Lab 4: Basic Op-Amp Circuits

4.1 Objective

The objectives of this lab are gain familiarity with operational amplifiers, read and understand terms related to the parameters of operational amplifiers from its data-sheets, and learn to measure and understand limiting factors to op-amp operation.

4.2 Pre-Lab Preparation

Read the lab overview in section 4.3 and answer the questions below. The instructor is to review your answers before you begin the lab tasks.

1. Download the LM741 specifications from the course web site. For the LM741C, tabulate the typical and maximum (if given) input offset voltage, input offset current, input bias current, input resistance, and slew rate. Include units in your table!

2. Label all op-amp diagrams in this lab writeup with correct pin numbers on all input/output and power supply signals.

Come prepared to work efficiently. There are a lot of circuits to build. Also, if you have one handy, bring a large mongoose. You never know…

4.3 Background

Operational Amplifiers: Operational amplifiers, or op-amps for short, got their name from the modules used in analog computers to perform “operations” such as adding, multiplying and so forth. Now they are integrated circuits for application as general feedback amplifiers. They seem easy to use, but the many types available and the great variety of ratings hint that their use requires considerable knowledge and skill, which is true. In this lab and the next, we will examine a dozen or so circuits that will give a good understanding of how to use op-amps in various applications.

The power supply for an op-amp is normally bipolar, with voltages above and below ground, called $V_+$ and $V_-$. Most common op-amps can stand up to 36 V, or $\pm18$ V. It is convenient for our experiments to use $\pm15$ V, but $\pm12$ V and even $\pm9$ V will also work, (the latter are usually available from multi-output power supplies). You can always arrange a bipolar supply from two ordinary supplies. Ground in this case is merely a voltage between the supply “rails”, as they are called, of no special significance. Op-amps have no ground terminal, since this reference is unnecessary. If you have trouble remembering polarity, have lots of op-amps around, since they are instantly destroyed by any mistake. (Just kidding. Sort of. Don’t be burning up my op-amps!)

The pinouts of several common op-amps are shown in Fig. 4.1. They are packaged in standard “dual-inline-packages” (DIP) with 0.1” spacing between pins and 0.4” spacing between one row of pins and the other. You can identify which is pin 1 by the indent on the top of the actual IC, which corresponds to the indent drawn in the
The figure shows the op-amp from the top, with pins numbered from upper left, down one side and up the other to upper right, according to standard convention. The 411 uses JFET-type transistors in its input stage, and is quite suitable for our purposes. The 741 uses bipolar-type transistors, long a standard. These two op-amps can be used interchangeably in most circuits. The dual 411 is the 412, and the dual 741 is the 1458. The 351 is another popular JFET-input op-amp. The actual part numbers of a 741 op-amp, for example, are often preceded with letters like “LM” and followed by other letters, like “CN”. These distinguish one flavor of the 741 op-amp from another, each having slightly different specifications, but overall the same pinout and design. We will simply refer to the basic type of op-amp by its number.

![Op-amp pinouts](image)

**Figure 4.1 Op-amp pinouts.**

The connections marked + and − are the inputs to the op-amp, and the connection from the point of the triangle is the output. The output can go from a value near \( V_+ \) to a value near \( V_- \). When the output is near one of these limits and can go no farther, it is said to be saturated. You can short-circuit an output if you want, since it is internally protected against too much current. On the other hand, the output will handle only up to about 20mA at best. Op-amps are not for power applications, but can drive a power amplifier (usually transistors) if power is needed. The output is proportional to the difference in voltage \( v_+ - v_- \) between the two inputs, where \( v_+ \) is the voltage at the + or non-inverting input, and \( v_- \) the voltage at the − or inverting input. The voltage gain of the amplifier is perhaps 100,000 or 100 dB at low frequencies for open-circuit operation (no feedback).

