ENGR 206

Experiment 7
Operational Amplifiers, I

Objective

To experiment with operational amplifiers connected in inverting and non-inverting configurations. To gain an understanding of the effects of loading.

Introduction

Operational amplifiers (or “op amps” for short) are differential voltage amplifiers with very high open-loop gain, very high input impedance, and very low output impedance. They are commonly available in an integrated circuit (IC) package which comprises many transistors, diodes, resistors, and capacitors integrated onto a tiny silicon chip. Op amps are cheap, powerful, easy to use and extremely versatile. There are hundreds of different uses for op amps, and in this laboratory, we'll investigate some of the most common ones. As preparation for this laboratory, please read the excellent treatment of op amps given in Chapter 6 of Prof. Sergio Franco’s book, *Electric Circuit Fundamentals*, on which I’ve based a lot of the material presented here.

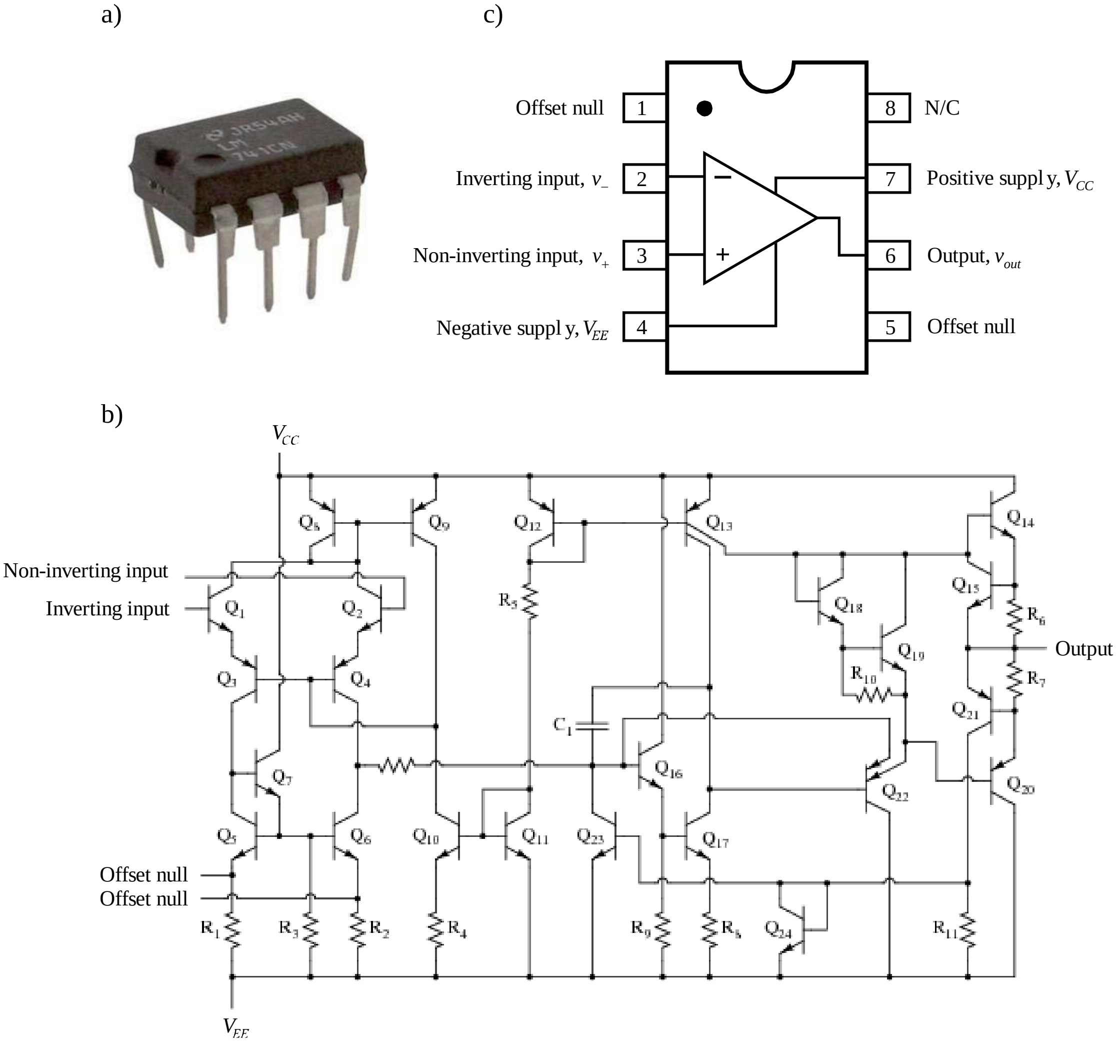


Figure 1: Op amp package and pin configuration

Figure 1a shows a picture of a typical op amp, the venerable type 741 that we'll be using in these experiments. The 741 is one of the earliest op amp designs, dating from 1968, and still one of the most utilized, finding its way into countless designs. The op amp comes in a plastic dual in-line package (DIP) with eight leads or pins whose 0.1" spacing will fit neatly into your breadboards. Just for your amusement/amazement, Figure 1b shows the internal schematic of the 741 pin configuration of the 741. Figure 1c shows the pin configuration of the 741. Pins are numbered counter clockwise from 1 through 8 starting on the top left of the package, which is generally marked by a little cutout and/or a dimple at the location of pin 1. There are five pin connections that we will always make. The op amp requires two regulated DC power supply voltages, a *positive supply*, V_{CC} , (pin 7) which is typically +15V; and a *negative supply*, V_{EE} , (pin 4) which is typically -15V. Since the power supply must always be applied in order for the op amp to work, its connections to the power supply pins are customarily omitted in a schematic diagram in order to avoid over-crowding the diagram. There are two signal inputs, a non-inverting input, v_+ , (pin 3) and an inverting input, v_- , (pin 2) and an output, v_O (pin 6). In addition to these five pins, there are two pins (1 and 5, labeled 'Offset null'), that permit the voltage output of the amplifier to be zeroed when the inputs are shorted together. We'll not bother with the offset null in this laboratory. Finally, pin 8 is not connected. The manufacturer's data sheet for the 741 is found here.

Analysis of the op amp

Figure 2a shows a simple circuit model of the op amp.

a) Op amp circuit model

b) Ideal op amp model

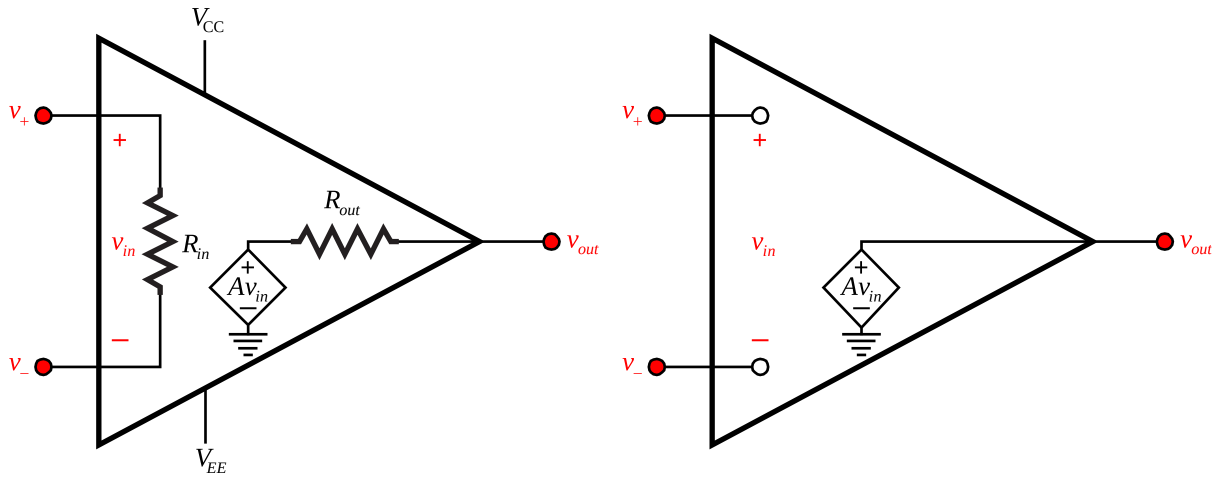


Figure 2: Op amp model

The op amp looks like a voltage-dependent voltage source whose output is the amplified difference between the non-inverting and inverting inputs, which is why is referred to as a differential amplifier:

$$v_{out} = Av_{in} = A(v_+ - v_-)\,, \tag{1}$$

where A is termed the *open-loop gain* of the op amp, and is typically enormous. For the 741, the open-loop gain is nominally 200,000. The 741 has a nominal input resistance of $R_{in} = 2\,M\Omega$ and a nominal output resistance of $R_{out} = 75\,\Omega$. More modern op amps can have open-loop gains exceeding 10^7 , input resistances exceeding $10^7\ \Omega$ and output resistances as low as $10\,\Omega$. In the limit as $A \to \infty$, $R_{in} \to \infty$ and $R_{out} \to 0$, we arrive at the model for the ideal op amp, shown in Figure 2b. In the analysis that follows, we'll assume that the op amp is ideal.

Notice that the op amp itself has no explicit, external ground connection. The ground of the dependent source in Figure 2 is taken to be the common ground of the two power supplies, V_{CC} and V_{EE} .

