Basic Electronics
Prof. Mahesh Patil
Department of Electrical Engineering
Indian Institute of Technology, Bombay

Lecture - 33
Op-amp circuits

Welcome back to Basic Electronics. In the last class, we have presented two approximations which can be used in op-amp circuit analysis, when the op-amp is operating in the linear region. In this class, we will look at two op-amp based amplifier configurations; the inverting and non inverting amplifiers. We will see that the analysis as well as design of these circuits is very easy, almost trivial. So, let us get started.

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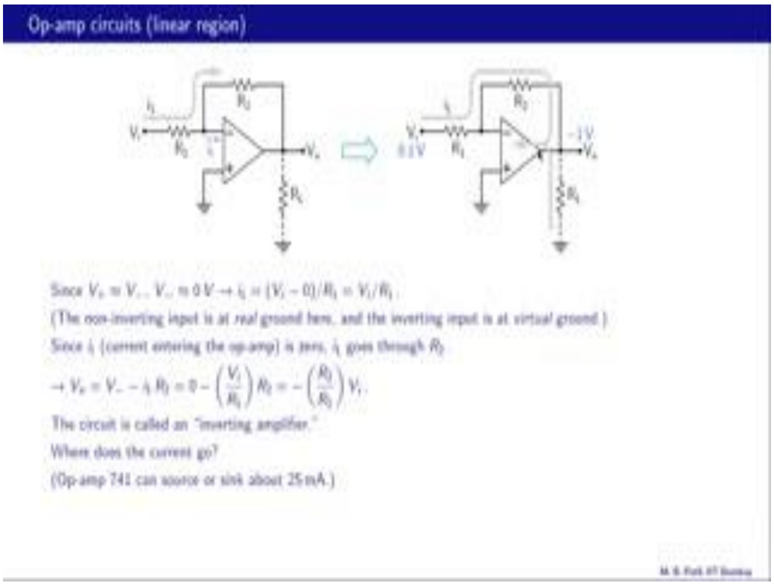

Op-amp circuits (linear region)

Since $V_+ = V_-$, $V_- = 0\,V \rightarrow i_1 = (V_i - 0)/R_1 = V_i/R_1$.

(The non-inverting input is at *real ground* here, and the inverting input is at *virtual ground*.)

Since i_i (current entering the op-amp) is zero, i_1 goes through R_2.

$\rightarrow V_o = V_- - i_1 R_2 = 0 - \left(\frac{V_i}{R_1}\right) R_2 = -\left(\frac{R_2}{R_1}\right) V_i$.

The circuit is called an "inverting amplifier."

Where does the current go?

(Op-amp 741 can source or sink about 25 mA.)

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Let us start with this circuit here. The non-inverting input of the op-amp is connected to ground, that is the input voltage, that is the output voltage. And, we will work out the relationship between the input and the output. The load resistance is connected here. And we have shown that with dash lines, because we will see that whether we connect R L or not, the functionality of the circuit does not change.

To begin with, we know that V plus and V minus are nearly the same. And therefore, V minus is 0 volts because V plus is 0. And that tells us that i 1, this current, is V i minus 0 divided by R 1, that is V i by R 1. Now, let us note that the non-inverting input here is at real ground. It is physically connected to ground and the inverting input is at virtual ground. So, this node is also at approximately 0 volts, but it is not physically connected to the ground node.

Let us now use the second golden rule. This was the first one. And that is that the input current of the op-amp is 0. So, in this circuit this current marked i i is 0. And therefore, i 1 goes through R 2. So, this current must go around like that because no current can enter the op-amp. And that tells us that V o, this voltage is V minus minus this voltage drop. What is that voltage drop? That is i 1 times R 2. So, V o is V minus minus i 1 times R 2. V minus, as we saw earlier is nearly equal to V plus, which is 0 and i 1 is V i by R 1. So, that tells us that V o is 0 minus i 1, which is V i by i 1 times R 2. And that turns out to be minus R 2 divided by R 1 times V i. So, V o is proportional to V i. And, if R 2 by R 1 is larger than 1, then we have an amplifier. And, the relationship between V i and V o has a negative sign; that means, they are out of phase.

