ECE20007: Experiment 8

Operational Amplifiers

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1 Application

Throughout this course, loading has been mentioned as a phenomenon that needs to be controlled properly numerous times, as it can cause tedious feedback and make our systems less efficient. To combat loading, we can use loading resistors, which allow us to treat the system as a voltage divider and at least make sure that most of the signal gets through, but that only works to a point. It would be nice to be able to add power back into the system to compensate for the lost power, but then we would have to deal with superposition, and then we are back to another loading situation! Fortunately for us, there is device that we can use that allows us to isolate different parts of a system from each other and add power back in at the same time if we want to, known as an operational amplifier, or more commonly called an op-amp.

An op-amp essentially allows us to compare two voltage values, and send a signal out depending on the difference of those two values. We can change how these signals interact, and even feed the output back into one of the input signals to change how the op-amp acts. Understanding how to create and use an op-amp circuit will open up a wide variety of control circuits to your arsenal of electronics tricks including circuit isolation, gain control, comparators, and oscillators.

2 Experiment Purpose

This lab will also be one of your first steps into analog electronics, where our circuits can now manage and control different levels of voltage in a circuit. These principles combined with a microprocessor allows for almost all of modern electronics and computers to be possible.

Op-amps can probably be considered one of the most helpful electrical tools to a scientist or engineer, right next to the voltage divider, simply because it can be used in so many different ways in so many applications. If one wanted to, there could probably be a whole course dedicated to different uses of an op-amp, one of the big uses being the next mini project. This experiment will get you familiar with the general ways to setup an op-amp circuit along with the general rules to follow when designing circuits using an op-amp.

3 The Op-Amp

Simply put, an op-amp allows the user to determine which input has a larger voltage. If the inverting input voltage (v_-) is larger than the non-inverting input voltage (v_+), then the output will drive itself towards the negative supply voltage. If the non-inverting voltage input is larger than the inverting input voltage, then the output will drive itself towards the positive supply voltage. The output voltage can be defined by Equation 1.

$$v_{out} = A_o(v_+ - v_-) \tag{1}$$

Where A_o is the **open loop voltage gain**, or the internal gain of the op-amp. In an ideal op-amp, the open loop gain of an op-amp is usually defined as infinite. The actual gain of an op-amp will vary depending on the type and manufacturer, but can range from around 10^5 to 10^{15}. Make sure to check the datasheet!

An op-amp has at least 5 nodes that we need to keep track of: a non-inverting input (v_+), inverting input (v_-), two supply voltages (one positive and one negative), and an output. More specialized op-amps can have more inputs to help with precision and tuning, but we will not be worrying about that in this lab.

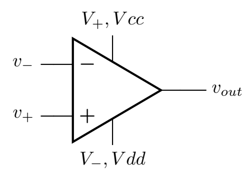

Figure 1: General schematic for an Op-amp

While the gain may not actually be infinite, it is still very large. So, looking at Equation 1, if the input voltages are far apart then the output of the op-amp will be fairly stable, but even extremely small changes in v_+ or v_- (even on the order a few microvolts) can cause some chaotic outputs. This can be combated with feedback which will be discussed in the next section. Obviously, we cannot get infinite voltage from the op-amp; we are limited by the voltages of our supply inputs. The open loop gain tells us that the op-amp will try to push itself as close as it can to either of the supply voltages depending on the difference at the inputs.

You can think of the two voltage inputs of an op-amp (v_+ and v_-) as inputs to a voltmeter. This makes sense when looking at Equation 1 since we are essentially looking at voltage difference between the two inputs. Just like a voltmeter, the voltage inputs of an op-amp also have a very large resistance between them. In an ideal op-amp, like in an ideal voltmeter, we would like the resistance between the inputs to be infinite, but in reality, the resistance is usually on the order of a megaohm. For applications in this lab, and even for the majority of your future classes, that still means that we can assume that there will be no current draw between the two inputs of the op-amp.

We can also think of the output of the op-amp as a variable power supply, not unlike the benchtop PSU or function generator, but instead of us turning a knob to adjust the power, the input voltages adjust it instead. Just like any power supply, there is some open loop resistance on the supply output (usually fairly low, often less than $1K\Omega$) but, again, can vary based on the type of op-amp and manufacturer. If you are working with very low load resistances, loading can be an issue, but can usually be managed in an easier sense since the open loop resistance is low and the load would be isolated from the inputs.

4 Feedback

So we can see which input is larger. Great. What else can this thing do?

Yes, by itself, an op-amp isn't too astounding, but we can change how the op-amp acts depending on what components we use and how we setup the inputs and the output. The simplest way to setup a very helpful circuit is by introducing feedback, where we take the output of the op-amp and send it back to one (or both) of the inputs of the op-amp.