The output of the op amp is limited to the range $V_{EE} + \Delta v < v_o < V_{CC} - \Delta v$., where Δv is generally on the order of 1V. If an attempt is made to force the output outside of that range, the op amp will saturate; that is, it will pin at the limit of the range, either $V_{EE} + \Delta v$ or $V_{CC} - \Delta v$. Using Equation (1), you can quickly calculate that the largest voltage difference that can be presented to the input of the 741 without driving the output into saturation is

$$v_{in} = \frac{V_{CC}}{A} = \frac{15\text{V}}{200,000} = 75\,\mu V \,.$$

For the ideal op amp, where $A \to \infty$, the largest input voltage difference is 0V! What good is an amplifier with a huge open-loop gain if the maximum allowable input voltage swing approaches zero? The answer is that the op amp is never used in the open loop configuration; it is used in a *closed-loop* configuration with *negative feedback* between the output and the input, as we'll now discuss.

Figure 3 shows an ideal op amp in a negative feedback configuration. A voltage source, V_S , has been hooked up to the non-inverting input of the op amp so that $v_+ = v_s$. Two external resistors have been applied: R_1 goes from the inverting input to ground and R_2 is a *feedback resistor* that "feeds back" current from the output to one of the inverting terminal.

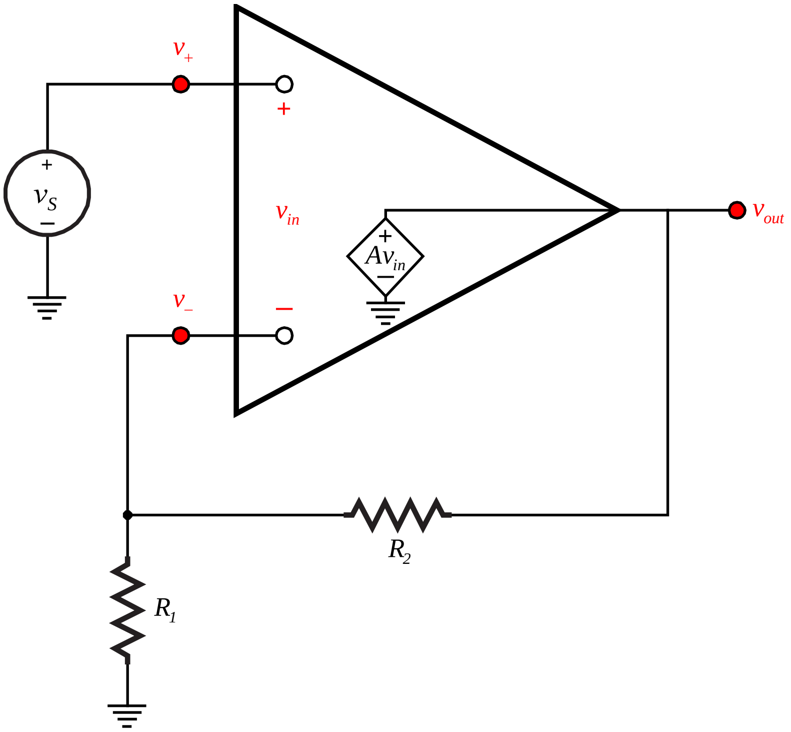


Figure 3: Op amp in feedback configuration

For the ideal op amp, the input impedence is infinite, $R_{in} = \infty$. Hence, no current flows into the input terminals of the device. The voltage at the non-inverting terminal is just v_s , and the voltage at the inverting terminal is given by the voltage divider relation:

$$v_- = v_{out} \frac{R_1}{R_1 + R_2} \,.$$

The output voltage, v_{out} , is A times the voltage difference:

$$v_{out} = Av_{in} = A(v_+ - v_-) = A\left(v_s - v_{out} \frac{R_1}{R_1 + R_2} \right).$$

Solving for v_{out} gives

$$v_{out} = v_s \frac{A}{1 + A\dfrac{R_1}{R_1 + R_2}}$$

Defining the *closed-loop gain*, *G*, as the ratio of v_{out} to v_s , we get

$$G = \frac{v_{out}}{v_s} = \frac{A}{1 + A\left(\dfrac{R_1}{R_1 + R_2}\right)}. \qquad (2)$$

You can see that for the ideal op amp, in the limit as $A \to \infty$,

$$\lim_{A\to\infty} G = \frac{1}{\left(\dfrac{R_1}{R_1 + R_2}\right)} = 1 + \frac{R_2}{R_1}. \qquad (3)$$

Because the sign of *G* is positive, this is termed the *non-inverting amplifier* configuration.

The key point here is that the closed-loop gain of the ideal op amp in the feedback configuration is completely determined by the values of the two external resistors! There are many other practical benefits to the feedback configuration that you may cover in lecture, including the insensitivity of *G* to variations in component parameters and non-linearities or to changes in the open-loop gain, *A*, due to manufacturing differences or changes in operating temperatures.

The "Golden Rules of Op Amps"

The analysis of circuits with ideal op amps in the feedback configuration is greatly simplified by application of the two *golden rules of op amps*:

1. The input terminals draw no current.
2. The output of the amplifier does whatever is necessary to make the voltage difference between the inputs zero.