With such a gain, the voltage difference between the inputs must be very small if the output voltage is not to be at saturation. This amounts to a rule: the voltages at the inputs are equal when a circuit is working properly. In order to make the voltages at the inputs equal to each other, it is necessary to arrange this by feedback. (Essentially) all op-amp circuits use feedback, and the properties of the circuit are determined by the feedback, not by the properties of the op-amp.

The common-mode input signal is the average of the potentials of the two input connections. Since they are usually at the same voltage, this voltage is the common-mode input voltage. The op-amp ignores the common-mode input, and determines its output only by the difference signal. Nevertheless, it is important to look at the common-mode input voltage and see that it does not leave its permissible range. The common-mode range of an op-amp is almost always less than from \( V_+ \) to \( V_- \), and the op-amp usually does something unpleasant when the range is exceeded (the 411, for example, goes from a large negative output suddenly to a large positive output when this happens).

That the inputs are usually at the same voltage does not mean that they can be connected to each other. If you do this, the output usually saturates. The voltages must be held equal by the active participation of the output, acting through the feedback network. The inputs also carry a small dc bias or leakage current that must have a route to the power supply. With bipolar op-amps, this current is actually the base bias current for the input transistors, and sometimes has to be considered in the circuit design. JFET’s, on the other hand, have a much smaller input current that is largely leakage, and does not affect the circuit much—except that it has to have a route to ground. In ordinary circuit analysis, the bias currents can be neglected, and it can be assumed that the inputs carry no current. Don’t forget that this is only approximate!
The most important factor hidden from the casual user of op-amps is the question of stability. Stability is always important with high-gain amplifiers, and when feedback is applied. The feedback loop can become the route for a signal to be fed back to the input in the proper phase to cause oscillation, called instability. Without some care, feedback always results in instability, which is always fatal. The oscillation can occur either at a higher or a lower frequency than that for which the circuit is designed, usually higher (like the feedback with a microphone and speaker). With ordinary op-amps (e.g., 741), stability is guaranteed by making the gain fall off at 20 dB per decade of frequency, beginning at about 10 Hz, so that the gain of the amplifier falls to unity at around 1 MHz. Unless you have capacitors in unfortunate places, this guarantees that the circuits you put together will be stable, no matter what you do. What you pay for this is a severe restriction on the bandwidth of op-amp circuits, and overcoming it is advanced work.

**Op-Amp Specifications: Reading the data sheet.** When you download the “data sheet” for an op-amp (a technical publication describing a device’s function, ratings, and limitations), you will see quite a number of parameters of the device described. You should understand how to read a data sheet and discover the information that you need. *Absolute Maximum Ratings* tabulate factors that the op-amp can safely tolerate without the possibility (likelihood?) of destroying it. However, it is generally recommended that you operate a device at 75% or less of its maximum ratings.

- Supply Voltage ($\pm V_S$): The maximum positive and negative voltages that can be used to power the op-amp.
- Power Dissipation ($P_d$): The maximum power the op-amp is able to dissipate, at ambient temperature.
- Differential Input Voltage ($V_{id}$): This is the maximum voltage that can be applied across the $+$ and $-$ inputs.
- Input Voltage ($V_{icm}$): The maximum input voltage that can be simultaneously applied between either input and ground (also referred to as the common-mode voltage).
- Output Short Circuit Duration: How long a short circuit (output to ground or to either supply voltage) can be sustained without damaging the device.
- Operating Temperature Range ($T_a$): This is the ambient temperature range for which the op-amp will operate within the manufacturer’s specifications. Note that the military grade versions have a wider temperature range than the commercial, or hobbyist, grade version.

*Electrical Characteristics* tabulate factors that describe how the input and output parameters of the op-amp differ from an ideal op-amp model.

