Analog Electronic Circuits
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Lecture - 22
Negative Feedback Continued

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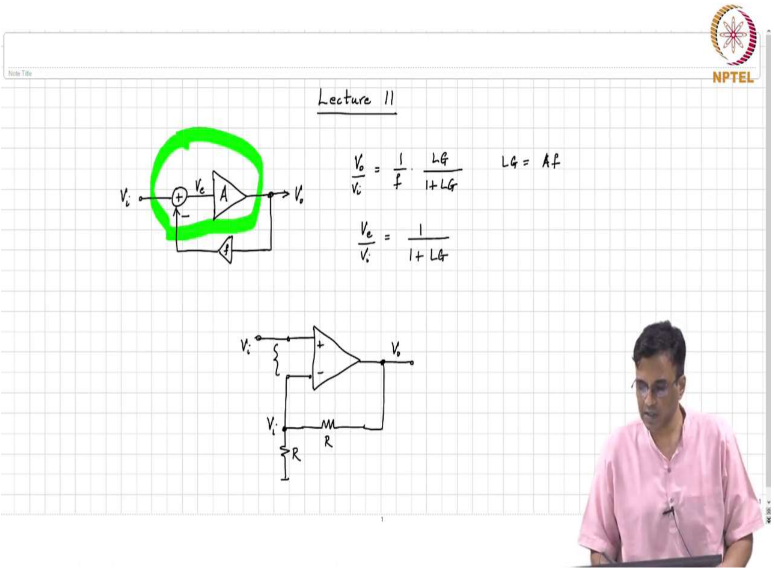

Alright people, good evening and welcome to Analog Electronic Circuits. This is lecture 11. So, in the last class we were looking at the basic negative feedback loop where you have a feedback block, forward amplifier, this is V_i this is V_o. And we set that,

$$\frac{V_o}{V_{in}} = \frac{1}{f}\,\frac{Af}{1+Af}$$

where, this loop gain is Af and is physically interpreted as the gain that you get when you break open the loop.

You know excite one side and see what comes back on the other side and what comes back is Af in magnitude and must be in the opposite direction. The opposite direction is needed for negative feedback and as we said analogy for negative feedback is like the legal system in any country if the laws are strict and the implementation is strict, then people will tend to commit fewer crimes.

And so, if Af, the loop gain goes to infinity then the error voltage V_e/V_i is nothing but 1/(1 + loop gain), again loop gain is Af. So, if loop gain tends to infinity, it basically means that the error voltage is 0. So, again coming back to our social analogy, it basically means that if crime in society is 0, it does not mean that people are honest. It just means that the laws are so strict that the penalty for being dishonest is so high that you dare not commit a crime, alright. So, that is just like how the error voltage is 0.

The error voltage is 0 because the forward amplifier gain is infinite. The moment the amplifier gain becomes small that error voltage is no longer 0, alright. And under the condition that you have a very large loop gain, the closed loop gain which is V_o/V_i as you can see is largely independent of the loop gain itself correct and the closed loop gain is simply 1/f and is governed by the feedback block, alright.

So, it turns out that this is a great way of realizing amplifiers with very stable gain. For example, let us say you wanted to realize a gain of 2. We already have seen a common source amplifier. Its gain is $-g_mR_L$ and nothing prevents us from choosing $R_L=2/g_m$ so that you get a gain of -2, alright.

But what are the problems with this kind of amplifier? Well temperature changes, g_m will change which basically means that g_mR_L will change and so, therefore, this way of realizing gain is not robust. Now if we realize that using negative feedback if we wanted to realize a gain of two using a negative feedback loop what should f be? f should be half, correct. So, if f has to be half, what is the easiest way of getting f equal to half?

Student: basically, potential divider.

Yeah, just basically use a potential divider now if temperature varies what comment can you make about the values of the resistors? The values of the resistors will change, but these are we are looking for a resistor ratio and therefore, even though the individual resistance is changed both of them will change in the same manner and therefore, the ratio is very very robust even though the individual values of the resistances are not.