The first rule follows from the fact that the input resistance of the ideal op amp is infinite ($R_{in} = \infty$), so no current can flow into the input terminals. The second rule deserves a few words. In response to an input voltage at the non-inverting terminal, $v_+ = v_s$, the output is

$$v_{out} = Gv_s = \left(\frac{R_1 + R_2}{R_1}\right)v_+ ,$$

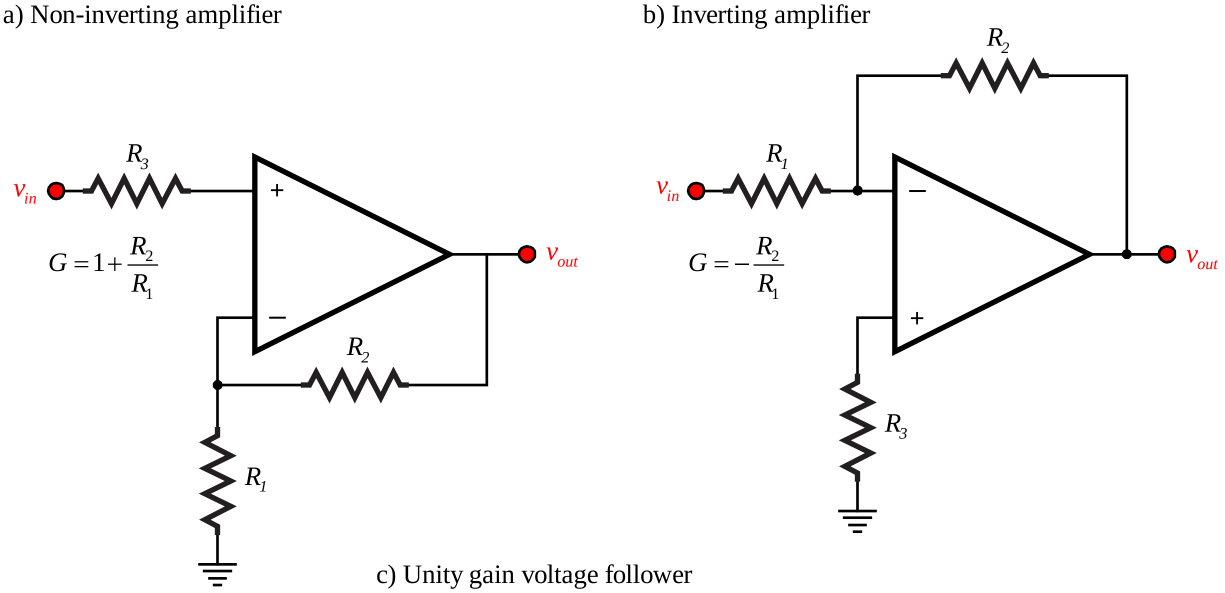
and hence the voltage at the inverting terminal is

$$v_- = \left(\frac{R_1}{R_1 + R_2}\right)v_{out} = \left(\frac{R_1}{R_1 + R_2}\right)\left(\frac{R_1 + R_2}{R_1}\right)v_+ = v_+ .$$

So, $v_+ = v_-$. Now consider what would happen if the output voltage were to rise slightly. The voltage at v_- would go up and thus the difference in the voltage of the input terminals, $v_+ - v_-$ would fall, which would bring the output voltage back down. The complementary situation would occur if the output voltage were to fall slightly. Thus, in the negative feedback configuration, the amplifier adjusts its output to make the voltage of the two input terminals equal.

Common op amp circuits

Figure 4 shows a number of common circuits built with op amps in the feedback configuration that we're going to explore in this laboratory. Given the two golden rules of op amps, we (i.e. you) can quickly analyze these circuits.


a) Non-inverting amplifier

b) Inverting amplifier

c) Unity gain voltage follower

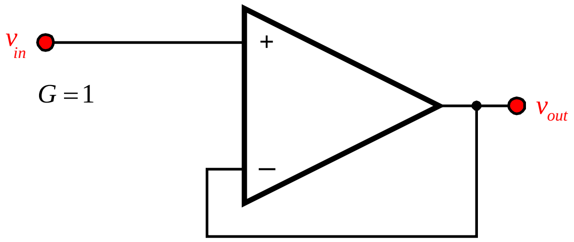


Figure 4: Op amp circuits

In this figure we've dispensed with the showing the "insides" of the op amp and just show its connections to the rest of the circuit with feedback provided by external components.