- Input Offset Voltage ($V_{oi}$): This is the voltage that must be applied to one of the input pins to give a zero output voltage. Remember, for an ideal op-amp, input offset voltage is zero!
- Input Bias Current ($I_b$): This is the average of the currents flowing into both inputs. Op-amps are designed so that the two input bias currents are nearly equal and nearly zero.
- Input Offset Current ($I_{os}$): This is the difference of the two input bias currents when the output voltage is zero.
- Input Voltage Range ($V_{icm}$): The range of the common-mode input voltage (*i.e.*, the voltage common to both inputs and ground).
- Input Resistance ($Z_i$): The resistance “looking-in” at either input with the remaining input grounded.
- Output Resistance ($Z_{out}$): The resistance seen “looking into” the op-amp’s output.
- Output Voltage Swing ($V_{oomax}$): Depending on what the load resistance is, this is the maximum “peak” output voltage that the op-amp can supply without saturation or clipping.
• Output Short-Circuit Current ($I_{osc}$): This is the maximum output current that the op-amp can deliver to a load.

• Slew Rate (SR): The time rate of change of the output voltage with the op-amp circuit having a voltage gain of unity (1.0).

• Common-Mode Rejection Ratio (CMRR): A measure of the ability of the op-amp to reject signals that are simultaneously present at both inputs. It is the ratio of the common-mode input voltage to the generated output voltage, usually expressed in decibels (dB).

**Push-Pull Transistor Amplifier.** Most op-amps cannot provide very large output currents. This means that they cannot directly drive low-impedance loads, such as speakers for audio application, and motors for robotic application. In these situations, the designer has two options: (1) purchase an expensive op-amp that is designed for high-current output, or (2) build a separate current-amplifier circuit. The second scenario is frequently chosen because it is often less expensive.

The current amplifier we will build is a simple “push-pull” circuit. It consists of two power transistors: one to “push” current through the load, and one to “pull” current through the load, allowing us to apply bi-directional voltages across the load. This is important for audio applications, otherwise we would clip half the signal, and for motor applications, otherwise we could only run the motor in one direction. (If we only wished to run the motor in one direction, a single transistor would suffice.)

The push-pull amplifier that we will use is incorporated in the circuit drawn in Fig. 4.17. The push-pull section itself is the portion of the circuit to the right of the 390 $\Omega$ resistor and to the left of the 1 k$\Omega$ resistor (not including the resistors). The three-terminal component on the top (connected to the +15 V supply, the 390 $\Omega$ resistor and the output) is called an NPN transistor (you can tell because the arrow is Not Pointing iN). The three terminals are called the base (B), collector (C), and emitter (E). This transistor allows current to flow from its collector to emitter (“turns on”) if the base voltage is (sufficiently—approximately 0.7 V) higher than its emitter voltage. The three-terminal component on the bottom is called a PNP transistor (you can tell because the arrow is Pointing iN Perpetually). This transistor allows current to flow from its emitter to collector (“turns on”) if its base voltage is (sufficiently) lower than its emitter voltage.

Thorough discussion of transistor function is beyond the scope of this course. Even so, we can easily understand the macroscopic operation of this circuit. For sufficiently positive values of the input voltage, the NPN transistor will turn on, and the output voltage (at its emitter) will be about 0.7 V lower than the input voltage (at its base). Current flows from the +15 V supply through the load to ground. For sufficiently negative values of the input voltage, the PNP transistor will turn on, and the output voltage will be about 0.7 V higher than the input voltage. Current flows from ground through the load to the −15 V supply. Notice that both transistors will never be simultaneously “on”.

This is a very simple amplifier. It has some undesirable properties, such as a deadband when the input voltage is around 0 V ($|v_{in}| \lesssim 0.7$ V). We could do better by incorporating feedback around the push-pull circuit. Also, it may be a good idea to protect the amplifier using additional “flyback” diodes if driving an inductive load such as a motor. The latter will be done in Lab 5. For now, this simple circuit will serve the purpose.