So, therefore, the situation boils down, because if we are able to realize a negative feedback loop with a large loop gain then all that we need to do to make the performance robust is make sure that the feedback block whatever it is, its properties are very well controlled. And fortunately if you want a closed loop gain then the feedback factor must be smaller than 1 which is easy to realize using some kind of passive element and the forward amplifiers gain which is needed to be very large. It will be realized using some kind of transistor network.

The transistors and networks of transistors as we will see going forward are very good at giving you a lot of gain, but that gain also changes a lot over temperature and supply voltage change and all that stuff. So, but fortunately as you can see thanks to negative feedback if that gain is large enough.

The sensitivity of the closed loop gain or the input output V_o/V_i to changes in the gain of the forward amplifier is actually very very low. For example, if the loop gain is a 1000 what is the closed loop gain its 1/f x 1000/1000 and 1 which is 1/f x0.999.

Now let us say the loop gain for some reason went down from 1000 to 500 that is either a 50 percent change. If you want to be conservative or it is a hundred percent change if you use a different denominator. You can see that you have a huge change in gain, but the closed loop gain is still 1/f x(500/501) which is only changes in the third decimal place.

So, a 100 percent change in the gain has only changed the closed loop gain by some point, something percent, alright. So, just like money, if you have enough of it then you do not have to worry about it, correct, just like that in a negative feedback loop if you have enough loop gain you do not have to worry about how much loop gain you have.

So, having seen that now let us put this principle to some use and see some of these are circuits that we are very very familiar with. And as we saw last time, it makes business sense to sell that part as a separate building block so that users can put their favourite feedback factor and get whatever gain they want, closed loop gain they want. And that is the operational amplifier, which is basically a voltage controlled voltage source whose gain is ideally infinity, but in reality it is a large number. It is not typically if you go and pick up an off the shelf op-amp. It is not uncommon to get a gain of maybe 10^7, 10^8 that sort of thing. So, if the op-amp is enclosed inside a negative feedback loop we saw that the error voltage must be 0.

So, the difference between the two input terminals of an op-amp must be 0 if it is enclosed inside a negative feedback loop, which is the virtual short that you are very familiar with. So, now, let's say you want a voltage amplifier with a gain of 2. What will we do? This is our op-amp. What do we do?

Well, that is very straightforward. We just identify just there at the block diagram we want a feedback block with a gain of?

Student: 1.

Half. So, you put R there, you put another R there. So, this is V_o and this is $V_o/2$, and this is V_i. So, if the op-amps gain is infinity then clearly this difference is 0. That basically means this is V_i which is the same as V_o by 0 which basically means that well the output is twice the input. This is all a very well known circuit from your childhood days. So, it is not something particularly new. Now, let's say you had never seen the circuit before and you wanted to figure out what the signs of the op-amp must be. So, what do you do? Well, you don't know the science. So, what do you do?

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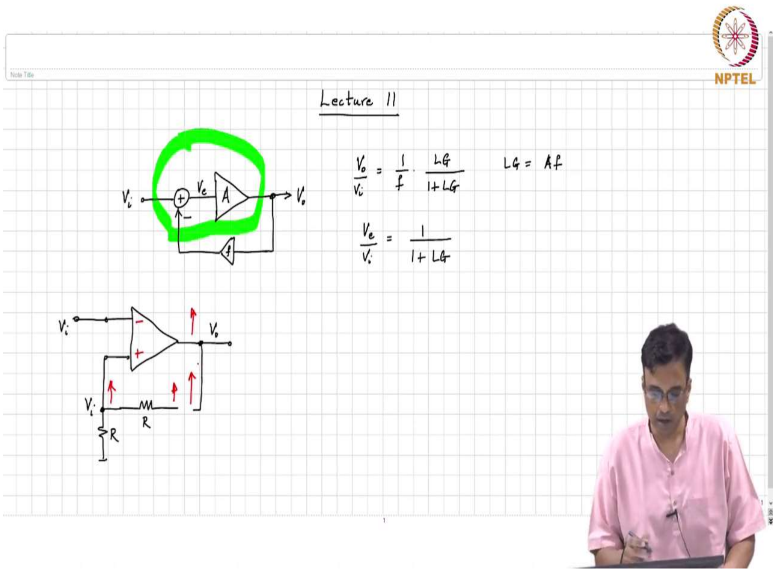

