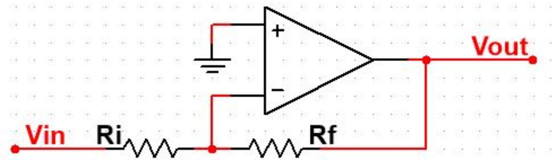
Op Amp Configurations

We've already investigated one of the most commonly used configurations of op amp circuits. so we'll formalize that discussion here before going on to others.

Inverting Op Amp Circuit



We've determined the gain previously, so it will be included in the key points below.

Notice that this simplified diagram doesn't include power connections. No op amp, or any other semiconductor circuit, can operate without power -- this is just an over-simplification that is frequently used to emphasize the importance of the feedback network. In reality, you would source a physical op amp, determine what its pin numbers are, and power it using DC power supplies -- typically two supplies, one positive and one negative, although there are some "single rail' op amps available. (These cannot produce negative voltages at the output, so they introduce a whole host of issues with trying to add a DC offset to any AC signals that are to be amplified. We won't concern ourselves with this issue in this course.)

As with all op amp circuits, the output impedance of the inverting amplifier is so small as to be negligible, so we typically consider it to be zero.

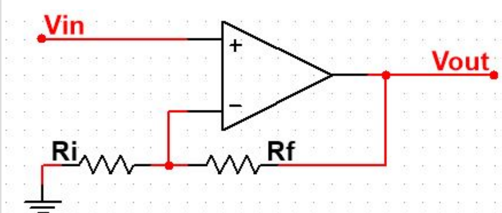
Unfortunately, even though the inverting input of the op amp has a practically infinite impedance, current flows from the signal source through R_i to a virtual ground point. Any time current is drawn from the signal source, the input impedance is not infinite. In this case, the input impedance is, in fact, R_i.

$$A_v = -\frac{R_f}{R_i}$$

$$r_{in} = R_i$$

$$r_{out} = 0$$

Non-Inverting Op Amp



Notice the similarities and differences between this circuit and the previous one. The two resistors are still in a network with the inverting pin -- to reduce the gain, negative feedback is required. However, the Ground and V_{in} have been swapped. Let's do a quick analysis of this configuration, using our two-piece model, then summarize the results below.

1. If, as before, the input signal was +0.5 V, what is the voltage expected at the inverting input, using our model?

   0.5 V

2. If, again as before, R_i = 1 kΩ, how much current, in milliamps, will flow through it from the voltage present at the inverting input? 0.5 mA

3. Using our model, how much current comes out of the inverting input? 0 mA

4. Given that the current has to come from somewhere, what voltage must exist across R_f in order to supply this current, if R_f = 10 kΩ? 5 V

5. Now, add the voltage across R_f to the voltage at the inverting pin to determine what V_{out} must be, referenced to ground.

   5.5 V

6. Determine the gain of this amplifier, based upon V_{out} and V_{in}. 11

Using Ohm's law, we can once again determine how the gain of this amplifier relates to the resistors in the feedback network:

$$A_v = \frac{V_{out}}{V_{in}} = \frac{IR_f + IR_i}{IR_i} = \frac{R_f + R_i}{R_i} = \frac{R_f}{R_i} + 1$$

7. Notice that the input signal goes directly to the non-inverting input, with no other resistors either in series or to ground. From our model, this means that the input impedance is infinite

Again, the output impedance is practically zero.

So, in summary, for the non-inverting op amp circuit:

$$A_v = \frac{R_f}{R_i} + 1$$

$$r_{in} = \infty$$

$$r_{out} = 0$$

In other words, this is almost the ideal amplifier, if it weren't for the "+1" in the gain expression. In fact, this limits the non-inverting amplifier significantly, because it cannot be used as an "attenuator" -- a circuit that decreases the amplitude of the input signal.

However, for the optimists in our midst, this offers the opportunity for one more useful op amp configuration -- the Unity Gain Buffer. We've discussed current buffers previously in terms of switches that drive LEDs, relays, or motors, but now we can do the same with an amplifier. Let's develop it from the non-inverting amplifier.

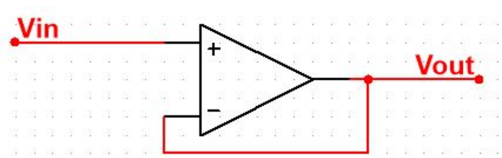
8. If we wanted to reduce the gain of the non-inverting amplifier to +1, the "R_f/R_i" would need to be reduced to 0

9. In order to reduce the "R_f/R_i" part to zero, R_f could be 0 . In a circuit, this would be a(n) short . In other words, we could replace the resistor with a wire jumper.