As a practical note, the NPN transistor we will be using is a TIP31C, and the PNP transistor we will be using is a TIP32C. Both have an industry-standard package termed a “TO-220” three-terminal case. This is also drawn in Fig. 4.17, with the base, collector, and emitter pins labeled. The three terminals need to be twisted 90° using needle-nose pliers in order to properly fit in your breadboard. Also, you will need to attach heatsinks to both parts to help dissipate heat.

### 4.4 Lab Assignment

**Task 1: Prelab certification.** Have the Lab Assistant/Instructor review your answers to the prelab assignment questions and sign the certifications page.
Task 2: **Open-loop test circuit.** Before you to build your first op-amp circuit we make three practical points:

1. First, how the integrated circuit (“IC”) package goes into the breadboard. It straddles the trench, as shown in Fig. 4.2. A white dot sometimes identifies pin 1, and a divot on the top is also generally used to identify the top (and hence pin 1 is to the left of the divot).

![Figure 4.2 Op-amp on a breadboard.](image)

2. Second, a point that may seem to go without saying, but sometimes needs a mention: the op-amp always needs power, applied at two pins; nearly always that means ±15V in this course. We remind you of this because circuit diagrams ordinarily omit the power connections. On the other hand, many op-amp circuits make no direct connection between the chip and ground. Don’t let that worry you; the circuit always includes a ground—in the important sense: common reference called zero volts. Whatever color convention you use for your wires, you should use the green binding post of the breadboard for ground, the black for $-15$ V and the red for $+15$ V.

3. “Decouple” the power supplies with a small ceramic capacitor (0.01 µF to 0.1 µF) if you begin to see fuzz on your circuit outputs. Op-amp circuits, using feedback in all cases, are peculiarly vulnerable to “parasitic oscillations.” The decoupling method is shown in Fig. 4.3. Place the capacitors physically as close to the op-amp as possible. The capacitors act as high-pass filters that let high frequencies escape to the power supply.

![Figure 4.3 Decoupling the op-amp from the power supply using ceramic capacitors.](image)

4. Construct the open-loop test circuit in Fig. 4.4 using a 411 op-amp. Pin 8 is not connected. (Honest, it’s only there so that the amplifier can fit in a standard 8-pin package.) Pins 1 and 5 are used to eliminate offset voltage—we won’t be using this feature right away, so don’t connect anything to these pins either.

5. With the power supply not yet connected, set the meter selector on the power supply to the $+20$ V setting. Adjust the voltage until the meter reads $+15$ V. Turn off the supply, and connect it to the binding posts, as directed above.

6. Watch the output voltage as you slowly adjust the pot, trying to apply 0 volts to $v_+$. Is the behavior consistent with the 411 specification that claims “Gain (typical) = 200V/mV”? Don’t spend too long on this step, however; this is a most abnormal way to use an op-amp. Hurry on to the useful circuits!

**Warning:** Do not try to unplug the op-amp with your thumb and forefinger. It’s a good way to end up with the op-amp plugged into your fingertip. Use an IC puller (in your toolboxes), or carefully use a small screwdriver to pry the op-amp off of the breadboard.

**Caution:** The components we’ve used so far have been simple (only two terminals) and fairly rugged (connecting a resistor or most capacitors “backward” won’t harm them). The op-amp has four times as many pins, so it’s easier to make a mistake in wiring it. Unfortunately, it’s also considerably more delicate, so connecting it incorrectly can
destroy it (often without so much as a puff of smoke to let you know that it has become an inoperational amplifier). The moral—always wire your circuit with the power turned off and check your wiring carefully before turning the power on.

**Task 3: Non-inverting amplifier.** The first feedback circuit we analyze is a non-inverting amplifier.

1. Wire up the non-inverting amplifier shown in Fig. 4.5. Measure and record the actual resistance values used. What is the theoretical gain of this amplifier? Measure and record the actual gain.
2. What is the maximum output swing? How about linearity (try a triangle wave)?
3. Try sine waves of different frequencies. Note that at some fairly high frequency the amplifier ceases to work well: sinusoidal input does not produce sinusoidal output. What is the approximate range of frequencies that produce sinusoidal output? (We will postpone until later measuring the slew rate that imposes this limit; we are still on our honeymoon with the op-amp: it is still ideal.).

