Foreword

In this lab you will build, test, and utilize four of the most common op-amp circuits: the inverting amplifier; the non-inverting amplifier; and the buffer follower (aka voltage follower), and the comparator. If you do anything with science or engineering in the future, you are guaranteed to become very good friends with many of these ubiquitous configurations.

The goals of this lab are to:

- Become acquainted with wiring op-amp circuits.
- Learn how to measure input-output amplifier relationships ($V_{out}/V_{in}$).
- Understand the virtues of using a voltage follower/buffer amplifier.
- Understand the difference between op-amps operating with and without negative feedback.

What to turn in: You don’t need to write a formal lab report. Simply provide responses to the questions posed in each sections 1 and 2. Sections 3 and 4 could be nicely documented in live video/audio format, since we’re dealing with audio applications. You still need to be quantitative, where appropriate! When comparing expected vs measured results—the gain of the amplifier for instance—do NOT sweat small discrepancies—general rule of thumb, $\leq 5\%$ difference is “good enough.”

1 Introduction

The Operational Amplifier—or op amp for short—is one of the most important integrated circuits in modern electronics. Its small size, low cost, and superb reliability have led to its use in a large number of applications. We will investigate four applications of op amps in this lab. More (exciting and complex) op-amp circuits will be considered in a future laboratory session, so what you learn today is important for future experiments (and your circuits skills in general!).

The particular flavor of op amp that we will use in this lab is the LM747 integrated circuit (IC), or ’747 for short. You can identify an IC by the number printed on the top of the chip. The IC number is often preceded by two letters such as “LM”, “LS”, “TL”, or “OP”. (Don’t worry about what these letter mean; they usually have to do something with what company makes the chip, how the chip is manufactured, and the operations it performs “inside the black box.”)

The 747 that we will use today contains two separate op amps on a single chip, hence it termed a dual package op-amp. (If you are in the market for stocking your circuits kit, you can find single,
dual or quad packages—1, 2, or 4 op-amps on one chip.) The 747 is a standard general-purpose popular that has remained popular ever since it was originally designed. With exception of sharing the negative power supply pin (what we call $-V_{cc}$ in class, pin number 4), these op-amps operate entirely independent of one another.

The schematic and pin-out diagram of the 747 chip is shown in Figure 1. Acquire a 747 chip from the proper bin. If there’s any justice in the world, the bin labeled 747 will contain only 747 chips. However, double-check to make sure you have the right model of IC by noting its model number. Note how the pins are numbered. If you orient the notch facing toward the top (as if you rotated Figure 1(a) 90 degrees clockwise...or for our math and physics friends $\pi/2$ radians), then pin number 1 is on the upper left; pin 7 at lower left; pin 8 at lower right; pin 14 at upper right, as shown in Figure 1(b).

![Schematic for 747 op-amp](image1)

![Pin-out for 747 op-amp](image2)

Figure 1: Schematic and Pin-outs for the 747 IC with dual op-amp package.

Note the locations of the inverting and non-inverting inputs, the output pin, and the power supply or (“biasing voltage”) pins. You can ignore the nulling pins for the time being. The chip is typically powered with +15 V and -15 V from a split supply. Without power, op-amp won’t do anything.

A couple quick words of caution when working with op-amps: First, do NOT power up the op-amp circuits until they are fully wired. Otherwise you run the risk of having something mis-wired, which can lead to a nicely toasted op-amp. The corollary is that you should always power down your circuit before un-wiring it and returning components to the bins.

Also, you’ll quickly notice that the pins extending from the chip are easily bent. When the pins are bent, getting the chip into and out of your board can be a pain. So, take care of your chip, be careful not to bend the pins. Unfortunately this lab is not equipped with IC pullers, so the next best thing is to use a small screwdriver, gradually easing it underneath the chip. Once you have the screwdriver all the way under the chip, gently work it out of the breadboard sockets.
2 Non-inverting Amplifier

1. Non-inverting amplifiers are standard-issue in so many applications where you simply want to amplify a relatively small input signal. So, let’s actually make one! Build the non-inverting amplifier shown in Fig. 2. Use $R_f = 5.6 \text{k}\Omega$, $R_i = 1 \text{k}\Omega$, and $R_3 = R_f || R_i$. For $V_{in}$, use a 2 V p-p, 1 kHz sine wave. ±$V_{cc} = ±15$ V. Display the input and output voltage sinusoids $V_{in}$ and $V_{out}$ simultaneously on the oscilloscope. Carefully sketch what you see.