10. In order to reduce the "R_f/R_i" part to zero, R_i could be infinite . In a circuit, this would be a(n) open . In other words, we could simply not put a resistor to ground, and eliminate any reference to ground.

The resulting circuit would look like the one below.

Unity Gain Buffer



Notice that, according to our model, V_{out} has to be equal to V_{in}, because the inverting terminal, which is directly connected to V_{out}, has to be identical to V_{in} (virtual short). Also notice that V_{in} has no current path, since it is connected to a high-impedance input, so the input impedance is practically infinite.

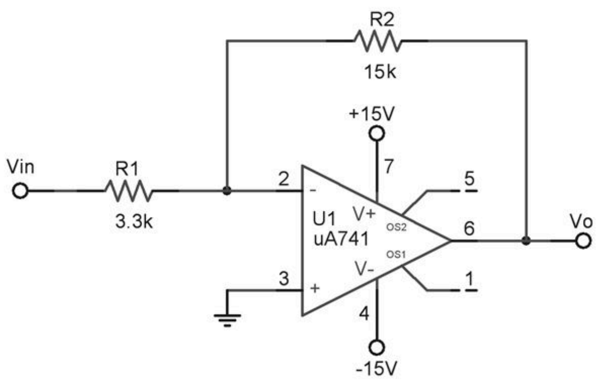
$$A_v = +1$$

$$r_{in} = \infty$$

$$r_{out} = 0$$

Exercises and Applications

Use the schematic diagram below to answer the questions that follow. (Note that sometimes the amplifiers are drawn with the inverting terminal on top, sometimes with the non-inverting terminal on top. Nothing changes in their functionality.)



11. This amplifier is inverting

12. What is the voltage gain? -4.55

13. What is the input impedance of this amplifier? 3.3 kohm

14. What is the output impedance of this amplifier? zero

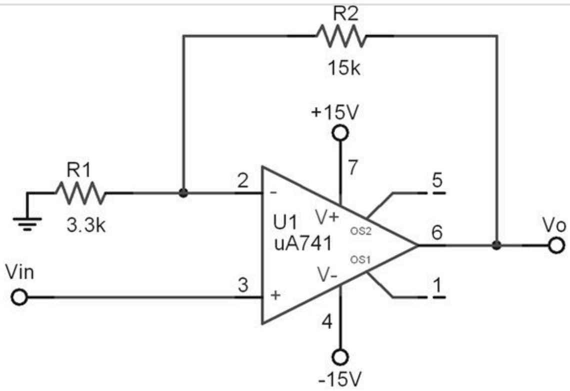
15. Fill in the missing values in the following table, You may want to draw the "black box" amplifier model to help you with your results.

V_S, mV	R_S, Ω	V_{in}, mV	V_{oc}, mV	R_L, Ω	V_o, mV
+118	600	99.8	-454	270	-454
-373	1000	-286	1300	1000	+1300

16. If this amplifier were to be driven by a function generator with an output impedance of 600 Ω set to a 50 mV_p sine wave at a frequency of 500 Hz, what would the output voltage be? 192 mV_p at 500 Hz, inverted

17. If a Unity Gain Buffer were to be placed between the function generator and this amplifier circuit, what would the output voltage be? 227 mV_p at 500 Hz, inverted

Use the schematic diagram below to answer the questions that follow.



18. This amplifier is non-inverting

19. What is the voltage gain? 5.55

20. What is the input impedance of this amplifier? infinite

21. What is the output impedance of this amplifier? zero

22. Fill in the missing values in the following table, You may want to draw the "black box" amplifier model to help you with your results.