You break the loop somewhere and you yank one side of the loop up here. So, what happens to this node here? What direction does it go? Let's assume some random signs like that. So, if this goes up, that goes up. If that goes up and for this choice of signs this also goes up and so, what comes back is of course, larger than what you put in, but is it in the?

Student: Same direction.

Same direction. So, therefore, this is?

Student: Positive feedback.

Positive feedback and therefore, that is not good as far as making a closed loop amplifier is concerned. So, what should we do?

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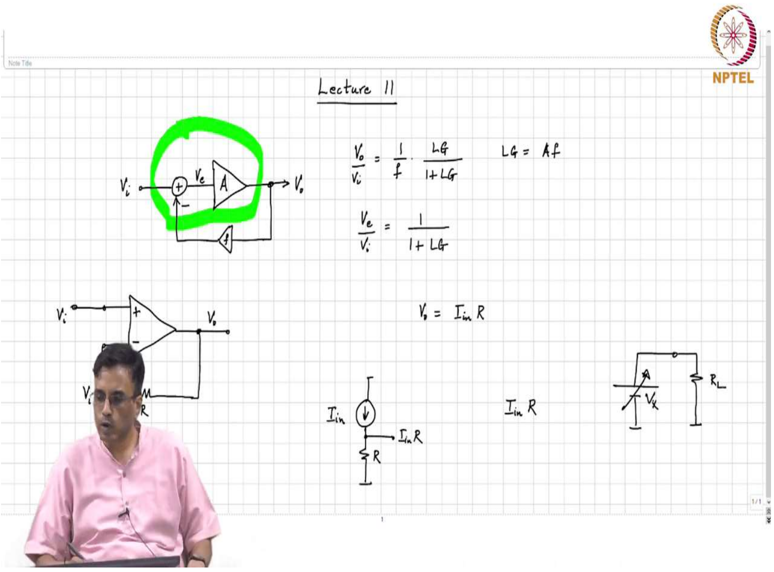

Flip the signs on the op-amps. So, that becomes alright. So, now, let us do another example again, something that you are most likely to be familiar with. Let's say we want an output. We want to make a current controlled voltage source. So, let say we want V_o, that is some In times some number. So, it is a current control voltage source. So, controlling that proportionality factor will have dimensions of resistance.

So, that is basically what is often called a trans resistance amplifier. So, again we would like to use negative feedback. So, in principle what are we going to do? Let us say you are in a lab and you are given a current I_{in}. So, let us say you are given some current I_{in} and I need to generate $I_{in}R$ what will I do? So, well one idea is to put a resistor here and this gives me?

Student: $I_{in}R$.

$I_{in}R$, my job is done and what is the problem with this? Is this a current controlled voltage source? The test for a voltage source is that you change the load resistance and the output voltage should not?

Student: Should not change.

Should not change, correct? So, here the idea that we first had was to take that current pump to a resistor R to get this $I_{in}R$. We said now I am done, let me go home. So, is this a current control voltage source, why? Well, if I put a load resistor the voltage instead of being $I_{in}R$ becomes I_{in} (R // R_L). So, therefore, it is not a voltage source. So, that is no good. So, you are in a lab now you have a current source I_{in} and I told you to produce a voltage $I_{in}R$. What will you need and how will we go about doing this? You have a variable voltage source. You want to make the fact that you have a voltage source with a knob alright. That already means that by definition whatever R_L you put the voltage will be whatever you put there, whatever voltage V_x is there, whatever R_L you put across it, the voltage will remain V_x. So, we have solved that part of the problem. So, you have a variable voltage source with the knob you have seen in the lab. Now I am telling you to make that voltage source equal to?

