California State University, Fresno
Department of Electrical and Computer Engineering

ECE 90L Principles of Electrical Circuits Laboratory
Experiment No. 7: Operational Amplifiers

Objective

The operational amplifier (op amp) has many applications in electronics. In this experiment you will gain experience using op amps.

Prelab

The op amp (operational amplifier) is a standard integrated circuit that is commonly used in analog electronics. In this experiment, we will use the LM741 op amp. There are many different op-amp chips available on the market, but all of them work in a similar way to the LM741.

Figure 1 shows the diagram used to represent an op amp in a circuit schematic. There are two signal inputs: the inverting input and the non-inverting input. There is one signal output. The inverting input is labeled with a minus ($-$) sign in the diagram, and the non-inverting input is labeled with a plus ($+$) sign. These two inputs play different roles, so it is essential to be always mindful of which input is which. In a circuit schematic, the inverting input might appear on top or on bottom, as indicated in Figure 1.

When we connect an op amp into a circuit, we will also apply two DC sources to the op amp. Figure 2 shows what this looks like. A positive DC voltage V^+ (relative to ground) will be applied to pin 7 of the op amp package. A negative DC voltage V^- (relative to ground) will be applied to pin 4 of the op amp package. In this experiment, we will use

$$V^+ = 12 \text{ V, and } V^- = -12 \text{ V.}$$

In general, we have flexibility in choosing V^+, but 12 V is a typical value. Also, in general, V^- will not necessarily equal $-V^+$. In our experiments in this laboratory, we will always choose $V^- = -V^+$.

Associated with the DC supply voltages V^+ and V^- ($V^- = -V^+$) are the related voltages V_{rail} and $-V_{\text{rail}}$, which are called the “rails”. The relationships among these voltages are illustrated in Figure 3. V_{rail} is somewhat smaller than V^+ (and therefore $-V_{\text{rail}}$ is somewhat larger than V^-). The output voltage v_0 of the op amp is constrained by:

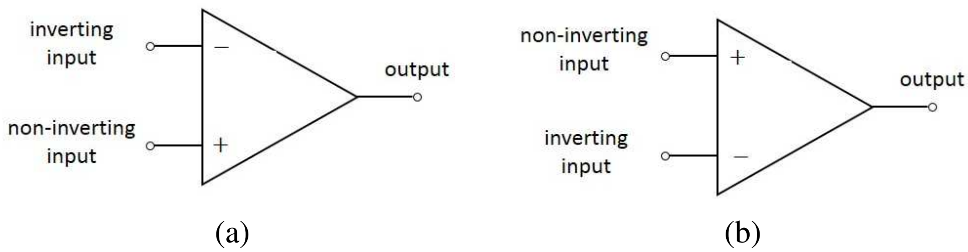


Figure 1: (a) Op-amp diagram and (b) another op-amp diagram

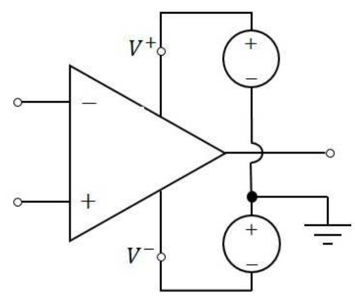


Figure 2: Op amp with DC sources connected

$$-V_{\text{rail}} \leq v_0 \leq V_{\text{rail}}$$

The value V_{rail} depends on V^+. If you were to increase V^+ from 12 V to 13 V, for example, V_{rail} would increase by approximately 1 V.

In circuit schematics we don't usually show the DC power supply connections to the op amp. This is because we are trying to make the schematics as uncluttered and intuitive as possible. But, of course, it is important to bear in mind that the DC power supply connections must be in place for the circuit to work.

When a *non-zero* voltage difference is applied to the two signal inputs of an op amp, the output voltage v_0 will be at one of the two rails. v_d is the non-inverting input voltage minus the inverting input voltage. If $v_d > 0$, $v_0 = V_{\text{rail}}$. If $v_d < 0$, $v_0 = -V_{\text{rail}}$. Figure 4 illustrates this.