And, now we understand why this circuit is called an inverting amplifier; inverting because we have this minus sign here, amplifier because we can choose R 2 and R 1 appropriately, so that R 2 by R 1 is greater than 1. So, therefore the output voltage is an amplified version of the input voltage.

Now the next question that we must address is; where does this current go; the current that we have shown over here. And, here is the answer to that question. Let us take an example say V i is 0.1 volt, R 2 is 10 K, R 1 is 1 K. So, the gain is minus 10 k by 1 k. That is minus 10. If V i is 0.1 volt, then V o would be ten times that; minus ten times that; that is minus 1 volt. Now, in this scenario we have 0 volts here, minus 1 volt here. So, therefore the current through R L would be that. We have 0.1 volt. Here, the inverting terminal is at virtual ground. So, we have a current going like that and these two currents essentially combine and enter the op-amp as shown here. And, in this situation we say that the op-amp is sinking this current. And, if the current was in the other direction, then we would say that the op-amp is sourcing that much current.

Now, the 741 op-amp can source or sink about 25 milliamps, not more than that. And, in the circuits that we come across in this course, we will not really exceed this limit. But, nevertheless it is important to keep this number in mind. If you have to design a new op-amp circuit, then you should check whether that the current that the op-amp has to sink or source is within this limit or not. Now, what we will do is go inside the op-amp. That is, look at the internal circuit of the 741 op-amp. And, see what exactly is happening, when we say that the op-amp is sinking a current or sourcing a current.

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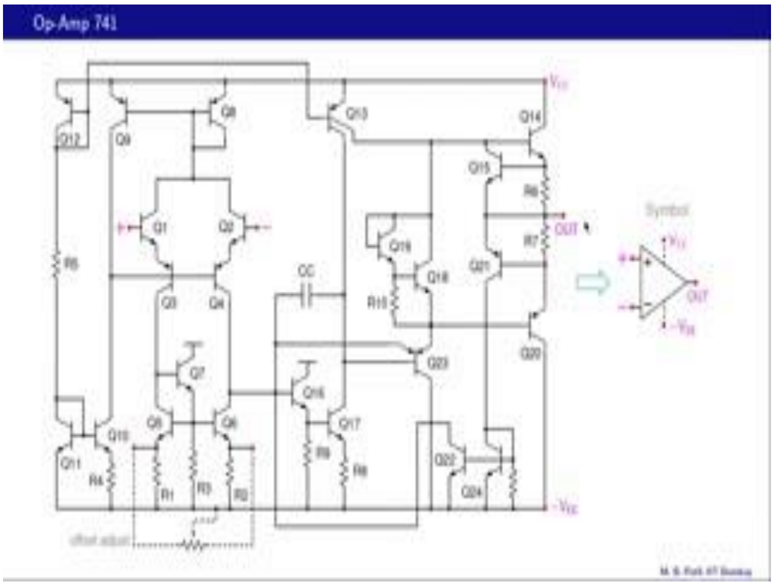

Op-Amp 741

And, here is the internal circuit of the op-amp again. And, when we say that the op-amp is sinking the current; that means, the current is entering like that. What is actually happening is the current enters like that and goes through this Q 20, the transistor. And, eventually to this minus V EE power supply. And that is how the circuit is completed. When we say the op-amp is sourcing a current; that means, the current is coming out of the op-amp, then the paths that the current takes is from V CC through Q 14 and out like that. So, these currents are actually getting supplied by the power supply. And that becomes clear, when we look at this internal circuit of the op-amp.