Non-inverting amplifier

We've already analyzed the non-inverting amplifier in conjunction Figure 3. The only difference between Figure 3 and Figure 4a is presence of the resistor, R_3, in Figure 4a at the input of the non-inverting terminal. This resistor does not affect the closed-loop gain, but does take care of a practical imperfection in a real op amp such as the 741. In any real op amp, a small amount of current, termed the *input offset current*, i_b, must flow into the each input terminal to provide the bias current for the transistors in the amplifier's input stage. In the 741, i_b is typically 20nA. That's a very small current, but it can have a measurable effect on the output. In the circuit of Figure 3, if the feedback resistors R_1 and R_2 connected to the non-inverting terminal are large, then i_b flowing into this terminal will produce a voltage drop, $\Delta v_- = i_b(R_1 \| R_2)$, which results in a voltage offset at the output of $G\Delta v_- = i_b R_2$. Since each input has roughly the same input offset current, the solution to this problem is to create a equal voltage drop at the non-inverting terminal: $\Delta v_+ = i_b(R_1 \| R_2)$. Then the differential effect of the input offset current on the output is zero. In our laboratory exercises, we really don't need to worry about the input offset current, but nevertheless, it's good circuit "hygiene" to learn to include them in your circuit design.

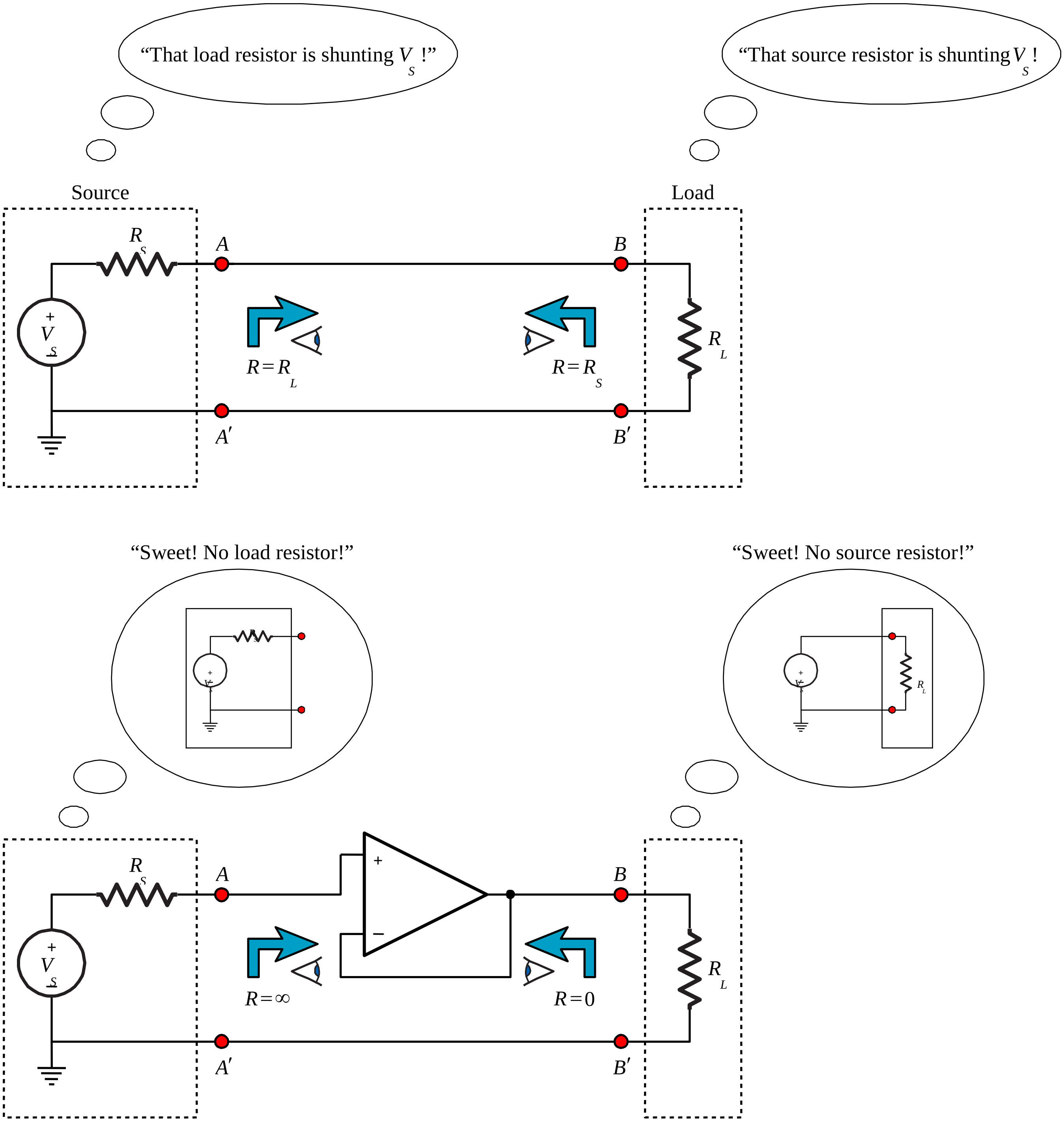


Figure 5: Use of follower to prevent loading

Inverting amplifier

For the inverting amplifier of Figure 4b, the second golden rule says that no current flows into either input terminal of the amplifier. Hence, the voltage at the non-inverting terminal is zero: $v_+ = 0$. Hence, the non-inverting terminal is effectively at ground. The first golden rule says that $v_- = v_+$, so the inverting terminal is also effectively at ground. We call this a *virtual ground*. The close-loop gain is found by applying KCL at the inverting input terminal under the assumption that the terminal is a virtual ground and that no current flows into the terminal. Then, the currents flowing into the terminal R_1 and R_2 must sum to zero:

$$\frac{v_{in}}{R_1} + \frac{v_{out}}{R_2} = 0\,,$$

which results in the close-loop gain,

$$G = \frac{v_{out}}{v_{in}} = -\frac{R_2}{R_1}\,.$$

As with the non-inverting amplifier, a resistor, $R_3 = R_1 \,||\, R_2$, is conventionally placed in series with the non-inverting terminal in order to reduce the effect of the input offset current.

Unity gain voltage follower

The unity gain voltage follower can be viewed as a non-inverting amplifier with $R_1 = \infty$ and $R_2 = 0$. Therefore, the closed-loop gain is $G = 1$! What's the point of an amplifier with a gain of one? The answer is that amplifiers have other functions than just providing voltage gain. The follower is an example of an amplifier being used to the prevent circuits from loading one another. Consider the circuit of Figure 5a. A source circuit, modeled by its Thévenin equivalent of a voltage source, V_S, in series with a resistance, R_S, is connected to a load, which is modeled by a resistor, R_L. In this circuit, we say that the source "sees" a load resistance of $R = R_L$ and the load "sees" a source resistance of $R = R_S$. From the point of view of the source, the load resistor causes the voltage at the output of the source (between terminal *A* and ground) to be shunted (i.e. to be less than V_S), because R_L and R_S form a voltage divider:

$$V_A = V_S \frac{R_L}{R_S + R_L}\,.$$

From the point of view of the load, there is a voltage drop across the source resistance, which causes the voltage across the load resistor (between terminal *B* and ground) to be less than V_S:

$$V_B = V_S \frac{R_L}{R_S + R_L}\,.$$

Of course, since terminals *A* and *B* are connected with a wire, $V_A = V_B$. Now consider what happens if we interpose a voltage follower between the source and the load, as shown in Figure 5b. The input resistance of the ideal op amp is effectively infinite, so the source now "sees" a load resistance of $R = \infty$. Since no current flows into the input of the op amp, no current flows through R_S and $V_A = V_S$. Furthermore, because the output resistance of the ideal op amp is zero, the load effectively "sees" voltage source V_S connected via a source resistance of $R = 0$, and hence $V_B = V_S$. This example shows that the voltage follower can be used to isolate or "decouple" circuits or parts of circuits from each other.

Laboratory work

1. <u>Set up op amp circuit</u>. A neat and clean op-amp setup can help you prevent wiring errors.
   a. Before you connect the power supply to anything, turn it on and adjust the ±25V outputs to ±15V. Then turn the power off while you connect the op amp.
   b. Figure 6a shows the pin configuration of the 741 op amp. In all circuits, pin 4 of the op amp will be connected to -15V and pin 7 to +15 volt.
   c. The ground connections of elements in the circuits should be attached to the COM terminal of the power supply.
   d. There's one additional step you have to take: "bypass" the power supply. Although the DC power supply that provides the ±15 V to the op amp is well regulated, there are numerous sources of AC noise that can end up coupling into your op amp through the power supply leads, which are just unshielded lengths of wire. The solution is to place a relatively sizable bypass capacitor – $0.1\mu F$ is typical – between each power supply pin and ground, as shown in Figure 6a . The bypass capacitors don't affect the DC voltage, but do attenuate the AC noise.