Student: R.

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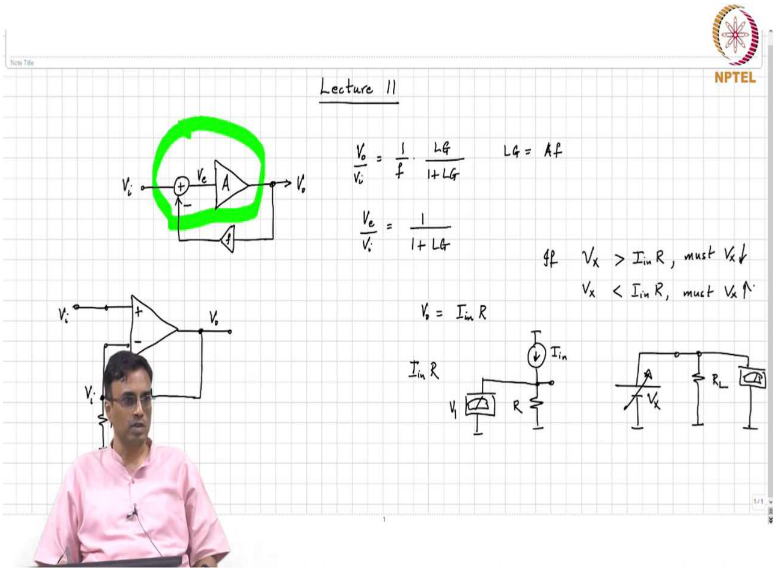

$I_{in}R$. So, what will I do? So, what you are telling me therefore, is you generate I_{in} R somehow and the easy way to generate is simply pump in the current into a resistor then generate that resistor that I_{in} R. Tell me clearly what I should do this is V_x there is I_{in} R. Now what do we do? You put a voltmeter here that is a voltmeter. So, you have to put another voltmeter here. So basically, you measure you compare V_x with V_1 which is?

Student: I_{in} R.

I_{in} R. If V_x is greater than I_{in} R it basically means that you must?

Student: Reduce the V_x

Reduce V_x. If V_x is less than I_{in} R, you must?

Student: Must increase V.

Must increase V, alright and how will you increase V_x. You basically turn the knob this much you understand, clear? Is this basic idea clear to people? So, what are we comparing therefore? We are comparing two voltages V_x and?

Student: I_{in} R.

I_{in} R. Eventually when you are done the output voltage V_x will be exactly equal to $I_{in}R$ regardless of what R_L you put and therefore, this is a what kind of control source?

Student: Current controlled voltage source.

Now there is a slight problem in the sense that there are two volt meters. Can somebody think of getting rid of 1 volt meter? Yeah, well it is pretty straight forward. We are only not interested in the individual voltages.

V_x and V_1 are we only interested in?

Student: Difference.

Difference. So, then the next thing is to say we do not really need that stuff.