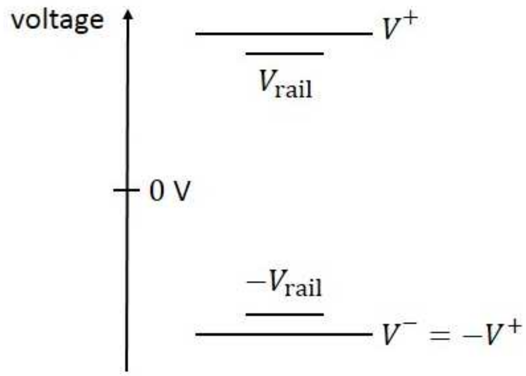


Figure 3: $V^- < -V_{\text{rail}} < V_{\text{rail}} < V^+$

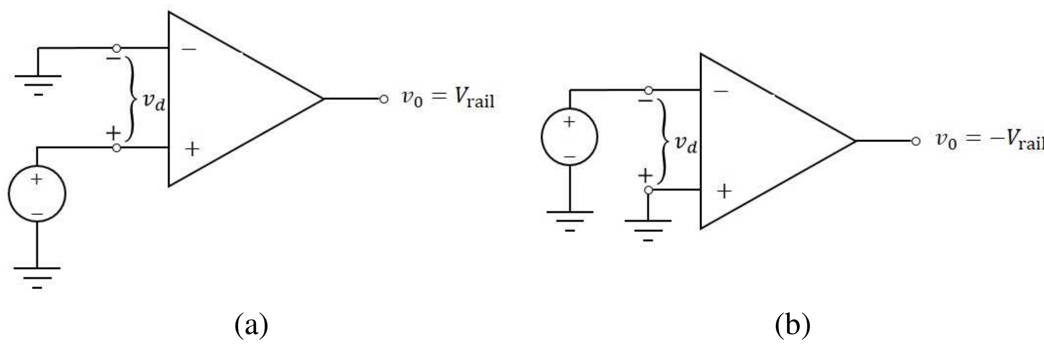


Figure 4: Op-amp output voltage v_o when (a) $v_d > 0$, and (b) $v_d < 0$

Most of the time we will use negative feedback with an op amp. Figure 5 shows a circuit employing an op amp that is connected for negative feedback. The circuit of Figure 5 is an inverting amplifier. An input signal voltage v_i is applied to a resistor R_i, which is connected to the inverting input of the op amp. The resistor R_f connects the op amp output to the inverting input. Negative feedback is defined for an op amp as an external (*i.e.*, outside the op-amp chip) electrical connection between the op-amp output and the inverting input. In the case of the inverting amplifier of Figure 5, the feedback path consists of the resistor R_f.

In general, an op amp that is connected for negative feedback may have a resistor in the feedback path, or a simple conductor, or something more complicated, such as a parallel combination of a capacitor and a resistor. We will not examine *positive* feedback, for which there is an external electrical connection between the output and the *non-inverting* input.