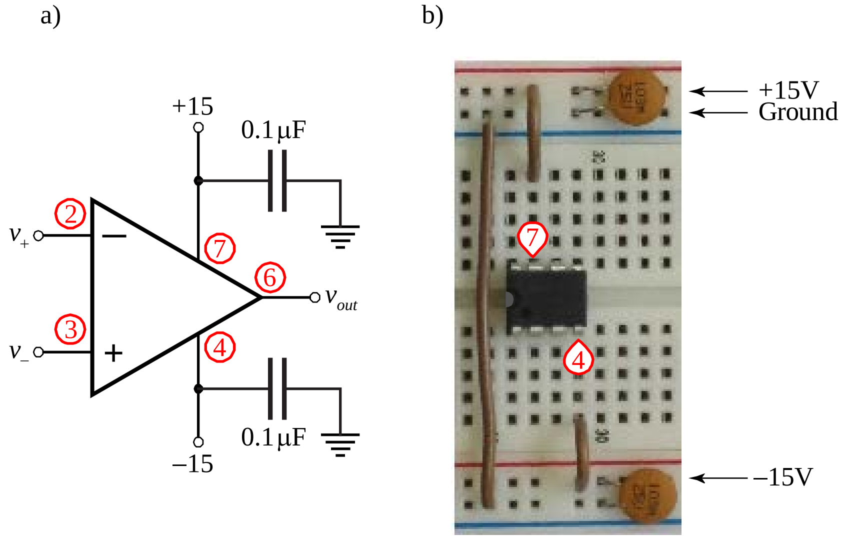


Figure 6: Op amp connections

Figure 6b shows a tidy way of connecting your op amp to the circuit board that keeps the power supply and ground connections out of the way of the other leads and components. Connect the top rail of pins near the red line to the +15V supply and the bottom rail of pins nearest the red line to the -15V supply. Connect the blue lines together and to the COM terminal of the power supply, which acts as the ground for all circuits in this laboratory. You can make your connections between the ±15 and ground of the circuit board and the power supply just using two-foot-long pieces of wire, which will free a bunch of your cables, alligator clips and push-hooks for other purposes.

2. <u>Non-inverting amplifier</u>. In this part, you will measure the gain of a non-inverting amplifier in response to DC and AC signals and compare it to the theoretical gain.
   a. Assemble the non-inverting amplifier circuit shown in Figure 4a with $R_1 = 10\,K\Omega$, $R_2 = 5.1\,K\Omega$ and $R_3 \approx R_1 \,||\, R_2 = 3.3\,K\Omega$ in order to reduce the effect of the input offset current. Obtain $v_{in} = 5\text{V}$ from the +6V supply.
   b. Measure v_{in} and v_{out} with a voltmeter and determine the closed-loop circuit voltage gain, *G*. How does the value of *G* that you get compare with the gain predicated from Equation (3) with the nominal resistor values?
   c. If the discrepancy between the predicted and measured gain is larger than 5%, it is very likely due to resistor tolerance. Pull resistors R_1 and R_2 out of the circuit and measure them using the ohmmeter. Recompute the theoretical gain using the measured resistor values and compare with the measured gain. Does your result

suggest that the “ideal op amp” gain formula for G (Equation (3)) is a good approximation to the actual gain (Equation (2))?

   d. Now apply a 1-kHz sinusoidal (AC) signal of 1V peak amplitude, 0V DC offset as the input voltage, v_{in} , of the circuit using a BNC-to-alligator cable. Also attach this input to Ch1 of the scope using a BNC cable and a T-splitter and attach the output of the circuit (v_{out}) to Ch2 of the scope. Use the scope to monitor v_{in} and v_{out} simultaneously. Make sure the signal inputs to the scope are both DC coupled. Adjust the horizontal sweep rate so that you see at least a couple of cycles of the waveforms on the display. You may find it useful to adjust the vertical position of the two waveforms to be the same. Set the scope to trigger on v_{in} (Ch1) and make the triggering AC Coupled. (Remember that the AC coupling of the triggering is set separately from the DC coupling of the signal inputs to the scope)
   e. Compute is the observed AC voltage gain. To assist you, you may wish to use the ‘Acquire’ menu to average the waveforms to reduce noise, and use the ‘Measure’ menu to measure the peak-to-peak voltage of the two channels. Is there any difference between the AC gain and the DC gain of the previous part? What can you say about the phase relationship between the two waveforms? Save the display with the two waveforms for your report.

3. Inverting amplifier.
   a. Assemble the inverting amplifier circuit of Figure 4b with $R_1 = 5.1K\Omega$, $R_2 = 10\,K\Omega$ and $R_3 \approx R_1 \| R_2 = 3.3K\Omega$.
   b. Repeat parts 2d and e to measure the AC gain of the inverting amplifier in response to a 1-kHz sinusoidal signal of 1V peak amplitude.
   c. Leave $R_2 = 10\,K\Omega$ unchanged but select a new value of R_1 such that the predicted gain would be -10. Display both input and output waveforms on the scope and measure their peak-to-peak values. What is the observed gain? Does it match your prediction?
   d. Gradually increase the amplitude of the input, v_{in} . Notice that at some point, the output begins to saturate. At what value of v_{in} does this saturation begin? What’s the explanation?
   e. Reduce the amplitude of v_{in} to 1V peak. Now gradually increase the DC offset of the function generator and observe the output waveform until it clips. Repeat for negative offset. Explain what is going on.
   f. When the offset of v_{in} is adjusted to 0.1V, what will the DC reading of the output be? Why? (You can use the scope to measure the mean value, which will be the DC)

4. Effect of loading.
   a. Assemble the circuit of Figure 7a. For now, points ‘A’ and ‘B’ should just be connected by a wire, ‘W’. We’ll modify this in the next part.
   b. Apply 5V to point ‘A’ from the +6V DC power supply output and measure the output voltage, v_{out} . Does it agree with what you would predict for an amplifier in the inverting configuration given the values of the components?
   c. Next, add the $39\,K\Omega$ resistor in series with the voltage source as shown in Figure 7b. The circuit in the dotted box now represents the Thévenin equivalent of an input device that has a Thévenin equivalent voltage of +5V and a Thévenin equivalent resistance of $39\,K\Omega$. Measure and record the voltage at point ‘A’ and the output voltage, v_{out} . Do these values agree with the values from part b)? Probably not. Give a detailed explanation of what is happening, including a theoretical calculation of what you should expect to measure at point ‘A’ and v_{out} .