**Task 4: Inverting amplifier.** Now, we construct a simple inverting amplifier.

1. Construct the inverting amplifier drawn in Fig. 4.6. If you have been paying attention, you will notice that you don’t need to start fresh: you can use the non-inverting amplifier, simply redefining which terminal is input, which is grounded.
2. Drive the amplifier with a 1 kHz sine wave. What is the theoretical gain? What is the measured gain? Is it the same as for the non-inverting amp you built a few minutes ago?
3. Now drive the circuit with a sine wave at 1 kHz again. Measure the input impedance of this amplifier circuit by adding 1 kΩ in series with the signal source (simulating a signal source with crummy $R_{out}$). If you suppose that the 1 kΩ in series with your signal source represents $R_{out}$ for your source, then use the voltage-divider equation to find the amplifier’s input resistance.
4. Using a second 411, build a voltage-follower circuit to place between the source with crummy $R_{out}$ and the input to this inverting amplifier. This should solve the poor $R_{source}$ problem we have created for you. With the follower’s help, your circuit’s overall gain should jump back up to its original value. Does it?
**Task 5: Summing amplifier.** Modify the inverting amplifier slightly, to form the circuit shown in Fig. 4.7.

1. This circuit sums a dc level with the input signal, letting you add a dc offset to a signal. What is the maximum positive dc level added to the output voltage? What is the maximum negative dc level added to the output voltage?

**Task 6: Integrator.** Now, we construct an (approximate) integrating circuit.

1. Build the circuit shown in Fig. 4.8.
2. Try driving your integrator with a 1 kHz square wave. This circuit is sensitive to small dc offsets of the input waveform (its gain at dc is 100); if the output appears to go into saturation near ±15 V, you may have to adjust the function generator’s dc-offset control.
3. From the component values, predict the peak-to-peak triangle wave amplitude at the output that should result from a 2 V peak-to-peak, 500 Hz square wave input. Then try it.
4. This is not an “ideal” integrator circuit, in part due to the addition of the 10 MΩ resistor. What is the function of that resistor? What would happen if you were to remove it? Try it. Now have some fun playing around with the function generator’s dc offset—the circuit will help you gain a real gut feeling for the meaning of an integral!
5. Don’t take this circuit apart. You will need it in the next task.

![Figure 4.8 Integrator.](image)

**Task 7: Differentiator.**

1. Now, build the differentiator circuit in Fig. 4.9. Leave your integrator circuit intact, and use a second op-amp to build this circuit. Try driving it with a 1 kHz triangle wave.
2. A note on stability: Here we are obliged to mention the difficult topic of stability. A simple differentiator necessarily lives at the edge of instability for reasons beyond the scope of our discussion here. To circumvent this problem, it is traditional to include a series resistor at the input, and a parallel capacitor across the feedback resistor, converting the (low-frequency) differentiator to an integrator above some cutoff frequency. You can determine this crossover frequency by monitoring the input and output of the differentiator when the input is a sinusoid. When there is no phase shift, the circuit is crossing from one type to the other. For this circuit, what is that crossing point? Incidentally, a faster op-amp would perform better: the switch-over to integrator must be made, but the faster op-amp allows one to set that switchover point at a higher frequency.
3. Integrate the Derivative—A more intriguing way to see the imperfection of the differentiator is to feed its output to the integrator you built earlier, then compare original against output waveforms. Ideally, they would be identical—at least in phase (that is, apart from gain artifacts). Are they? Does the answer depend on input frequency?
Task 8: Voltage follower—slew rate. We now introduce you to the sordid truth about op-amps: they’re not as good as we’ve been saying! Sorry.

