowing through the resistor R? That current remains i_{in}, regardless of you knowing what happens because after all i_{in} the current source; so, what is the voltage drop across R is I_{in} R, alright; so, now, what is the only unknown or if you want to solve this network what will we do?

You either find v_x or you find v_o. So, it does not matter. So, let us call the v_o is nothing but $v_x + i_{in}R$ which is v_o. And you write which basically is equivalent to saying that if we want to find v_o directly, then this voltage is not nothing but $v_o - i_{in}R$. So, we write KCL at the output node; so, g_m v_x which is nothing but $v_o - i_{in}R + v_o/R_L + i_{in} = 0$ alright. So, v_o $g_m + 1/R_L$ must be equal to i_{in} $(1- g_m R_L)$ alright.

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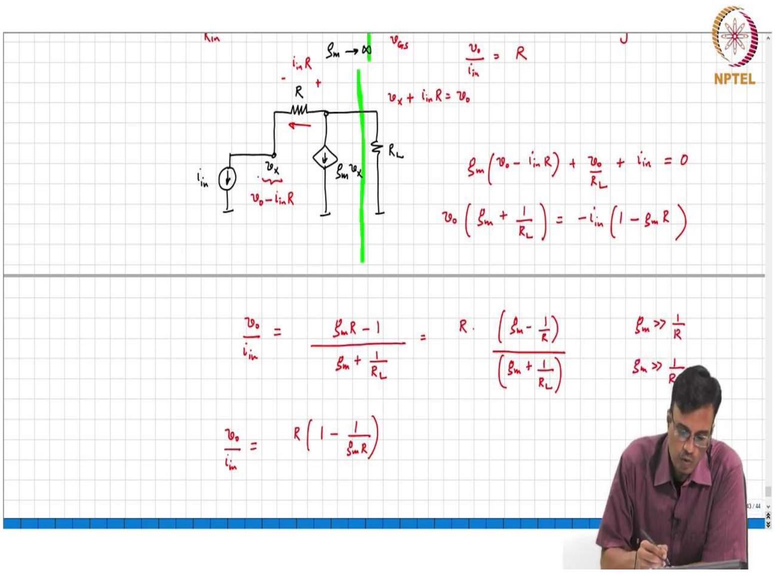

So, v_o/i_{in} therefore, must be?

Sorry yeah, it is basically $(g_m R – 1)/(g_m + 1/R_L)$.

So, which is nothing but I will write it in terms of the ideal value R times. How do we write this in a way which is? So, this becomes R $(g_m - 1/R)/(g_m + 1/R_L)$ ok. So, what comment can you make, what is considered a large g_m? Sanity check.

As g_m tends to infinity, well the output of the trans conductance trans resistance becomes R and; so, what constitutes a large g_m therefore? What about R_L? What constitutes a large g_m? So, g_m must be much much larger than?

Student: 1/R.

1/R alright; so, what comment can you make about the output resistance? So, looking at the output resistance, how will you figure that out? One way of doing it is to simply write the expression for v_o/i_{in} when R_L tends to infinity. When R_L tends to infinity what is it? Stare at this expression and tell me what it is, g_m tends to infinity and R_L tends to infinity what is the output voltage? It just becomes g_m, it basically comes R (1 -1/g_mR), and I guess it is much easier to do it the other way which is the standard way to do it which is basically you apply a test voltage and measure the current that is going in. So, we de-energize the input source. This is what we have.

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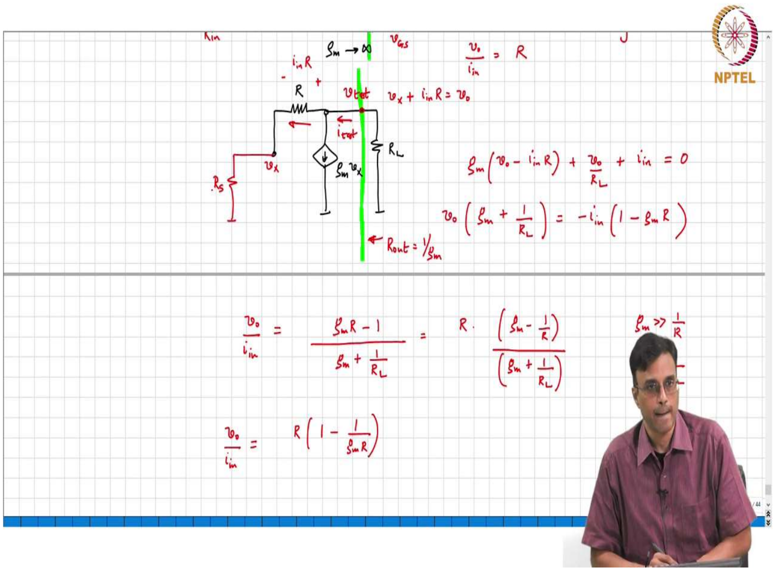


And this is v_x, we apply a v_{test} here. What is the i_{test} going? What is the current flowing? What is v_x?

Student: v_{test}.

v_{test} ok, why?