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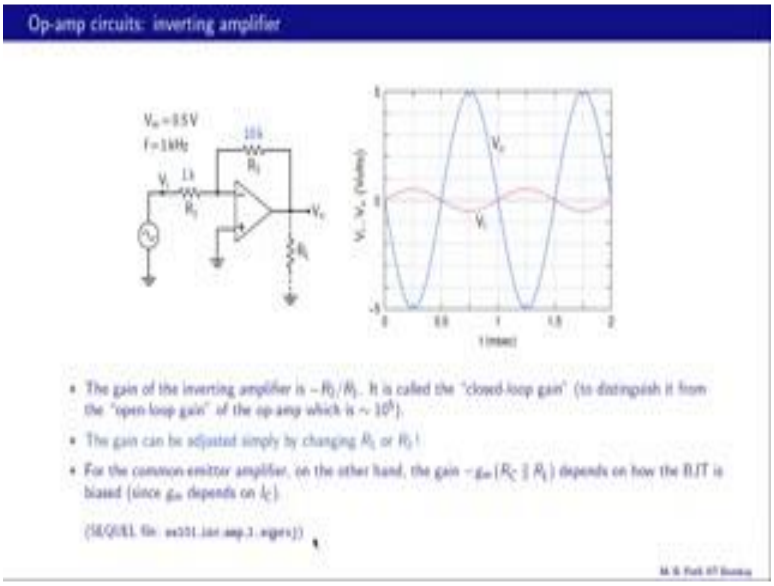

Op-amp circuits: inverting amplifier

- The gain of the inverting amplifier is $-R_2/R_1$. It is called the "closed-loop gain" (to distinguish it from the "open-loop gain" of the op-amp which is $\sim 10^5$).
- The gain can be adjusted simply by changing R_1 or R_2!
- For the common-emitter amplifier, on the other hand, the gain $-g_m(R_C \parallel R_L)$ depends on how the BJT is biased (since g_m depends on I_C).

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Here is a sample simulation result for the inverting amplifier. We have R 2 equal to 10 k R 1 equal to 1 k. So, the gain of this amplifier is minus 10 k divided by 1 k or minus 10. So, we expect V o to be ten times V i with a negative sign. The input is a sinusoid with amplitude of 0.5 volts and frequency 1 kilo hertz. And, we have shown a load resistor here. But, as we have seen in the last slide it really does not change the relationship between V o and V i. So, we have not put down a value for this R L. Here is the input voltage. The amplitude is 0.5, this is 1 volt, here 0.5 and the frequency is 1 kilohertz. So, the period from there to there is 1 millisecond.

The output voltage is expected to be ten times larger in amplitude. So, that is 0.5 times 10 or 5. And that is what we see; 5 volts in amplitude. And, of course it is out of phase with respect to the input voltage because of the negative sign in the inverting amplifier relationship. So, the output voltage therefore goes negative, when the input voltage goes positive. Let us make a few observations. The gain of the inverting amplifier is minus R 2 by R 1, as we have already seen. And, it is called the closed-loop gain to distinguish it from the open loop gain of the op-amp, which is very large; ten is to five or so for the 741 op-amp. Now, this open loop refers to a configuration in which there is no connection between the output side and the input side like this one. And, the op-amp is then set to be operating in the open loop configuration. In contrast, this configuration is called closed-loop configuration.

The gain can be adjusted simply by changing R 1 or R 2. And that is that follows from this expression. You want a gain of 10; make this 10 k, make this 1 k. You want a gain of 20; make this 20 k, make this 1 k, so as simple as that. And, let us compare that simplicity with another amplifier we have seen earlier. That is common emitter amplifier. For the common emitter amplifier, on the other hand the gain was minus g m times R c parallel R L. So first of all, it depended on the load resistance. This one does not. And, also it depends on g m. So, the gain depends on how the B J T is biased because g m has the dependence on I c.

So, it is surely it is not as simple as using an op-amp circuit for amplification. There is a readymade circuit file, which you can checkout and generate these results and change this resistance value and so on.