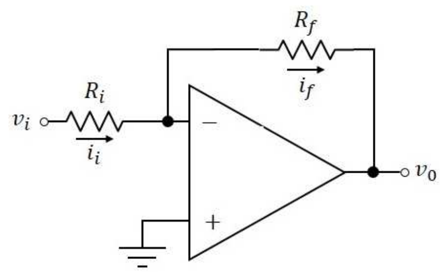
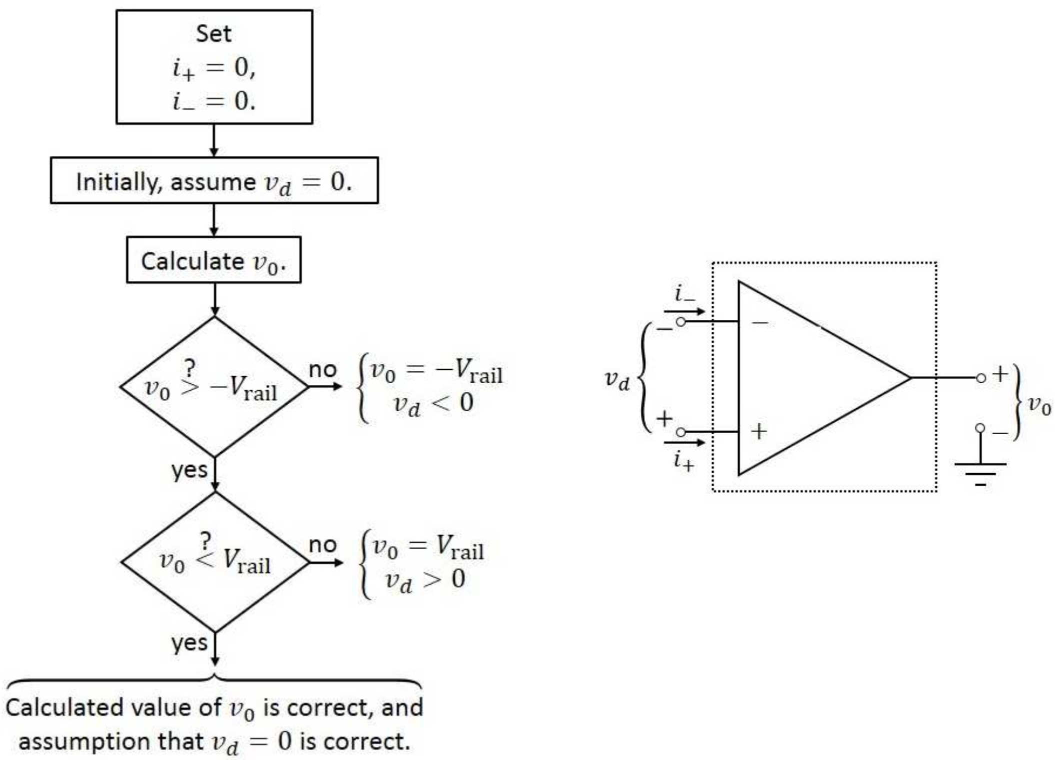


Figure 5: Inverting amplifier



(a) (b)

Figure 6: (a) Flow chart for analysis of op-amp circuit having negative feedback, and (b) definitions of the variables i_+, i_-, v_d, and v_0.

For an op-amp circuit with negative feedback we can use the flow chart of Figure 6 (a) to find the output voltage v_0. The variables i_+, i_-, v_d, and v_0 used in the flow chart are defined in Figure 6 (b). We can summarize the procedure for finding v_0 as follows. No current enters the inverting and non-inverting inputs of the op amp. Initially, we assume that the two signal inputs to the op amp have the same voltage. (This assumption will sometimes be proved incorrect. More on that later.) With that combination of starting facts and initial assumption, it is generally possible to calculate v_0. If the calculated v_0 lies between the rails ($-V_{\text{rail}} < v_0 < V_{\text{rail}}$), then we

(a) (b)

Figure 7: When operating a train, we want its center of gravity to pass (a) between the rails, and not (b) through a rail.

have our solution. However, if the calculated v_0 lies outside the bounds $-V_{\text{rail}}$ to V_{rail}, then the true value for v_0 does not equal the calculated v_0 and v_d does not equal 0. If the calculated v_0 is less than $-V_{\text{rail}}$, then the true v_d is negative and the true v_0 is $-V_{\text{rail}}$. If the calculated v_0 is greater than V_{rail}, then the true v_d is positive and the true v_0 is V_{rail}.

Our expectations for an op-amp circuit with negative feedback is something like that for a train: we generally expect to be between the rails, not on one of the rails. See Figure 7.

As an example of how to use the flow chart of Figure 6, we consider the inverting amplifier of Figure 5. We assume that $v_d = 0$, so the voltage at the inverting input is 0 relative to ground. The currents i_i and i_f are therefore:

$$i_i = \frac{v_i - 0}{R_i},$$

$$i_f = \frac{0 - v_0}{R_f},$$

Since $i_- = 0$, Kirchhoff's Current Law tells us that $i_f = i_i$. Therefore, as long as $v_d = 0$ and $-V_{\text{rail}} < v_0 < V_{\text{rail}}$:

$$\frac{-v_0}{R_f} = \frac{v_i}{R_i},$$

or

$$v_0 = \frac{-R_f}{R_i} \cdot v_i.$$

This is called an inverting amplifier because v_0 has the opposite sign from v_i. The gain of this circuit, defined as v_0/v_i, equals $-R_f/R_i$.