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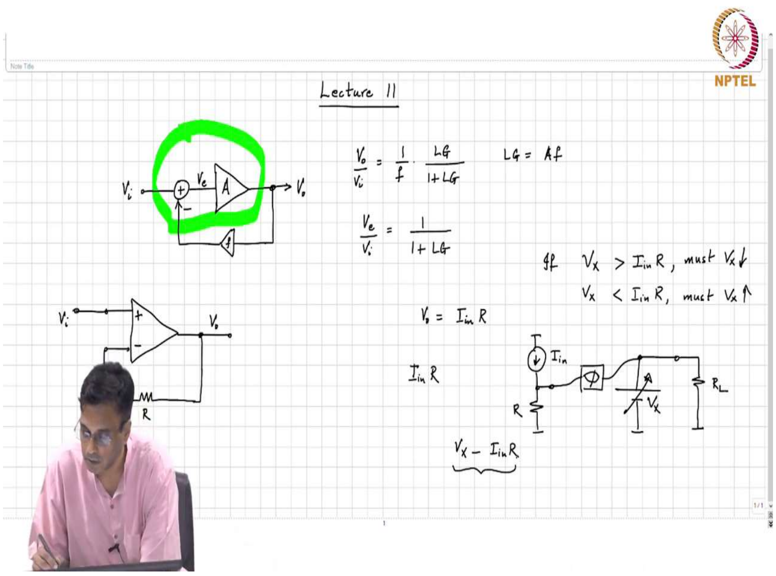

We can just put a voltmeter between these two terms, does that make sense? So, we are comparing two voltages and what is the meaning of compare?

A comparing V_x and I_{in} R. So, the meaning of compare is finding the difference and what physical principle will you use to find the difference between two voltages?

Ok. If you want to compare two voltages, what physical principle will we use?

Student: KVL.

So, how will we subtract therefore, we therefore, need to find V_x -I_{in}R. So, can you tell me how we can find this quantity V_x -I_{in}R?

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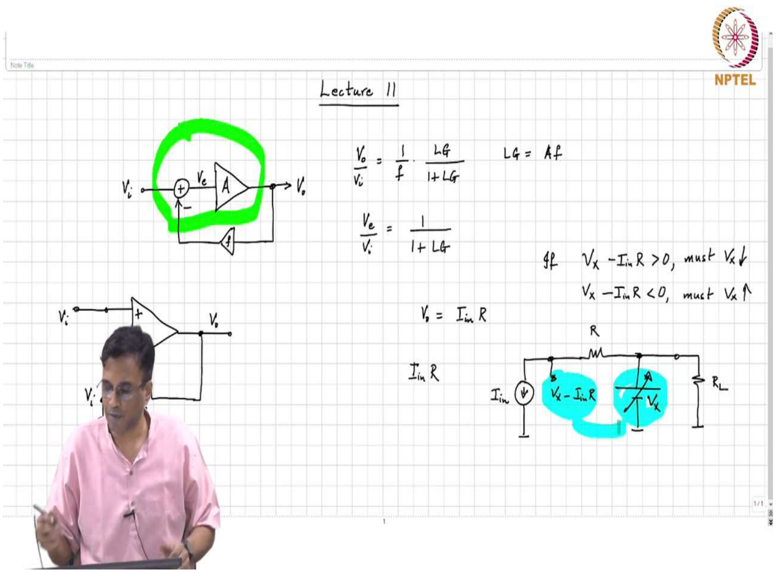

So, in other words, if V_x - I_{in} R is greater than 0, it means that V_x is too high and V_x must therefore, be reduced. And if V_x -I_{in}R is less than 0, it means that V_x is too small and must be increased, alright. So, now, how will I find this quantity? V_x -I_{in}R. So, in other words, I need to compare V_x -I_{in} R with 0, correct. So, any suggestions on how I can find V_x -I_{in}R? How can I generate that voltage V_x -I_{in}R.

Yeah. So, basically you recognize that you simply connect a resistance R in at the output of V_x and then pull a current I_{in} like this. What is this potential?

Student: V_x - $I_{in}R$ and if this potential is greater than 0, you must reduce V_x. If this potential is less than 0 we must increase V_x, is this clear? So, therefore, V_x is a voltage source which is controlled by voltage. What is V? What are the dimensions of V_x -I_{in} R?

Student: Voltage.