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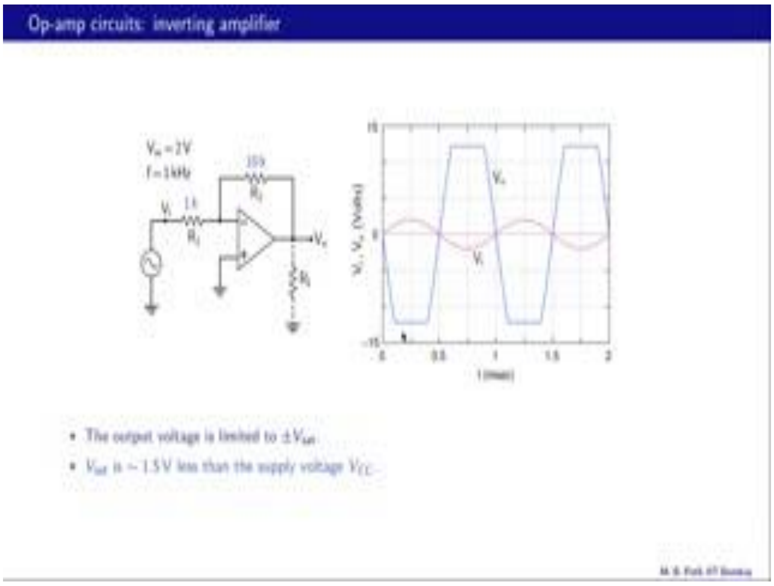

Op-amp circuits: inverting amplifier

- The output voltage is limited to $\pm V_{sat}$.
- V_{sat} is ~ 1.5 V less than the supply voltage V_{CC}.

So, we have seen that an inverting amplifier provides the gain of minus R 2 by R 1. However, there are some limitations that we need to understand. Number one, this output voltage is limited to plus minus V sat, where V sat is the saturation voltage of the op-amp. So, point number one, the output voltage is limited to plus minus V sat. What is v sat? V sat is about 1.5 less than supply voltage V CC. So, if V CC is 15 volts, for example, then V sat would be 13.5 volts; that means, the output voltage would be limited to 13.5 volts on the positive side and minus 13.5 volts on the negative side. Here is an example. The input amplitude is 2 volts; the amplifier gain is minus 10. And therefore, we expect an output voltage amplitude equal to ten times two or 20 volts; that means, we expect the output voltage to go up to 20 volts in the positive direction and minus 20 volts in the negative direction. But because of saturation, the output voltage is limited here by V sat and here by minus V sat. And, this is something that you can easily check in the lab.

So, hook up this circuit in your electronics lab and observe the wave forms. As you keep increasing the input amplitude, at some point you will start seeing this effect of saturation.

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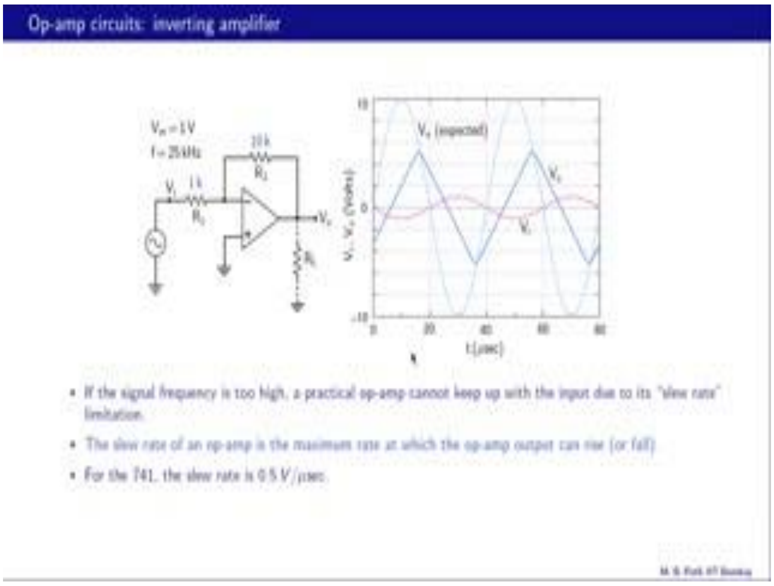

Op-amp circuits: inverting amplifier

- If the signal frequency is too high, a practical op-amp cannot keep up with the input due to its "slew rate" limitation.
- The slew rate of an op-amp is the maximum rate at which the op-amp output can rise (or fall)
- For the 741, the slew rate is 0.5 V/μsec.

