Lab 2: DIP Chips and Op-Amps
Week 3

In this lab, you will learn some more fundamentals of circuit building, this time focusing on integrated circuits (ICs). The IC we will focus on will be the LM741 Operational Amplifier (op-amp). As opposed to what you will learn in the classroom about op-amps, here we will show the practical aspects of circuit design using these versatile ICs.

1 Integrated Circuits

1.1 Introduction to Integrated Circuits

Electronic circuits, at their most fundamental level, are just a bunch of resistors, capacitors, inductors, diodes, transistors, and wires. When these basic elements are all hooked up together in just the right way, they can create something as simple as a voltage divider, or something as complicated as a computer. In reality, many of the most common and useful circuits happen to be far more complex than a voltage divider, but far less complex than a computer. Instead of having to build these circuits from scratch with individual resistors, transistors, etc, many of the most commonly-used circuits are fabricated onto a simple chip that you can plug into your breadboard. These are called “Integrated Circuits” (ICs).

1.2 Operational Amplifiers

This lab will focus on one of the most useful and widely-used ICs: the operational amplifier, or “op-amp” for short. Op-amps are utilized in many applications such as amplifiers, filters, waveform generators, analog-to-digital and digital-to-analog converters (ADC and DAC), and many more. Because of the wide versatility and applicability of the op-amp, we will be using them throughout this course in several different labs.

As you can see in Fig. 1, the inside of a 741 op-amp (which is a specific op-amp IC) contains many transistors and resistors, as well as a capacitor. It’s a rather complicated-looking circuit, but luckily you do not need to worry about the detailed inner workings! All you need to know for the purposes of this course is what an op-amp does and how to use it. If you do want to know how these op-amps work, there are plenty of upper-level courses you can take, starting with EECS 225.

Figure 1: Inside a 741 op-amp.
Fig. 2 shows the schematic symbol for an op-amp. Before we begin, we have to define some important terminology. Referring to Fig. 2:

- $V_{S+}$ is the positive supply voltage,
- $V_{S-}$ is the negative supply voltage,
- $V_+$ is the non-inverting input,
- $V_-$ is the inverting input,
- $V_{\text{out}}$ is the output voltage.

### 1.3 What The Op-Amp Does

When used by itself, an operational amplifier simply amplifies the difference in voltage between the two inputs, i.e., $V_{\text{out}} = A_{OL}(V_+ - V_-)$, where the amplification factor $A_{OL}$ is called the op-amp’s “open loop gain”. As you will see shortly, $A_{OL}$ is a huge number, generally in the range of hundreds of thousands or even millions! Because of slight variability in the manufacturing process, different op-amps will have slightly different values of $A_{OL}$. This is not a problem, though, because op-amps are generally not used by themselves, but rather as a part of a larger circuit where part of the output is fed back into one of the two inputs. To say this in EECS language, op-amps are generally used in a “closed-loop” configuration (i.e. with feedback) rather than an “open-loop” configuration (i.e. with no feedback). As you will see, the reason op-amps are useful is because closed-loop op-amp circuits do behave in a predictable manner, despite the unpredictability of $A_{OL}$!

### 1.4 Op-Amp Power Supplies

Most ICs have one positive supply and a ground connection, but the op-amp has a positive supply and a negative supply (as shown in Fig. 2). These provide the power necessary for the op-amp to work. The values of $V_{S-}$ and $V_{S+}$ are the minimum and maximum voltages that the op-amp is able to output. If $V_+ > V_-$, then the output will be a positive number (somewhere between 0 and $V_{S+}$), and if $V_+ < V_-$, the output will be a negative number (somewhere between 0 and $V_{S-}$). If the second supply voltage was 0 (ground) instead of $V_{S-}$, (a negative voltage), then the amplifier could never have a negative output. You will also see shortly what happens when the op-amp tries to exceed the supply voltages at the output. The DC voltage supply in your lab setup will be used to generate both positive and negative supply voltages.
ICs come in a variety of encasings. The most common one for prototyping on a breadboard is the “Dual Inline Package”, or DIP. An example is shown in Fig. 3(a). The DIP chip is designed in such a way that it fits across the bridge in a breadboard and places each leg of the chip in a separate row, so each one is electrically isolated and so that other components can be connected to them in the appropriate rows. An example of how to properly connect a DIP chip to a breadboard is shown in Fig. 3(b).