So, that V_x is controlled by another voltage and if we want that V_x -I_{in} R to be equal to 0. So, in other words even if we sense that this V_x - I_{in} R is infinitesimally greater than 0, what must we do? We must kick that V_x so, hard that it should go to 0. I mean V_x should be kicked so hard in the negative direction so that the error goes to 0. So, what comment can you make? So, this is clearly a voltage control voltage source and what is the gain of that voltage control voltage source? What should it be? What should it be? Even if you see an infinitesimally small voltage at V_x -I_{in} as V_x -$I_{in}R$, you must kick the output voltage very hard. So, what does this mean? The gain must be?

Student: Infinite.

Infinite. What should be the sign of the gain? If V_x -$I_{in}R$ is greater than 0, V_x must?

Student: Reduce.

Reduce. So, what must be the gain?

Student: Negative.

The sign of the gain must be negative.

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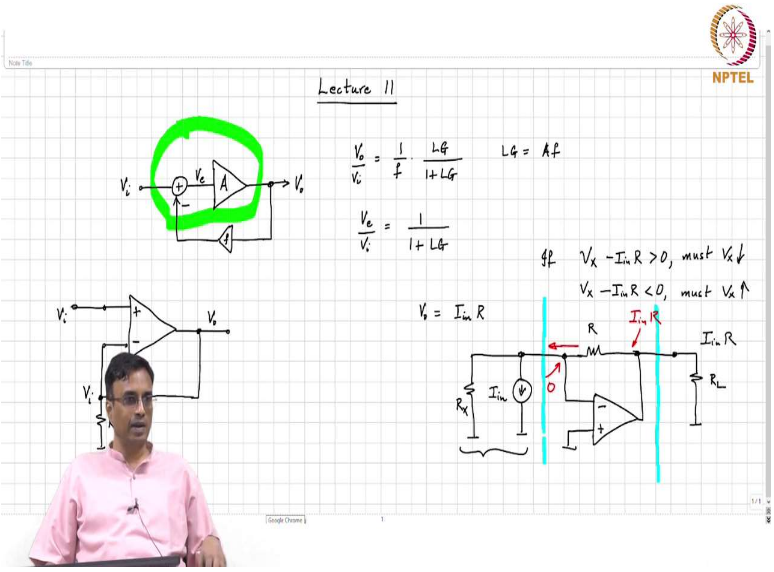

So, this therefore, is an op-amp and draws a more respectable picture. Does it make sense, alright? So, as you can see the signs on the op-amps come out naturally without having to guess a copy from the neighbour 's open textbook all that, alright. So, what is this voltage?

But we know that it is an op-amp whose gain is infinite. So, what comment can you make about that voltage? That voltage is 0. So, therefore, what is the input resistance looking in here? What is the input impedance of this? So, this is our claimed current control voltage source. What is the resistance as seen by the input source?

Student: 0.

0, why? Because that voltage regardless of how much current you pump in the voltage always remains?

Student: 0.

0. So, the input impedance is 0. What comment can you make about the output resistance? What is the output resistance?

Student: 0.

0, why?

Is there a simpler way of telling me that the output resistance is 0? If R_L changes, the output is not changing, correct? Because all this current I_{in} where is it going? Where is it going? Can it go into the op-amp?

Student: No.

No. So, it is all going through R. So, what is this voltage therefore?

Student: $I_{in}R$.

$I_{in}R$ irrespective of?

Student: R_L.

R_L. So, therefore, since the output voltage is independent of the load resistance, it must follow that the output resistance is 0. Is that clear? Alright. So, I mean if the input resistance of this current controlled voltage source is 0, what does it mean? I mean in practice why do you, for instance, use a current control voltage source? What does that buy you in terms of or in other words what I am saying is if the input resistance was not 0. Or rather let us now assume that we have a bad current source. What is the bad current source?

Ideal current source should have an output resistance of infinity. So, let us call this output resistance of this current source equal to R_x. So, now, what comment can you make about the output voltage?

Student: It will be the same.

It will be the same, why? Well one end of R_x is grounded, the other end of R_x is also virtual grounded. So, the voltage difference across the resistance is?