There is another limitation that arises for a practical op-amp, and that has to do with the signal frequency. If the signal frequency is too high, the input signal frequency, practical op-amp cannot keep up with the input, due to its slew rate limitations. And, let us see what this slew rate is. The slew rate of an op-amp is the maximum rate at which the op-amp output can rise or fall. And, for the 741 op-amp the slew rate is 0.5 volts per micro seconds. So, in 1 micro second the op-amp output can only rise or fall by 0.5 volts.

Here is an example. It is a same circuit that we saw earlier. R 2 is 10 k, R 1 is 1 k. So, the gain is minus 10 k by 1 k or minus 10, V m is 1 volt. And, the frequency now is higher is 25 kilohertz. 25 kilo hertz corresponds to a period of 40 microseconds. So, that is one period. This is the input signal going from minus 1 volt to plus 1 volt. And, the output that we expect is ten times the input voltage, so an amplitude of 10 volts. And, of course it is going to be out of phase with the input voltage. So, that is the output voltage that we expect. But, the actual output that we observe. And, we will observe this also on an oscilloscope, if you connect the circuit in the lab and make measurements. The actual output that we observe is this. Here, it looks substantially different from what we expect and this is entirely because of the slew rate limitation of the 741 op-amp.

Let us calculate this rate here. What is this voltage difference? Each division here is 2 volts. So, it is 2, 4, 6, 8, about 10 volts from there to there. And, this time is 20 microseconds. So, it is 10 volts. Delta V is 10 volts and delta t is 20 microseconds. So, 10 volts divided by 20 microseconds; that comes to half volt per microsecond. And that is exactly what the slew rate of the 741 is. And, this happens because this rate at which the output is expected to rise is higher than the slew rate. Therefore the op-amp cannot really keep up with that. So, this is a definitely a limitation in practice and we should be aware of that. So, what it means is we cannot use the inverting amplifier at arbitrarily higher frequencies. If our input frequency is higher, and there is an op-amp available with the higher slew rate, then that maybe a solution. Otherwise, we have to look for some other circuit.

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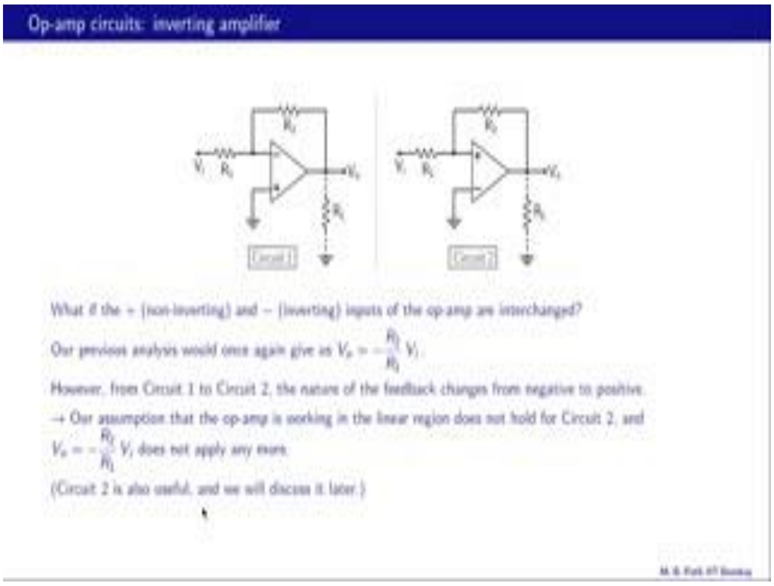

Op-amp circuits: inverting amplifier

What if the + (non-inverting) and − (inverting) inputs of the op-amp are interchanged?

Our previous analysis would once again give us $V_o = -\frac{R_2}{R_1} V_i$.

However, from Circuit 1 to Circuit 2, the nature of the feedback changes from negative to positive.

→ Our assumption that the op-amp is working in the linear region does not hold for Circuit 2, and $V_o = -\frac{R_2}{R_1} V_i$ does not apply any more.

(Circuit 2 is also useful, and we will discuss it later.)