![DIP IC Image](image)

(a) (b)

Figure 3: DIP IC.

A pinout diagram and photo of the 741 op-amp are both shown in Fig. 4. As you can see, the pins on the op-amp (along with most other types of DIP chips) are numbered counter-clockwise, starting from the top left. The top of the chip is usually indicated by a little circle or indentation in the package. Although the op-amp has eight pins, we will only use five of them during this course: pins 2, 3, 4, 6, and 7. These pins represent $V_-$, $V_+$, $V_{S-}$, $V_{out}$, and $V_{S+}$, respectively. The other three pins don’t need to be connected to anything.

![Pinout Diagram and Photo](image)

Figure 4: Pin numbers of DIP IC (741 op-amp).
3 Constructing a Circuit

3.1 Power Connections

Operational amplifiers are what is known as active components, which means they require a power source to do what you expect them to do. The components we had used previously, for example resistors, capacitors, and diodes, are passive components. They do not require an external power supply; they do what you expect as long as there is a voltage across them. With an op-amp such as the LM741, you must give it power for it to function. Specifically, pins 4 and 7 must be properly connected in order for pin 6 to output what you expect in response to input pins 2 and 3. If you simply make the connections to pins 2, 3, and 6 without making the power connections, it’s like trying to change the channel on your TV without first plugging it in! Let’s go through these power connections.

First, insert the LM741 IC into your breadboard. Pins 1, 5, and 8 will remain unconnected. To create the proper power supply voltages, we will use the ±25V output of the power supply. The red terminal with a + is the positive side, the red terminal with a − is the negative supply, and the black terminal in between is the ground. Make sure to adjust the voltage to 5 V before connecting to your circuit.

You now have a +5 V supply, a -5 V supply, and a common ground. Connect the +5 V supply to pin 7, and the -5 V supply to pin 4. Notice, there is no ground pin on the LM741. However, you will use ground when making other connections. Be careful when making connections in the subsequent circuits. Make sure to connect ground to the common ground, not to the -5 V supply!

3.2 Oscilloscope Connections

For each of the subsequent sections, and furthermore for all future labs, you will be using the oscilloscope to monitor both the inputs and outputs. This can be done simultaneously using the fact that the oscilloscope has 2 channels available for measurements. As a general rule, use Channel 1 to scope the input, and Channel 2 to scope the output. For either channel, you will generally connect the probe to the signal of interest (input, output, or some intermediate signal), and the black clip to the circuit’s common ground.

3.3 Open Loop Test

First, we will analyze the open loop gain $A_{OL}$. To do this, we will produce a signal with the waveform generator, send it into the op-amp, and see what comes out. Connect the waveform generator’s negative terminal (black) to your op-amp’s inverting input ($V_-$), and its positive terminal (red) to your op-amp’s non-inverting input ($V_+ - V_-)$. Use Channel 1 of the oscilloscope to monitor the input voltage ($V_+ - V_-)$. Use channel 2 of the oscilloscope to monitor the op-amp’s output voltage (pin 6) relative to ground.

Generate a 1 V, 100 Hz sine wave. *What do you see at the output?* Decrease the sine wave’s amplitude steadily until the output actually looks like a sine wave. *Can you ever reach this point? If so, what is the sine wave amplitude when this first occurs? Based on this, what is $A_{OL}$? If you are not able to get a sine wave, why do you think this is?*
3.4 Closed Loop Test

As mentioned earlier, op-amps are most often used in closed-loop configurations, meaning that part of the output is fed back to the input. A simple feedback circuit using op-amps is the “inverting amplifier”, shown in Fig. 5. The output of this circuit is characterized by \( V_{\text{out}} = -\frac{R_f}{R_{\text{in}}} V_{\text{in}} \).