V_S, mV	R_S, Ω	V_{in}, mV	V_{oc}, mV	R_L, Ω	V_o, mV
+118	600	118	654	270	654
234	1000	234	1300	1000	+1300

23. If this amplifier were to be driven by a function generator with an output impedance of 600 Ω set to a 50 mV_p sine wave at a frequency of 500 Hz, what would the output voltage be? 277 mV_p at 500 Hz, not inverted

24. Would there be any difference expected if a unity gain buffer were to be installed between the signal source and the input to this amplifier? No

Cascaded Amplifiers

As was hinted at above, it is possible to connect amplifiers together, something called "Cascading". There are really only about five things you need to know about cascading amplifiers:

- The overall gain of the amplifier is the ***product*** (i.e. multiply together) of the gains of the individual stages
- The input impedance of the cascaded amplifiers is the input impedance of the first stage
- The output impedance of the cascaded amplifiers is the output impedance of the last stage
- If the amplifier stages do not have ideal input impedances (i.e. infinite) or ideal output impedances (i.e. essentially zero), the losses between stages need to be determined using the "black box" model. This won't be an issue for op amps, because their output impedances are ideal.
- Good design puts the amplifier with the best (highest) input impedance first and the best (lowest) output impedance last

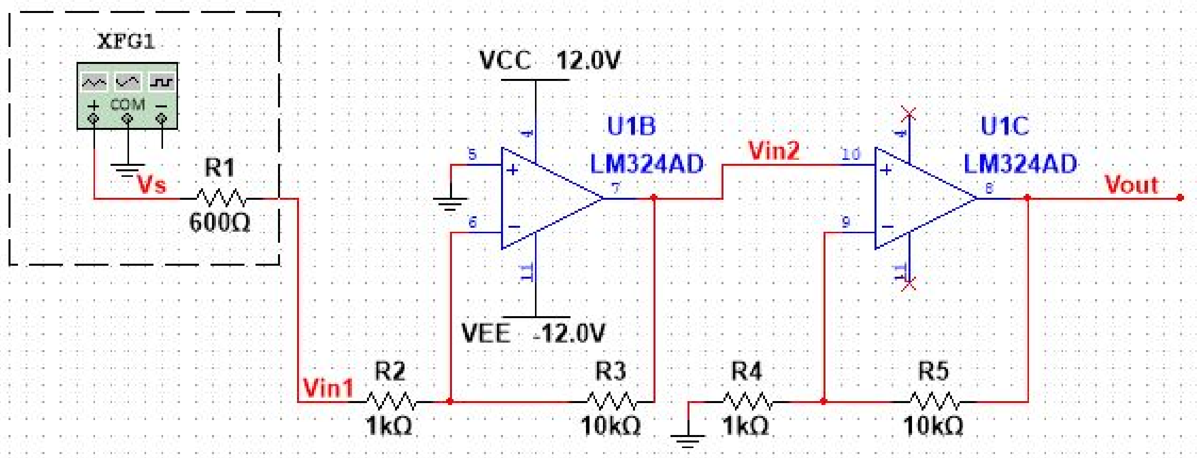
25. Two op amp circuits, both using R_i = 3.3 kΩ and R_f = 15 kΩ are to be cascaded together. One is inverting, the other is non-inverting. (You've just finished analyzing these two amplifiers in the preceding questions.) What is the overall gain of the cascaded amplifier? -25.2

26. How should they be connected together? non-inverting first, because it has the higher input imped…

27. If the non-inverting amplifier was put first and the amplifier was to be driven by a 50 mV_p sine wave from a function generator with an output impedance of 600 Ω, what would V_{in} be? 50 mV_p, and what would V_{out} be? 1.26 V_p, inverted

28. If the inverting amplifier was put first with the same signal from the same function generator, what would V_{in} be? 42.3 mV_p, and what would V_{out} be? 1.07 V_p, inverted

Carefully follow through the analysis of the worked example below.



V_s = 100 mV_p @ 1 kHz

U1B, the first stage, has the signal presented to its inverting terminal, with the non-inverting terminal grounded. This makes it a classic inverting amplifier.

Its gain, then, will be

$$A_{v1} = -\frac{R_f}{R_i} = -\frac{10\ k\Omega}{1\ k\Omega} = -10$$

U1C, the second stage, has a signal presented to its non-inverting terminal, with a grounded negative feedback network connected to its inverting terminal. This makes it a classic non-inverting amplifier.

Its gain, then, will be

$$A_{v2} = \frac{R_f}{R_i} + 1 = \frac{10\ k\Omega}{1\ k\Omega} + 1 = 11$$

The overall gain of the amplifier, then, will be

$$A_{vT} = A_{v1} \cdot A_{v2} = -10 \cdot 11 = -110$$

Since the first stage is an inverting amplifier, its input impedance is R_i = 1 kΩ

This means there is a voltage divider created by the internal impedance of the signal generator and the amplifier's input impedance.

$$V_{in1} = V_S \left(\frac{r_{in1}}{R_S + r_{in1}}\right) = 100\ mV_p \cdot \left(\frac{1\ k\Omega}{0.6\ k\Omega + 1\ k\Omega}\right) = 62.5\ mV_p$$

We can determine Vout two ways.