Let us now address a very important question. And that is, what if the non-inverting and inverting inputs of the op-amp are interchanged. This is our inverting amplifier. The non-inverting amplifier is going to ground. What will happen if we interchange this plus and minus to get this circuit? So, this circuit is the same as the first circuit, except here the inverting input is going to ground. Now, if we go back to our analysis of the inverting amplifier, we assume that the op-amp is operating in the linear region. Then, we say that this V minus and V plus are nearly equal. So, this is also 0 volts, and then we calculate with this current. Then we said that this current will not go into the op amps. So, it must go around like that. And then, we arrived at V o. We can do the same thing for this circuit and once again get the same results.

But, there is a very serious problem when we do that. And, the problem is the following: from circuit one to circuit two, the nature of the feedback changes from negative to positive. And, where is the feedback in these circuits? That is this connection from the output back to the input side through R 2. In circuit one; the feedback turns out to be negative. And, we will see later how to identify whether the feedback is positive or negative. In this circuit, it is negative. And when the feedback is negative, circuits are stable. And, our assumption that the op-amp is working in the linear region, holds in this case.

And then, we can do our analysis like we have seen earlier and arrive at this result. In circuit two, the feedback turns out to be positive. And with positive feedback, circuits become unstable. And therefore, this assumption that the op-amp is working in the linear region does not hold for circuit two. And therefore, all of these derivations goes for a task. This relationship does not apply anymore. And therefore, circuit two is not an amplifier. It turns out that circuit two is also useful for some other purpose. And, we will discuss that later.

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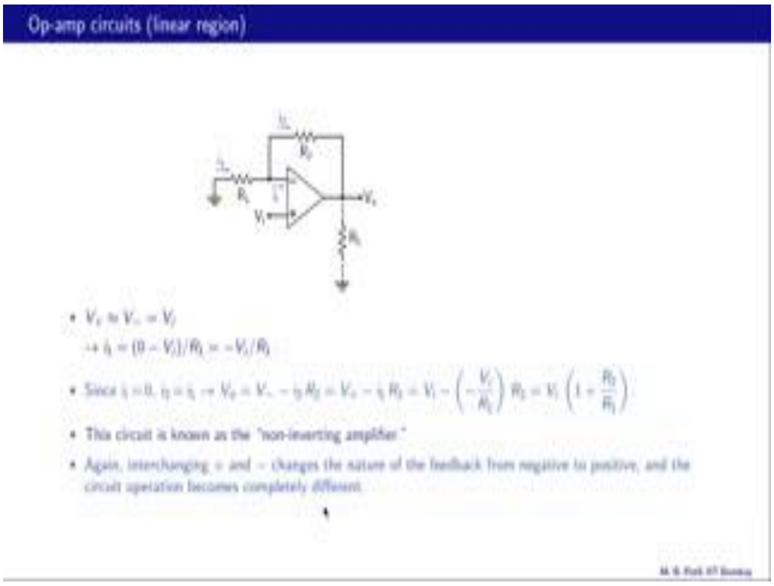

Op-amp circuits (linear region)

- $V_- \approx V_+ = V_i$
  $\rightarrow i_1 = (0 - V_i)/R_1 = -V_i/R_1$
- Since $i_i = 0$, $i_2 = i_1 \rightarrow V_o = V_- - i_2 R_2 = V_+ - i_1 R_2 = V_i - \left(-\frac{V_i}{R_1}\right) R_2 = V_i \left(1 + \frac{R_2}{R_1}\right)$
- This circuit is known as the "non-inverting amplifier."
- Again, interchanging + and − changes the nature of the feedback from negative to positive, and the circuit operation becomes completely different.

Here is another very commonly used circuit in which the op-amp operates in the linear region. The input is connected to the non-inverting op-amp input. That is the output. And, let us see how this works. Since the op-amp is assumed to be in the linear region, V plus and V minus are nearly equal. And therefore, V minus is nearly equal to V i. And once we know this voltage, we can find this current. That is 0 minus V minus which is the same as V i divided by R 1.