We begin by measuring slew rate and its effects, with the voltage-follower circuit in Fig. 4.10. Slew rate is the maximum rate at which the output of an op-amp can change. Ideally, the circuit has an output voltage that tracks the input voltage exactly, but in practice the slew rate will introduce a delay and a ramping shape. Explore slew rate in two phases:

1. Build the voltage follower circuit. (The 10 kΩ resistor prevents damage if the input is driven beyond the supply voltages.)
2. Square wave input: Drive the input with a square wave, in the neighborhood of 1 kHz, amplitude of 1 V, and look at the output with a scope. Measure the slew rate by observing the slope of the transitions.
3. Sine input: Switch to a sine wave, same amplitude, and measure the frequency at which the output waveform begins to distort (this is roughly the frequency at which amplitude begins to drop, as well). That is, slowly increase frequency on the function generator. Adjust the scope to observe the zero-crossing of the output of the amplifier. Is this result consistent with the slew rate that you measured in part 1), just above?
4. Now go back and make the same pair of measurements (slew rate, and sine at which its effect appears) with an older op-amp: a 741. The 741 claims a “typical” slew rate of 0.5V/µs; the 411 claims 15V/µs. How do these values compare with your measurements?

Task 9: Voltage follower—input and output impedance. Ideally, an amplifier circuit has infinite input impedance and zero output impedance. Here, we will estimate the impedances of the voltage-follower circuit based on the 411 op-amp.

1. Replace the 741 op-amp with the 411 op-amp in the voltage-follower circuit you already built. Also, replace the input resistor with a 1 MΩ resistor, as shown in Fig. 4.11. As always, measure and record the value of the resistor used.
2. Set the input voltage to 5 V. Carefully measure the output of the voltage source and the input voltage to the op-amp. Using the voltage-divider equation, compute the amplifier’s input impedance. Beware the finding “10 MΩ” (instrument limitation!). Does the resistance of the voltmeter interfere with your estimate? How so? How would you make a more precise measurement?
3. Now, construct the circuit in Fig. 4.12. The feedback path should use the solid line in this step.
4. We measure output impedance via voltage divider again. Measure the voltage at the output of the amplifier, and then between the two 1 kΩ resistors. (Use an input voltage that produces an output voltage in the linear range). Compute the output impedance. It had better be 1 kΩ! Note: This measurement is not the amplifier’s output impedance, but the output impedance plus the impedance of the resistor you added. From this step, what do you conclude the output impedance of the amplifier is?
5. Now, move the feedback path to use the dashed line instead. Insert a third 1 kΩ resistor after the feedback path and before the 1 kΩ resistor to ground. Use these final two resistors as a voltage divider to measure output impedance. What do you find it to be now? Is this a surprising result? Does the actual output impedance of the amplifier matter, with the effect of feedback operating on the circuit?
Task 10: Op-amp offset voltage. In this task we will measure the offset voltage of an op-amp. Note: use a 741, not a 411, for tasks 10 and 11. The 411 is too good for this exercise: its bias current is so tiny that you would not see appreciable errors attributable to \( I_b \). (You might reasonably infer that you can forget about \( I_b \), simply by choosing a good op-amp. Often you can. This exercise means to prepare you for the unusual case in which \( I_b \) does produce troublesome errors.)

![Offset-voltage measurement](image1)

![Offset trimming network](image2)

1. Construct the non-inverting amplifier shown in Fig. 4.13. Measure and record the values of all resistors used. What is the gain of this op-amp circuit?

   Note: Apply no input signal: we are interested in dc errors of a non-ideal op-amp. In the remainder of this section, you will use the amplifier itself to amplify input errors to measurable levels. Knowing the circuit gain, you will be able to infer the value of \( V_{oi} \) and \( I_b \). The only challenge will be to peel these two effects apart, so as to be able to assign a value to each error.