Student: 0.

So, what comment can you make about the current situation? No current flows through R_x. So, I_{in} basically continues to flow in R, alright. So, output voltage will be and this is exactly why you need a current control voltage source, so that you can suck out all the current from the current source even though the current source has got some output resistance.

If the current control voltage source was not ideal in the sense that it had some of its own input resistance was not 0, what comment can you make? Only a fraction of that input current

I_{in} will flow into the amplifier. Some of it will get lost through the output resistance R_x that is exactly what the ideal current control voltage source ensures. Is this clear folks? Alright.

Now, what comment can you make if you have a current like this output voltage is of course I_{in} R. Can I replace this current source in parallel with a with an equivalent? Current source in parallel with the resistor is equivalent to a voltage source in series with the resistor. So, what is the value of the voltage source?

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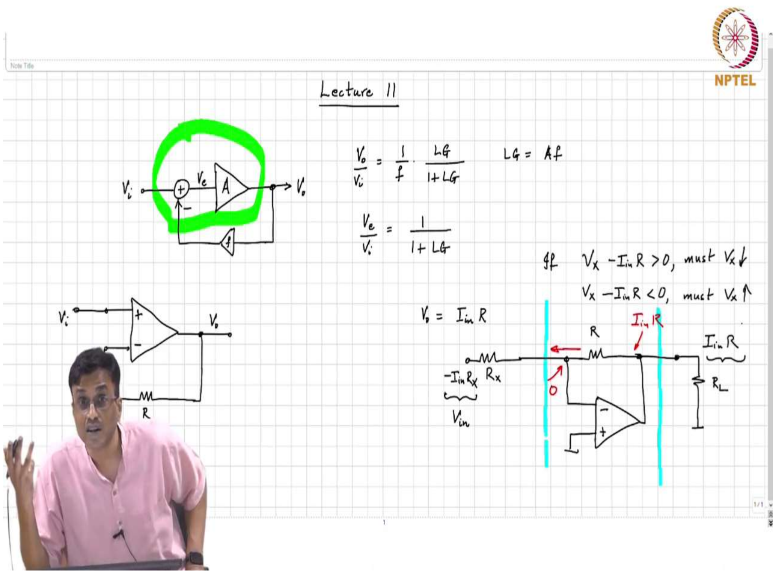

This is R_x. This is $-I_{in}R_x$, alright. So, now, I mean if you look at this picture now, it does not make any sense to call this I_{in} because there is no current at all. So, you might as well call this. If I call this V_{in} what can I call this? But what is V_{out} in terms of V_{in}.

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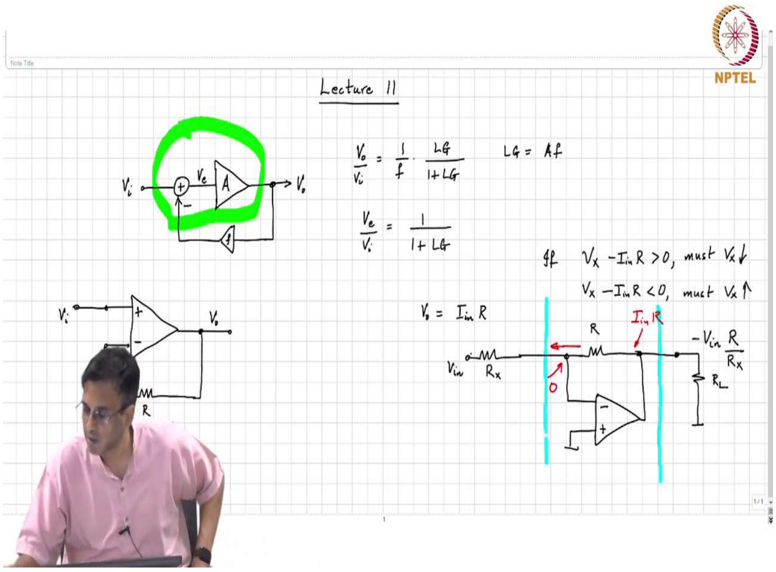

It is basically $V_{in}R_x$. Is this correct?