![Inverting amplifier schematic.](image)

Figure 5: Inverting amplifier schematic.

Choose values of \( R_f \) and \( R_{\text{in}} \) to create a gain with a magnitude of 10, and construct the circuit. Once again, the input will be produced by the function generator. Generate a 1 V, 100 Hz sine wave, and connect the positive terminal of the waveform generator to \( V_{\text{in}} \), and the ground to the circuit’s common ground. *What do you see at the output? Is it what you expect?* This time, steadily increase the amplitude of the input sine wave until the output is no longer a smooth sine wave. *What amplitude of the input sine wave did this occur at? What is the maximum output amplitude of the op-amp? Explain your observations.*
4 More Advanced Circuits

Here, we will build some other op-amp circuits. As before (and always), connect Channel 1 of the oscilloscope to the input, and Channel 2 to the output.

4.1 Differentiating Amplifier

First, we will build a differentiating amplifier, shown in Fig. 6.

![Differentiating amplifier schematic](image)

Figure 6: Differentiating amplifier schematic.

The equation that characterizes this circuit is $V_{out} = -RC \frac{dV_{in}}{dt}$. Choose values of $R$ between 10 kΩ and 100 kΩ, and a value of $C$ such that the gain is $\sim 1$.

To test this circuit, use the function generator to input a sawtooth waveform. Monitor the input and output on the scope. *What do you see? Is this what you expect?*

Now change the input from sawtooth to sine wave. *Now what do you see? Is it what you expect? What is the general relationship between the signals on Channel 1 and Channel 2?*

4.2 Integrating Amplifier

Next, we will build an integrating amplifier, shown in Fig. 7.

The equation that characterizes this circuit is $V_{out} = -\frac{1}{RC} \int_{t_0}^{t_1} V_{in}(t) dt$. Choose values of $R$ between 10 kΩ and 100 kΩ, and a value of $C$ such that the gain is $\sim 1$.

To test this circuit, use the function generator to input a square wave. Monitor the input and output on the scope. *What do you see? Is this what you expect?*

Now change the input from square wave to sine wave. *Now what do you see? Is it what you expect? What is the general relationship between the signals on Channel 1 and Channel 2?*
4.3 Op-Amp Oscillator

Up to this point, whenever we wanted to generate an oscillating signal, we had to use the waveform generator. Now, we will build our own oscillator using an op-amp.

4.3.1 Fixed Frequency Oscillator

The schematic is shown in Fig. 8(a). To find the frequency of oscillation, use the equations in Fig. 8(b).

![Fixed Frequency Oscillator Schematic](image)

Given that $R_1 = 35 \, \text{k}\Omega$ and $R = 50 \, \Omega$, find the values of $R_2$ and $C$ to give an output frequency of 1 kHz. Build the circuit and scope the output. *Do you get what you expect? What is the shape and amplitude of the output waveform?*
4.3.2 Variable Frequency Oscillator

The schematic is shown in Fig. 9(a). There is a new component here, specifically $R_2$, which is called a *potentiometer* (shown in Fig. 9(b)). This is basically a variable resistor. As you turn the dial, its effective resistance changes. Connect it as shown, with leg 1 at $\beta_1$, leg 3 at $\beta_2$, and the center leg at the positive input terminal of the op-amp.

![Figure 9: Op-amp oscillator with variable frequency schematic.](image)

Build the circuit and scope the output. *Do you get what you expect? What is the shape and amplitude of the output waveform? By turning the potentiometer, what is the maximum frequency of the output you can create? What is the minimum?*

5 Write-Up

In your write-up, answer all the questions posed throughout the lab handout.

Followup

If you are interested in learning more on this material, look into EECS 221 (Fundamentals of Circuits) and EECS 225 (Fundamentals of Electronics).