2. Since the input voltage is zero, the output voltage is simply an amplified version of \( V_{oi} \). Measure the output voltage and compute \( V_{oi} \). Compare your measured (or “inferred”) offset voltage against specs: \( V_{oi} = 2 \text{ mV} \) (typical), \( 6 \text{ mV} \) (maximum). Don’t be shocked if your \( V_{oi} \) is well under \( 2 \text{ mV} \). They just don’t make 741’s the way they used to! (But the manufacturer can’t change the data sheet to announce the improvement, because then the part would not be a 741; it would have to be called something like 741a.)

3. Minimize the effects of \( V_{oi} \): Trim the offset voltage to zero, using the recommended network shown in Fig. 4.14. Note, the pot is connected between pins 1 and 5 on the op-amp. Adjust the pot until the output voltage is as close to zero as you can get it. Leave the op-amp in this configuration for the remaining tasks.

Task 11: Op-amp bias current/offset current. We now measure the bias current for the 741.

1. Construct the circuit shown in Fig. 4.15. Pick a value of \( R \) to produce an output voltage in the linear range (non-saturated output). Make sure that your offset voltage has been zeroed as much as possible in the step above.

2. Compute \( I_b \) for the non-inverting input as the op-amp’s output voltage divided by the value of \( R \) that you found. The bias current is positive if it is entering the op-amp; it is negative if it is leaving the op-amp.

3. Now, construct the circuit shown in Fig. 4.16. Again, pick a value of \( R \) to produce an output voltage in the linear range.

4. Compute \( I_b \) for the inverting input as the op-amp’s output voltage divided by the value of \( R \) that you found.

5. Compute the input offset current. How do the bias currents and the offset current compare to spec?

Task 12: Push-pull buffer. Finally, build the push-pull buffer circuit, shown in Fig. 4.17. You should attach heatsinks to the transistors. Be careful not to get heat-sink grease on your clothing—it is impossible to remove.

1. The transistor on top is NPN (TIP31C) and the transistor on the bottom is PNP (TIP32C). At this point, \( v_{out} \) should only be connected to the 1 kΩ resistor.
2. Drive the circuit with a sine wave of 100 Hz–500 Hz. Look at the output of the op-amp, and then at the output of the push-pull stage (make sure you have at least a few volts of output, and that the function generator is set for no dc offset). You should see classic crossover distortion. Describe the distortion you see.

3. Now, attach an “8 Ω” speaker to \( v_{\text{out}} \) (Note: the speaker is rated by its frequency-dependent impedance to a sine wave at 1 kHz, which is 8 Ω). Listen to this waveform on the speaker. Your ears (and those of people near you) should protect you from overdriving the speaker. But it would be prudent, before driving the speaker, to determine the maximum safe amplitude, given the speaker’s modest power rating. The transistors are tough guys, but you can check whether you need to lower the power-supply levels on your breadboard, to keep the transistors cool, given the following power ratings:

- Transistors: 75W if very well heat-sunk, so that case remains at 25 degrees C. Much less if no heat-sink is used, as is likely in your setup.
- Speaker: 250 mW rms.

4. Now, disconnect the right side of the 100 kΩ feedback resistor and reconnect it to the right side of the push-pull section (where the transistor emitters join), and once again look at the push-pull output. The crossover distortion should be eliminated now. If that is so, what should the signal at the output of the op-amp look like? Take a look. (Ain’t that op-amp clever!)

5. Listen to this improved waveform: does it sound smoother (more flute-like) than the earlier waveform? Why did the crossover distortion sound buzzy—like a higher frequency mixed with the sine? If you increase signal frequency, you will discover the limitations of this remedy, as of all op-amp techniques: you will find a glitch beginning to reappear at the circuit output.

Task 13: Lab report. Submit your results in the form of a typed report. Refer to Lab 1 for instructions regarding proper format and content of an acceptable lab report. Please also address the following question:

- Explain how moving the feedback path in the push-pull amplifier improves our previous push-pull amplifier by eliminating the crossover deadband and by increasing the current gain (i.e., increasing the input impedance of the amplifier and load).