For the inverting amplifier, if the calculated v_0 is less than $-V_{\text{rail}}$, then we override the calculation and identify v_0 as equal to $-V_{\text{rail}}$. The assumption $v_d = 0$ in this case proves to be incorrect (because it leads to a value for v_0 that is less than $-V_{\text{rail}}$). If we want to know the true value for v_d in this case, we can proceed as follows. We treat v_d as a variable, set v_0 to $-V_{\text{rail}}$, and then solve for v_d. Since the voltage at the non-inverting input is 0 relative to ground, the voltage at the inverting input is $-v_d$. When $v_0 = -V_{\text{rail}}$ the currents i_i and i_f are

$$i_i = \frac{v_i - (-v_d)}{R_i}$$

$$i_f = \frac{-v_d - (-V_{\text{rail}})}{R_f}.$$

Since $i_f = i_i$,

$$\frac{-v_d + V_{\text{rail}}}{R_f} = \frac{v_i + v_d}{R_i},$$

and solving for v_d,

$$v_d = \frac{-R_f v_i + R_i V_{\text{rail}}}{R_i + R_f}.$$

You might like to know where the current i_f goes for the circuit of Figure 5. The current i_f passes through R_f, enters the output terminal of the op amp, and follows a path that leads to ground; this happens through the DC power supply's ground connection (and *not* through the non-inverting input, since $i_+ = 0$).

Some students will look at an op amp diagram and think that the current entering or leaving the op amp's output terminal must be zero. Figure 8 (a) illustrates this thinking. We can draw a dotted boundary around an op amp, defining a closed surface. One version of Kirchhoff's Current Law states that the current leaving a closed surface must sum (algebraically) to zero. Since both i_+ and i_- are zero, Figure 8 (a) seems to suggest that i_0 (the current leaving the op-amp's output terminal) must also be zero. But this thinking is wrong. You should recall that an

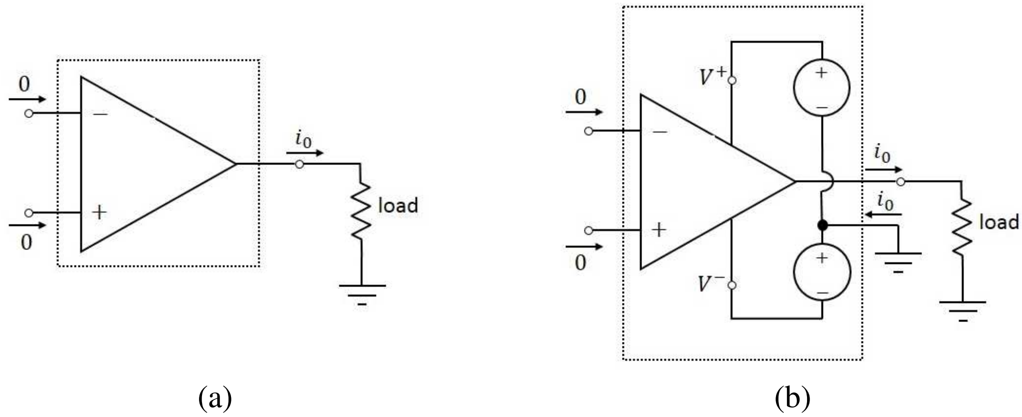


Figure 8: (a) Does i_0 equal 0? (b) No. Don't forget about the DC power supplies and the connection to ground.

op amp has (at least) five electrical connections, and not just three. Figure 8 (b) shows these five electrical connections, including a positive DC voltage V^+ and a negative DC voltage V^-.

When we examine the complete electrical picture of Figure 8 (b), we see that there are really four lines that pierce the closed surface that we have drawn: the inverting input, the non-inverting input, the output, and the connection to ground (which we associate with the DC power supply). We can see now that the current i_0 leaving the op amp's output terminal need not equal zero. However, an equal amount of current must enter the closed surface through the ground connection. (Of course, the current could go the other way. Current could enter the op-amp's output terminal, and an equal current would pass to ground.)