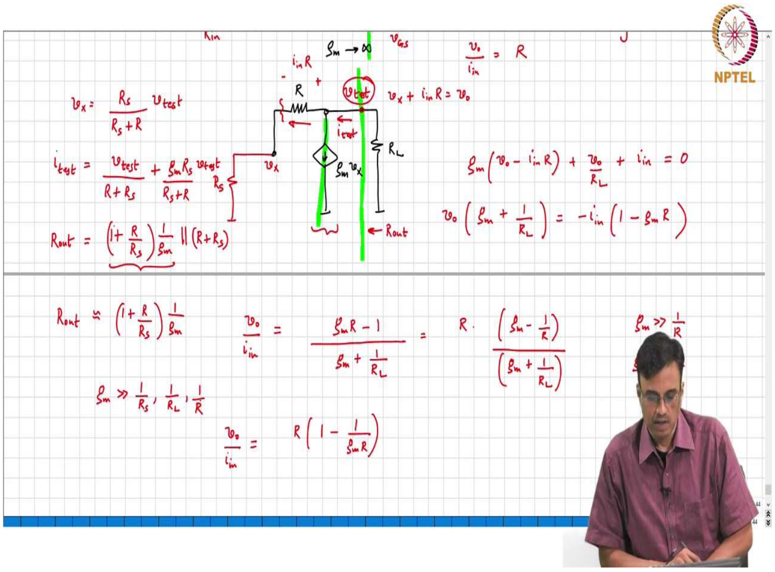
Student: No current flowing.

No current is flowing through the resistor ok; so, what is the what is the i_{test} therefore? g_m v_{test}; so, we apply a voltage v_{test} and the current flowing is g_m v_{test}; so, what is the output resistance?

Student: $1/g_m$.

So, now, if the output of the input current source had a resistance internal resistance or has an output impedance of R_S, what comment can you make about the output resistance?

Think carefully, what is v_x?



What is v_x?

$R_S/(R_S + R)$ v_{test} ok; so, what is i_{test}?

Student: $v_{test}/(R + R_S)$.

You mean to v_x which is, $R_S/(R_S + R)$ v_{test}

so, what is output resistance R_{out}?

Student: $(R_S + R)/R_S$.

It is basically $(R_S + R)/R_S$ which is $(1 + R/R_S)$ $1/g_m$ in parallel with I mean there is one current flowing like this there is another current flowing like that. So, it is the parallel combination of two impedances, one is $R + R_S$ and that is in parallel with this. Is that clear? So, what comment can we make about it? So, therefore, if the current source that is driving the current control voltage source has a finite source resistance, right. What comment can you make about the output resistance? Is it higher or is it lower? So, if R_S was infinite , what would be the output resistance?

It would be $1/g_m$ right and by the way what did we say as you know what is R in relation to g_m, if you want a good current control voltage source what comment can we make about g_m and R?

g_m must be much much larger than 1/R; so, what does it intuitively mean, what comment can you make about the current flowing here through the R versus g_m. You are applying for a vtest here, g_m is?

Student: Large.

Is very large; so, what comment can you make about this current versus the current flowing through R?

Student: Would be greater.

Which would be greater?

Student: g_m.

g_m; so, which of these two arms will dominate your parallel combination, the path through one the current through one path is much higher than the current through the other path; so, which path and which term will dominate?

Student: g_m path.

The g_m path will dominate; so, what comment can you make if you now put on R_S? what comment can you make about the output resistance? Will it increase or decrease?

Student: The other path will increase, so it will dominate.

If this path dominates what is the output resistance approximately?

It is $(1 + R/R_S)\ 1/g_m$; so, the question I am asking you is if R_S goes from infinity to a finite value will the output resistance of the amplifier increase or decrease? So, the finite impedance of the current source that is driving the current control voltage source will increase the output resistance. And basically you can see therefore, that the g_m must be chosen to be much much larger. So, the bottom line is that g_m must be much much larger than $1/R_S$, $1/R_L$, and 1/R ok. Under those circumstances the output gain will be minus i_o R irrespective of the properties of the transistor.

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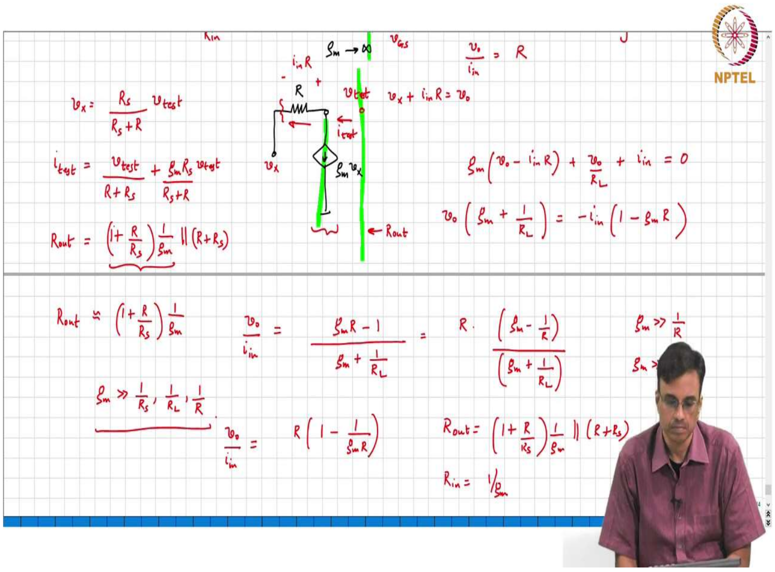

Now, if I remove R_L and if I want to find the input resistance, I mean let us do this quick, what is the input resistance?

Very good, R in is $1/g_m$ ok, and therefore, if you if the input resistance of the current control voltage source is $1/g_m$. You must make sure that the source impedance is much higher than the source you are driving it with right. Where has an output resistance of R_S and the g_m must be made sure if you want to make sure that this behaves like a good current control voltage source

The input resistance must be much smaller than that of the?

Student: Source.

Of the source; so, the input resistance is $1/g_m$ which must be much much smaller than the output resistance of the current source that is driving it. So, g_m must also be much much larger than 1/R. So, if all these three conditions are satisfied that is what qualifies that is what it means to say that the g_m is a large g_m, ok.