First, we can follow through the stages, determining the voltages as we go.

$V_{out1} = V_{in1} \cdot A_{v1} = 62.5\ mV_p \cdot -10\ =\ 625\ mV_p,\ inverted$

Since the output impedance of the first stage is practically zero, $V_{in2} = V_{out1}$ = 625 mV_p, inverted.

$V_{out} = V_{in2} \cdot A_{V2} = 625\ mV_p \cdot 11\ =\ 6.875\ V_p,\ inverted$

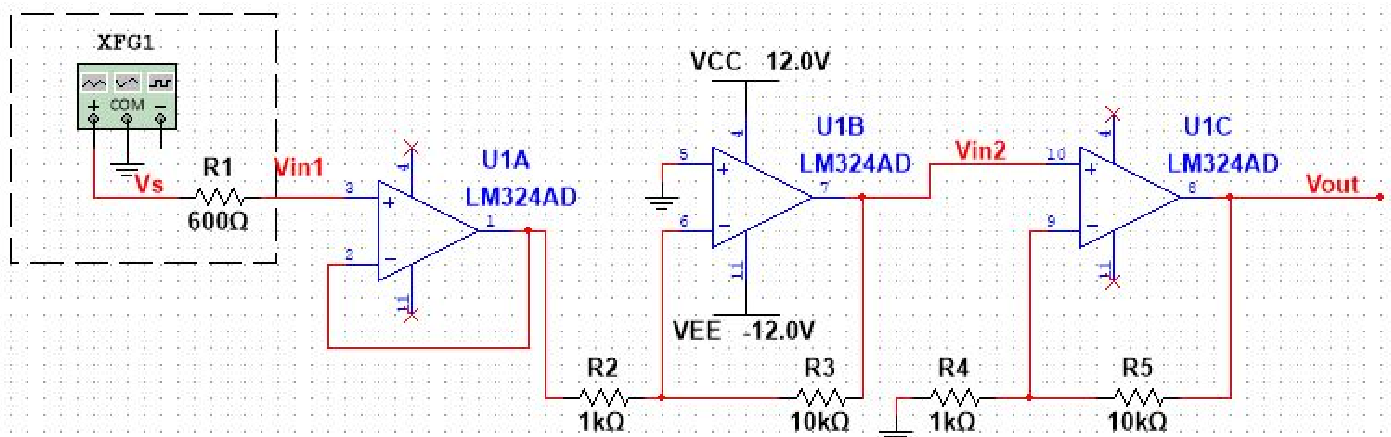
Since the output impedance of the second stage is practically zero, it wouldn't matter if we attached a load resistor (within reason) -- the loaded output would be the same as the open circuit output, at 6.875 V_p, inverted.

The simpler solution would be to take the input signal and multiply it by the overall gain:

$V_{out} = V_{in1} \cdot A_{VT} = 62.5\ mV_p \cdot -110 =\ 6.875\ V_p,\ inverted$

It's unfortunate that the input signal is less than the source signal, due to the imperfect input impedance of the first stage. We could fix this problem by reversing the two amplifiers -- put the non-inverting stage first, followed by the inverting amplifier. In this configuration, $V_{in1} = V_s$ so $V_{out} = V_{in1} \cdot A_{VT} = 100\ mV_p \cdot -110 = 11.0\ V_p,\ inverted$

Another solution, since we've got a quad op amp in the circuit, would be to place a unity gain buffer in front of the inverting amplifier, as shown here.



In this case, the input impedance of the unity gain buffer is practically infinite, so $V_{in1} = V_s$. The gain of the first stage is +1, so the overall gain is still -110. Thus,

$V_{out} = V_{in1} \cdot A_{VT} = 100\ mV_p \cdot -110 = 11.0\ V_p,\ inverted$

Non-Ideal Amplifier Characteristics

This topic isn't directly related to Op Amp Configurations, but it will help you understand why we assume the input and output impedances of the op amp are practically ideal.