A non-inverting amplifier is shown in Figure 9. This circuit's output voltage v_0 has the same sign as the input voltage v_i. (Here v_i is the voltage of the non-inverting input relative to ground.) Notice that in the circuit schematic of Figure 9 the non-inverting input is on top, unlike in previous schematics. This circuit, like the inverting amplifier, has negative feedback.

Exercise: For the non-inverting amplifier of Figure 9, find an expression for the output v_0 as a function of the input v_i. (The parameters R_a and R_b should also appear in your expression.) You only need to consider the case where $-V_{\text{rail}} < v_0 < V_{\text{rail}}$.

Exercise: For the non-inverting amplifier of Figure 9, assume that $v_0 = V_{\text{rail}}$ and write an expression for v_d as a function of v_i. (The parameters R_a, R_b, and V_{rail} should also appear in your expression.)

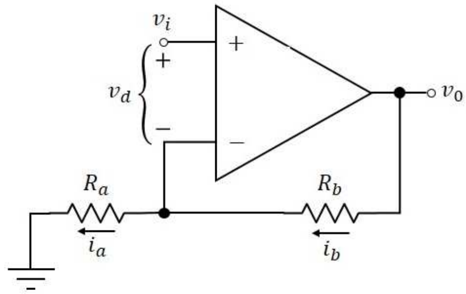


Figure 9: Non-inverting amplifier

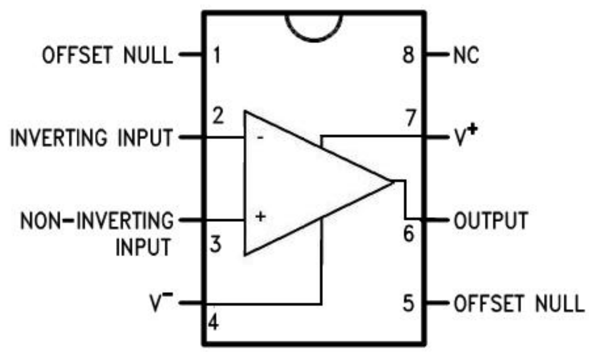


Figure 10: LM741 pin-out

The op amp is an *active* device. This means that one or more power supplies are attached to it, making it possible for the op amp to increase the signal power. The conservation of energy is not violated: the extra power added to the signal comes from the power supply. Resistors, capacitors and inductors, by contrast, are *passive* devices.

Procedure

The op-amp chip that you will be using, the LM741, comes in an 8-pin DIP (dual in-line package, which refers to the two rows of pins). The pins are not labeled on the chip, but you can identify the pins with the help of Figure 10. Place the op amp on the solderless breadboard, so that no two pins are connected underneath the plastic surface of the solderless breadboard. Figure 10 shows the locations of all pins, relative to the notch between pins 1 and 8.

Configure the Siglent DC power supply to be the source of $+12$ V for pin 7 and -12 V for pin 4. But do not apply live voltages to the op amp until ready to make measurements. Set the maximum current to 0.2 A for both sources. Place the DC power supply in series mode. Set the CH1 voltage to 12 V, causing the CH2 voltage to be 12 V also. Connect the CH2 $-$ terminal, which is internally connected to the CH1 $+$ terminal while in series mode, to ground. With this configuration, the CH2 $+$ terminal is at $+12$ V relative to ground and the CH1 $-$ terminal is at -12 V relative to ground.

Turn off CH1 and CH2. Connect the power supply's CH2 $+$ terminal to pin 7 and the CH1 $-$ terminal to pin 4.

Rails

Experimentally determine the positive and negative rails, using the procedure that follows. Set the Siglent third source to 5 V. With all sources turned off, connect the $+$ terminal of the third source to the non-inverting input (pin 3). Connect the $-$ terminal of the third source to ground. Connect the inverting input (pin 2) to ground. Your connections should match Figure 4 (a). Turn on all sources and measure V_{rail} at the op amp's output terminal using the multimeter.

Measure the negative rail using the circuit of Figure 4 (b). You should use 5 V for the source connected to the inverting input. The negative rail might not equal *exactly* $-V_{\text{rail}}$ (the negative of the positive rail), but it should be close to that value.