2. What is the phase relationship between the input and output?

3. Measure and report the voltage gain, $G_v = \left| \frac{V_{out}}{V_{in}} \right|$. (Note that the $G$ used here is NOT the decibel gain $G(\omega)$!)

4. Compute the theoretical voltage gain of this amplifier.

5. Compare the measured and theoretical voltage gain values. Compare and contrast—do they pass the sanity check?

6. Now, max out the input voltage of the input signal. (Your function generators will usually achieve something like 10V p-p.) Carefully sketch the input and output signals, and comment on what you effect you are seeing.

7. Finally, change your input signal to be a 1 V amplitude square wave. Carefully sketch the input and output signals. You should see that the output is more like a “trapezoidal wave” instead of a square wave because the op-amp isn’t infinitely fast. It takes some finite amount of time to work its magic and amplify a signal. The maximum possible rate of change of the output signal is called the **slew rate (SR)**. 

![Non-inverting Amplifier Diagram](image-url)

Figure 2: Non-inverting amplifier configurations. The voltage gain of non-inverting amplifier is $G_v = (1 + R_f/R_i)$.
\[ \text{SlewRate} = \max \left( \frac{dV_{\text{out}}}{dt} \right) \]

Carefully measure the slope of the output signal, \( \frac{dV_{\text{out}}}{dt} \).

In the spec-sheet, the manufacturer of the 747 lists a typical slew rate as 0.5 V/\( \mu \)s. Compare your measured value to the manufacturer’s spec. You should know they usually provide conservative estimates. No company wants irate customers calling up and saying “Hey, it’s slower than you promised!” On the contrary, a company is happy when users are thinking “Hey, nice...the slew rate is 1.5 or 2 times higher than the manufacturer promised!”. The take home message is that you can’t properly amplify high-frequencies without getting special op-amps that have very high slew-rates.

3 Summertime: 2-channel Audio Mixer

Yesterday in class, we designed a basic audio mixer for Sharon Jones and the Dap Kings. Now it is time to actually build and test-drive one!

![Figure 3: Dap Kings looking very retro dapper.](image)

1. Design and build a 2-channel audio mixer for which the weights—the \( \frac{R_f}{R_c} \) terms—can be varied between 0.1–10. Carefully diagram your circuit in your lab report and briefly provide rationale for your choice of component values.

2. Ground one of the inputs. Connect the other input to a 2V, 1 kHz sine wave. Carefully note the relationship between input and output signals and sketch what you see. Turn the weighting knob and note the effect on the output. Do you see what you expect to see?

3. Now time for the punchline. Use two audio sources as your inputs—computers, ipods, microphones, or similar. Connect the output of your mixer to an audio amplifier (additional units are available in the bottom-left corner cabinet in the Circuit labs). And of course connect the audio amp to a speaker so you can hear the result. Play with the knobs of your audio mixer. Listen carefully. How does what you hear correlate to the pot settings? Have a good play with it and see what good songs you can come up with. Who knows, you could be the next Alison Gold!
4 Noise Canceling Headphones

You’ve probably been on a bus, plane, a busy public space where you wish you could just zone out, listen to your music and not be bothered by external audio agitation (e.g., baby screaming, roosters clucking). Noise canceling headphones are just the ticket! You’ve likely heard of them, if not used them regularly already (see Fig 4). The principle of operation is illustrated in Fig. 5. A microphone is “listening” to the environmental noise. This noise is canceled by adding the inverted and scaled noise signal to itself. These (hopefully!) canceling signals are then added to the relaxing tune you are trying to listen to in the first place and then sent to the speaker.