5. Voltage follower.
   a. Do not disassemble the circuit of Figure 7b, but remove the wire ‘W’.
   b. Assemble a second op amp circuit as unity gain voltage follower, as shown in Figure 4c. Measure the gain of just this second circuit and you'll find that it is unity: the output simply follows the input. In this part, we are trying to answer the question, “Why waste an entire amplifier if it is not doing any amplification?”
   c. Connect the voltage follower between points ‘A’ and ‘B’, as shown in Figure 7c.
   d. Measure the voltage at point ‘A’ and v_{out} , and compare these values with those that you obtained in step 4b and 4c. Comment on the results. What function(s) did the voltage follower serve?

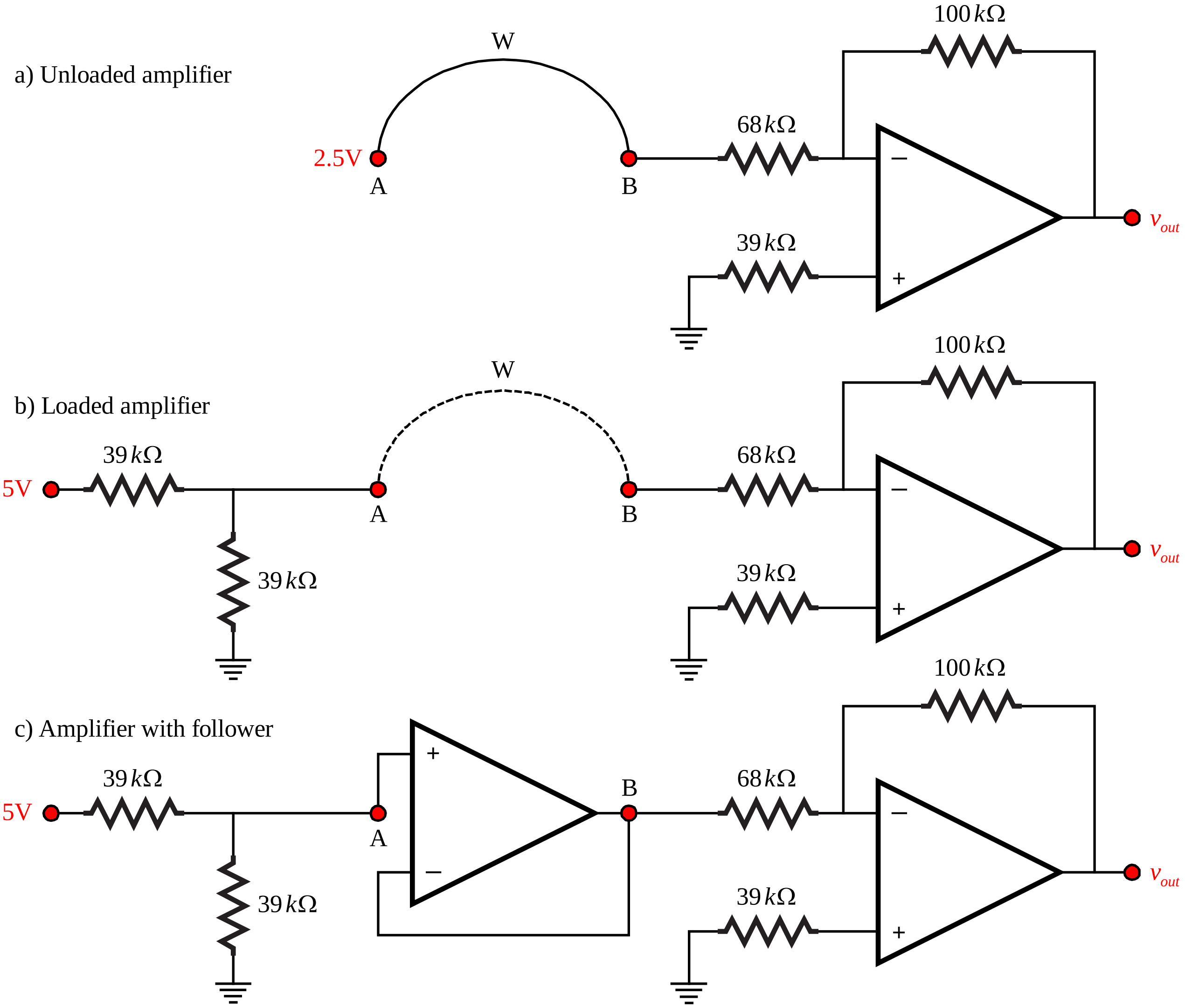


Figure 7: Op amp loading