Alright and this is this circuit familiar. So, this is the very well-known inverting amplifier, but now where it comes from. So, you try to make a current control voltage source. As a current source is bad then its equivalent is basically equivalent to an inverting amplifier.

I mean there is, of course, another way of deriving this. What do you call again from first principles. If you want V_{out} to be the negative of V_{in} what does it mean? V_{out} plus V_{in} must be equal to 0. So, you compare you add V_{out} and V_{in} and compare the result to 0, correct. And how will you add two voltages KVL of course, but how will you implement addition. Let say you want V_1 and V_2, you want $V_1 + V_2$, can you get $V_1 + V_2$ using only resistors? Can you get $(V_1 + V_2)/2$ using only resistors?

Yeah. So, basically if you take V_1, V_2 connect both of them together in order through two resistors, the midpoint will basically give you the sum of the two multiplied by some fraction, since we are only comparing it to 0. That fraction does not matter, correct.

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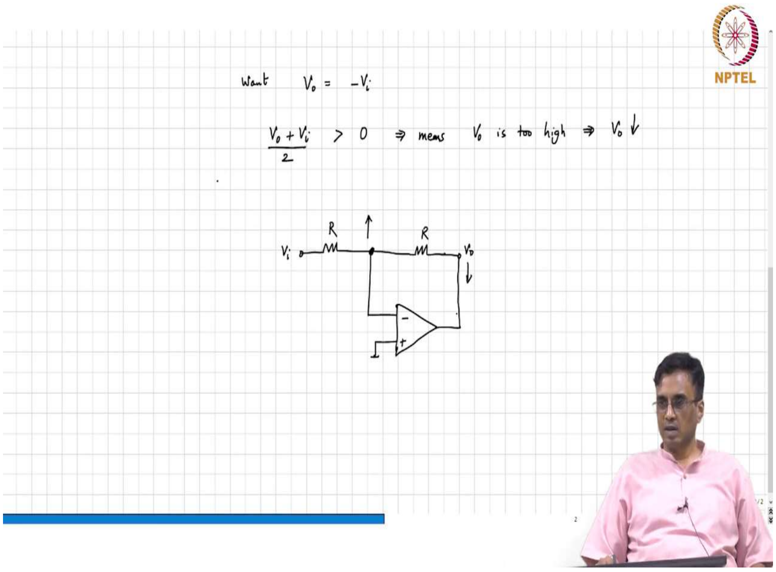

So, what I was saying was let us say we want V_o to be $-V_i$. So, what will we do? We will find $V_o + V_i$ if $V_o + V_i$ is greater than 0. What does it mean? It means V_0 is too high and therefore, V_0 must reduce and vice versa, is this clear? So, now, the question is $V_0 + V_i$ greater than 0 is equivalent to saying $(V_0 + V_i)/2$ is also greater than 0. So, how will you get $(V_0 + V_i)/2$?

Let's say you have V_o. You have V_i, how will I get $(V_0 + V_i)/2$?

Yeah. So, basically. So, this is R, this is R, alright. So, what is that voltage?

$(V_0 + V_i)/2$, and if that is greater than 0, V_o must go?

Student: Down.

If this goes up this must be pulled down. So what must be a voltage control voltage source between that midpoint of those resistors in the output and what must be the gain of that voltage control voltage source? Even if that voltage is infinitesimally greater than 0 or less than 0 you must kick this note so hard. So you must put an amplifier like this, an op-amp like this, to go and kick.

The output in the direction is correct and since the op-amp is ideal that the midpoint of those resistors is to be is condemned to be in ground and therefore, the output voltage is the negative of the input voltage. Does it make sense?