We've made reference to the Feedback Network of the op amp, and discovered that it establishes the gain of the op amp, assuming that the gain is so big that we can consider the voltage between the two input pins to be essentially zero (i.e. Virtual Short). Without going into too much detail, there's a mathematical reason for that, which comes down to an analysis of these two resistors appearing as a voltage divider between the output of the amplifier and ground, with the inverting input in the middle. To help with associated analyses, the resistor ratio in the voltage divider has been called β, which is unfortunate because it has nothing to do with the β we used for the BJT Transistor.

$$\beta = \frac{R_i}{R_f + R_i}$$

As you can see, this β can't be bigger than one.

This β is combined with the open circuit gain of the amplifier to create a new term, $1 + A_{vol}\beta$, that can be applied to the actual gain, the input impedance, and the output impedance of a non-ideal op amp (i.e.) one that doesn't have a huge gain. Here are the related expressions for the non-inverting configuration of the op amp, where the "ol" values are the open loop numbers from the manufacturer's specification sheet.

Non-Inverting Amplifier, Non-Ideal Calculations

$$A_v = \frac{A_{vol}}{1 + A_{vol}\beta}$$

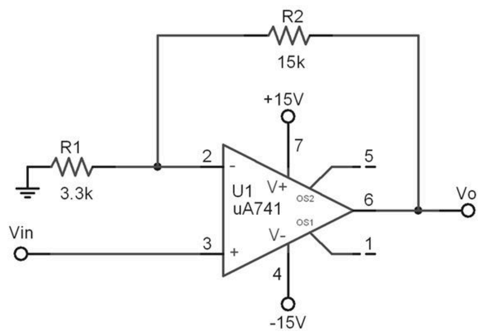
$$r_{in} = (1 + A_{vol}\beta) r_{in_{ol}}$$

$$r_{out} = \frac{r_{out_{ol}}}{1+A_{vol}\beta}$$

Interestingly, we'd have to have a really bad op amp for these formulas to show the non-ideal characteristics of the amplifier, so we'll start by assuming we've got an amplifier with similar characteristics to the 741, except the gain. For historical reasons, we'll give you that gain in dB, which will have to be converted to a V/V ratio before you can use it.

29. Our non-ideal amplifier has an open loop voltage gain of 34 dB. What is that as a V/V ratio? 50.1

    Round this value to the nearest whole number to simplify the rest of the calculations.
30. We'll use this amplifier in a non-inverting amplifier with the same resistors as our previous example:



31. What would the gain of this amplifier be, using the non-ideal non-inverting amplifier formulas above? 4.99

    , which is a bit lower than the +5.55 we got for our previous ideal calculation.
32. Given that the specification sheet gave us r_{inol} = 300 kΩ, determine the non-ideal r_{in} for this amplifier.

    3 Mohm
33. Assuming the op amp has an r_{outol} = 75 Ω, what is the output impedance for our non-ideal amplifier?

    7.5 ohm

Those input and output impedances look pretty good. But let's see what they look like if we use the real gain of the 741 op amp, 200,000 V/V.

34. What would the gain of this amplifier be, using the non-ideal non-inverting amplifier formulas above? 5.55

    , pretty much what we predicted with our ideal model.
35. Given that the specification sheet gave us r_{inol} = 300 kΩ, determine the non-ideal r_{in} for this amplifier.

    10.8 Gohm That's practically infinity!
36. Assuming the op amp has an r_{outol} = 75 Ω, what is the output impedance for our non-ideal amplifier?

    2.08 mohm And that's practically zero!

So, using our calculations for the non-ideal operational amplifier, we've finally proved that our model is actually valid: the input impedances of the inputs are practically infinite, the output impedance is practically zero, and we can predict the gains using just the feedback resistors.

Oddly, none of the textbooks on op amps include formulas for the non-ideal inverting amplifier. Here they are, just for you!

Inverting Amplifier, Non-Ideal Calculations

$$A_v = 1 - \frac{A_{vol}}{1+A_{vol}\beta}$$

$$r_{in} = R_i || \left((1 + A_{vol}\beta) r_{in_{ol}} \right)$$

$$r_{out} = \frac{r_{out_{ol}}}{1+A_{vol}\beta}$$

From what you remember about parallel components, it should be fairly obvious that, for r_{in}, putting a resistor like 3.3 kΩ in parallel with a resistance in the gigaohms will result in $r_{in} \approx R_i$.

Now that you've seen these non-ideal formulas at work, you won't need them again (except for in an online quiz) -- they've just proved to us that our model is adequate for predicting the behaviour of op amps in circuit.