Your task is to design, build, and test a noise-canceling headphone model. Use an ipod for your audio source. For your noise source, you will use a condenser microphone. This is nothing more than a battery powered device, which generates a voltage that depends on the incident sound. For your report, please be sure to:
Once you have set up your circuit, your first test is to make sure the noise canceling portion is working appropriately. To do this, ground the input that would be connected to your source of music. Connect the microphone or function generator to the other input on your circuit. Using your oscilloscope, show that output of your circuit is essentially 0V (flat-lined) even when you input a clearly non-zero noise signal.

1. Carefully diagram your circuit, labeling all component values.
2. In words, briefly explain your design rationale. Provide sample calculations justifying your design as well.
3. Show oscilloscope screen shots or sketches that demonstrate your noise-canceling headphones work as desired.
4. Test-drive your circuit with your instructor to demonstrate that the noise is canceled while the music plays cleanly through your circuit.

5 The Comparator

The comparator is a circuit that exploits the saturation region of an op-amp to act like a binary computer.

![Comparator Circuit Diagram](image)

Figure 6: (a) Op-amp comparator circuit with LED indicator. The LED illuminates when the output is high. The threshold voltage depends on the pot’s position.

If $v_+ > v_-$ then the output will be in the positive saturation region: $V_{out} \approx 15 \text{ V}$. Conversely, if $v_+ < v_-$ then the output will be in the negative saturation region: $V_{out} \approx -15 \text{ V}$. The output is either “high” (+Vcc) or “low” (-Vcc). You can think of these like being the 0’s and 1’s inside a computer!

1. Build the circuit shown in 6(a), fixing the boo-boo in the circuit diagram with the LED. The +5 V input in combination with the 5 kΩ pot is nothing more than a voltage divider that sets the threshold (or “reference”) voltage against which the non-inverting input signal is compared. For the input signal, use a sine wave of frequency $\leq 15 \text{ Hz}$ or signal from your ipod.
2. View the input and output signals simultaneously on the scope. Also, monitor your LED light. Carefully sketch a representative time segment (The run/stop button can "freeze" the scope display). Describe what you see both on the scope and for the indicator light.

3. Describe two practical applications for a comparator.

6 Buffer/Voltage Follower

A voltage follower, or buffer, is essentially a non-inverting amplifier with unity gain (that is, $V_{out}/V_{in}= 1$). You might ask, “That’s no voltage again at all....why on Earth is this useful?!” It is used frequently in circuits where one wishes to use a source having a high output impedance to drive a device with a low input impedance. To see how this can be useful, consider Figure 7.

In this circuit, the signal source is modeled by the components in the dotted box. The function generator in series with a 1 kΩ resistor represents a source with the output impedance which is large, relative to the 100 Ω load it is driving. We will pretend that we cannot get inside the dotted box. For example, what’s inside the dotted box might be electrical activity generated by the brain or heart that you are trying to measure. Or it might be the voltage output of pickup inside a guitar. We will also pretend that we can’t do anything to change the 100 Ω resistor; it might be the input impedance of a speaker or filter or other piece of electronics connected into the circuit.

![Figure 7: Model of a source with high output impedance driving a load with low-resistance](image)

1. For circuit (A) in Figure 7 what is the ratio between the input voltage and the voltage across the 100 Ω resistor? How much voltage are we losing compared to the ideal situation of no voltage being lost due to the output resistance of the driving device?

2. Now, consider the circuit shown in Figure 8. Here, a buffer is placed between the 1 kΩ and 100 Ω resistors. Now predict what voltage will appear across the 100 Ω resistor. Be sure to fully justify your answer in your lab report.

3. Wire the circuits of Figures 7 and 8. Measure the voltage across the 100 Ω resistor in each case. Compare the predicted and measured voltages. Explain what you observed. Hopefully, you will see why buffers are very useful in an everyday laboratory setting!
Figure 8: Measuring the voltage of a high impedance output source with a buffer amplifier. Power supply connections +Vcc = 15 V and -Vcc = -15 V not shown.