So, minus V i divided by R 1. That is, i 1. Now, since the op-amp input current i i here is 0, i 1 and i 2 must be the same. And, now we have a way to calculate V o. So, what is V o? V o is this voltage V minus minus this voltage drop. So, V o is V minus minus i 2 R 2. That voltage drop V minus is the same as V plus I two is the same as i 1. So, that is V plus minus i 1 times R 2 V plus is V i i 1 is minus V i divided by R 1. And when it put altogether, V i times 1 plus R 2 over R 1.

So, for this circuit we have the output voltage equal to the input voltage times 1 plus R 2 over R 1. So, this circuit is also an amplifier. And, it is known as the non-inverting amplifier because this gain is a positive number now. Unlike the previous amplifier, which was a inverting amplifier with a negative gain. Once again given the value of gain, it is very easy to choose R 2 and R 1. For example, if you want a gain of 10, we can choose R 1 equal to 1 k, R 2 equal to 9 k and get a gain of 1 plus 9 equal to 10. Once again interchanging plus and minus, the non-inverting and inverting inputs of the op-amp changes the nature of the feedback from negative to positive and the circuit operation becomes completely different. So, this order is rather important in all op-amp circuits. And, we should always keep that in mind.

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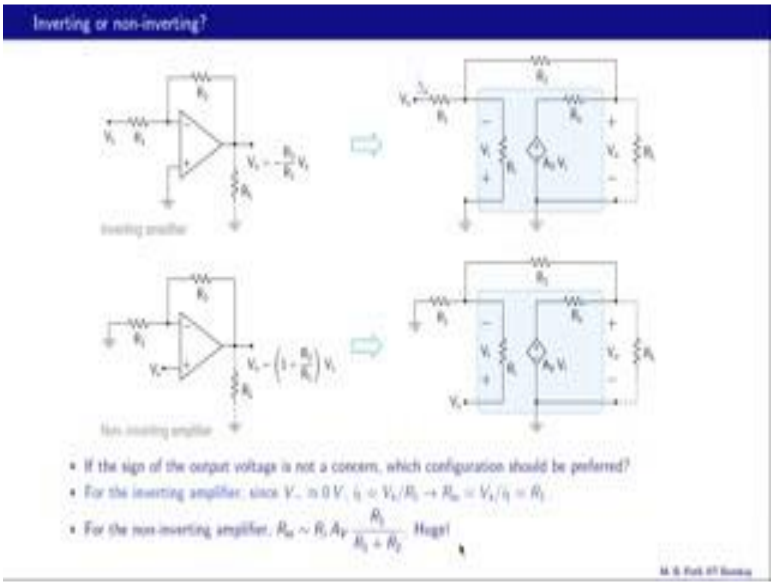

Inverting or non-inverting?

- If the sign of the output voltage is not a concern, which configuration should be preferred?
- For the inverting amplifier: since $V_- \approx 0\,V$, $i_1 = V_s/R_1 \rightarrow R_{in} = V_s/i_1 = R_1$
- For the non-inverting amplifier, $R_{in} \sim R_i A_V \frac{R_1}{R_1+R_2}$. Huge!

M. B. Patil, IIT Bombay

One important question that now arises is which one of these is better? Inverting amplifier or non-inverting amplifier? Of course, the inverting amplifier has the negative gain, whereas this one has a positive gain; that is negative that is positive. But, apart from that they are both easy to use. We can easily find R 1 and R 2 for a given value of gain. And, suppose the sign of the output voltage is not a concern. So, let us say we do not really mind this negative sign there, and then which configuration should be preferred. So, that is the question that we want to answer now.

Let us now replace the op-amp with this equivalent circuit like that. We have the input resistance of the op-amp appearing between the inverting and non inverting input terminals. Then, we have the voltage control, voltage source, which represents the gain of the op-amp. And then, we have the output resistance of the op-amp. Our interest is to find the input resistance as seen by this voltage source V s. And, what is that? That is V s divided by i 1. Now, since V minus is nearly 0, V minus and V plus are nearly the same. And therefore, V minus is 0, i 1 is V s minus 0 divided by R 1 or simply V s divided by R 1. So, i 1 is V s by R 1. And therefore, R in which is V s divided by i 1 is R 1. And, R 1 would typically be in the kilo ohms range.