Sinewave Input

You will now use a signal from the synthesized frequency generator as an input to the op amp, but the output of this generator typically has a DC bias. Set the synthesized frequency generator to produce a 1-kHz sinewave with an amplitude of 5 V. You should minimize the DC bias of the synthesized frequency generator. You can minimize the DC bias by adjusting the Offset knob of the generator (with the knob in the pulled-out position) while observing the generator output on the oscilloscope (using DC coupling).

Place the sinewave at the non-inverting input of the op amp. Connect the inverting input to ground. With ± 12 V applied to the op amp, observe the sinewave input on channel 1 and the op amp's output on channel 2 of the oscilloscope.

Inverting Amplifier with DC Input

Build the inverting amplifier of Figure 5. Use a 10.0-kΩ fixed (color-coded) resistor for R_i. Use a precision, adjustable resistance from a resistance decade box for R_f. (You will be adjusting the value of this resistance.) Initially, set R_f to 10.0 kΩ. Use $V^+ = 12$ V, and $V^- = -12$ V, so that the rails have the values that you already measured. Set v_i to 5 V, using the third source. The $-$ terminal of the third source should be connected to ground, as should the non-inverting terminal.

You will be setting R_f to several different values, but R_i will remain 10.0 kΩ. For each value of R_f, you will make two voltage measurements: the output voltage v_0 and the inverting input voltage v_-. For each measured value of v_-, you will calculate v_d as follows:

$$v_d = -v_-$$

(v_d is defined to be the non-inverting input voltage minus the inverting input voltage, and for this circuit the non-inverting input voltage is 0.)

Use 16 values for R_f: 10.0 kΩ to 25.0 kΩ, in 1-kΩ increments. Record v_d and v_0 for each value of R_f.

Inverting Amplifier with AC Input

You will use a 1-kHz sinewave with amplitude 5 V as input to the inverting amplifier. With R_f initially set to 10.0 kΩ, place the sinewave (with no DC bias) where v_i should be applied, replacing the 5-V DC source that you previously used. You will observe v_i on channel 1 and v_0 on channel 2. Use the multimeter to measure the rms value of v_i and the rms value of v_0. Calculate the absolute value of the gain.

Change R_f to 18.0 kΩ. Calculate the absolute value of the gain from rms voltage measurements.

Change R_f to 26.0 kΩ. Observe v_i and v_0 on the oscilloscope.

Non-Inverting Amplifier with DC Input

Build the non-inverting amplifier of Figure 9. Use a 10.0-kΩ fixed (color-coded) resistor for R_a. Use a precision, adjustable resistance from a resistance decade box for R_b. Initially, set R_b to 5.0 kΩ. Use $V^+ = 12$ V, and $V^- = -12$ V. Set v_i to 5 V, using the third source.

You will be setting R_b to several different values. For each value of R_b, you will make two voltage measurements: v_0 and v_d.

Use 11 values for R_b: 5.0 kΩ to 15.0 kΩ, in 1-kΩ increments. Record v_d and v_0 for each value of R_b.

Non-Inverting Amplifier with AC Input

You will use a 1-kHz sinewave with amplitude 5 V as input to the non-inverting amplifier circuit of Figure 9, with $R_a = 10.0$ kΩ and with a precision, adjustable resistance for R_b. With R_b initially set to 5.0 kΩ, place the sinewave (with no DC bias) where v_i should be applied, replacing the 5-V DC source that you previously used. You will observe v_i on channel 1 and v_0 on channel 2. Use the multimeter to measure the rms value of v_i and the rms value of v_0. Calculate the gain.

Change R_b to 15.0 kΩ. Observe v_i and v_0 on the oscilloscope.

Lab Report

For the inverting amplifier with a constant 5 V on the input, plot v_0 as a function of R_f. This figure should contain both a solid curve for the theory and discrete points for your measured data. In a separate figure, plot v_d as a function of R_f. This figure should contain both a solid curve for the theory and discrete points for your measured data.

For the non-inverting amplifier with a constant 5 V on the input, plot v_0 as a function of R_b. This figure should contain both a solid curve for the theory and discrete points for your measured data. In a separate figure, plot v_d as a function of R_b. This figure should contain both a solid curve for the theory and discrete points for your measured data.