Let us now look at the non-inverting amplifier. Once again, let us replace the op-amp with its equivalent circuit. And that is what we have the input resistance, then the gain element, then the output resistance. In this case, the input voltage is applied at the non-inverting input of the op-amp right there. And, now we can see that this voltage source, we will see a large resistance because this R i is very large, typically something like mega ohms. In fact, it turns out to be larger than simply R I. It is R I times A v times some factor. And, we will actually derive this result later. So, this is really quite huge. And therefore, for all practical purposes V s is looking at an open circuit.

So, this is really a big advantage of a non-inverting configuration. If we are concerned about the resistance seen by the input voltage source, then we should definitely choose the non-inverting amplifier configuration.

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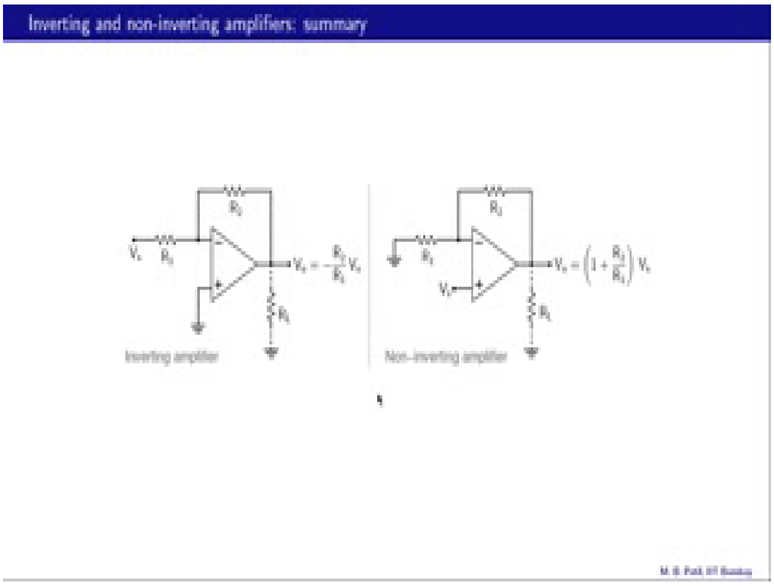
Inverting and non-inverting amplifiers: summary

M. B. Patil, IIT Bombay

Let us have a revision of what we have studied. Here are the inverting amplifier and non-inverting amplifier side by side. We, as we see there are some similarities between these two circuits. Both of these have two resistance R 1 and R 2. And, in both cases the feedback resistor goes back from the output to the inverting input of the op-amp, there as well. And, there are also some differences, of course. And, the inverting amplifier of course has this negative sign in the gain.

Apart from that, note that we only have one term in this expression. Here, we have two. And, let us see where this term came about. V minus in this case was 0 and the output voltage was 0 minus this drop. And, we see here is essentially just this drop because V minus was 0. On the other hand, for the non-inverting amplifier V o has two terms and these two terms came about because V i is nearly V s and then there is this voltage drop. So, V o is V minus minus this voltage drop, and that V minus was equal to V i or V s, as it is called here. That is why we have two terms here. And, as we have also seen there is a large difference between the input resistances of these two circuits. In this circuit, the input resistance is R 1 as seen by the voltage source, the input voltage source. And, in this circuit in the non-inverting amplifier, the input voltage source is much larger resistance.

So, it is a good idea to stop the video at this point. Draw these circuits yourselves, turn the monitor off, derive the V o versus V i relationships for both of these circuits. And, it is best not to learn these by heart. It is very easy to derive these relationships as we have already seen. And, when you go through the derivation, it will stay with you much longer than just learning things by heart.

In summary, we have looked at two op-amp based amplifier configurations. The gain is negative for the inverting amplifier and positive for the non-inverting amplifier. In other case, the gain can be adjusted simply by choosing two resistance values. We have also seen that the non-inverting amplifier is better because it offers a higher input resistance. In the next class, we will continue these discussions, until then goodbye.