4.1 Negative Feedback

Negative feedback with op-amps is when we take our output voltage, and send it back to the inverting input (v_-) of the op-amp. We can send in the voltage directly from the output, but more times than not, it is modified by a voltage divider or some other circuit to modify the voltage going into the inverting input. In general, we will say that the inverting input voltage is a fraction of the output voltage, almost always equal to or less than the output voltage.

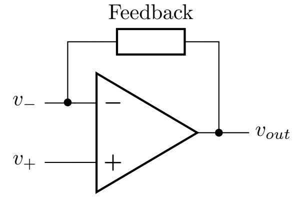

Figure 2: Op-amp with negative feedback where v_- is a function of the output voltage

Going back to Equation 1, we can rearrange it to have the voltage inputs on their own side of the equation.

$$V_{out}/A_o = v_+ - v_- \tag{2}$$

Since our open loop gain is "infinite" in an ideal op-amp, our left side of the equation goes to 0, and we can say that $v_+ - v_- = 0$, $v_+ = v_-$. Fundamentally, negative feedback with an op-amp is going to try to maintain an equal voltage between its two inputs if it is able. We can use this idea to our advantage, especially with negative feedback in a system. If we look at a negative feedback circuit, v_- is attached to our output voltage, so some amount of voltage from the output is going to feed back into the inverting input. This allows our op-amp to effectively reduce the difference between our inputs since we are subtracting our output by whatever is attached to our non-inverting input. The op-amp can quickly switch between the positive and negative supplies to push whatever voltage or current it needs to maintain $v_+ - v_- = 0$. Since there is no voltage drop across our two inputs, this is often reffered to as a "Virtual Short Circuit." **Note:** This mentality will only really be helpful for negative feedback. Positive feedback (next section) does not allow for this equilibrium to occur.

4.1.1 The Buffer

The simplest form of negative feedback is the buffer, where the output voltage is directly attached to the inverting input of an op-amp.

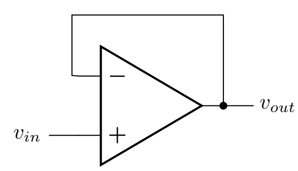

Figure 3: Buffer circuit

With a buffer (also called a voltage follower), we now have a direct connection between our output voltage and our inverting input. In Negative feedback, our op-amp is going to try to drive the two inputs to be equal, so we can say that $v_{in} - v_{out} = 0$, $v_{out} = v_{in}$. Since our inputs have a very large resistance between them, where there is effectively an open circuit between them, this allows us say that the output of the op-amp is isolated from the input signal. If we are able to isolate our input from our output, we have essentially removed loading as a potential issue in our circuit!

Well, not completely. We have removed loading as a potential issue for that specific location in our circuit. Loading can still be an issue before and after the buffer depending on what is happening on either side, but each side is effectively isolated from the other. This is still very helpful, especially if we have small equivalent resistances on either side of the buffer.

Wait, what happened to the infinite open loop gain of the op-amp? That gain is still there, but now we are able to control the gain of the op-amp using feedback. If our input voltage is equal to our output voltage, our effective gain of the op-amp is 1, like in our buffer. We can further adjust our gain by making an amplifier.

4.1.2 The Inverting Amplifier

Now that we can give our op-amp a gain that is more manageable than "infinite," we can have the op-amp provide a gain based on how much of the output voltage we feed into the inverting input, most commonly done with a voltage divider.

In Figure 4, a voltage divider is placed between the output voltage and the inverting input. An input voltage is also placed on the other side of the voltage divider with the non-inverting input being placed on a common ground. This circuit still has negative feedback even though there is a resistor in between, which means that the op-amp is still going to try to push the inverting and non-inverting inputs to be the same value. Since the non-inverting input is attached to a ground, or $0V$, we can also say that the inverting input has an input voltage at $0V$.

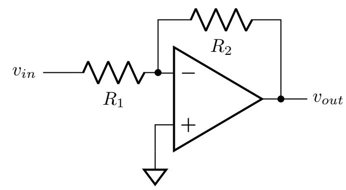

Figure 4: Inverting Amplifier

A tricky part here is that both v_{in} and v_{out} are feeding into our inverting input, which means we have to use superposition to determine our voltage at that point. There are few ways to approach finding this value. We can determine the current provided from both sources and find our total at v_- using Kirchhoff's Current Law, since we know that there will be no current flow entering v_- which means that $I_{R1} + I_{R2} = 0A$. From there, we can then calculate our current through each resistor.

$$I_{R1} = \frac{(v_{in} - v_-)}{R_1}, \quad I_{R2} = \frac{(v_{out} - v_-)}{R_2} \tag{3}$$

Add the currents using our virtual short circuit gives us the below equation:

$$\frac{(v_{in} - v_-)}{R_1} + \frac{(v_{out} - v_-)}{R_2} = 0A \tag{4}$$

Rearranging the above equation to solve for our gain of the system (v_{out}/v_{in}) allows us to get:

$$\frac{v_{out}}{v_{in}} = -\frac{R_2}{R_1} \tag{5}$$

We can also approach this system as two voltage dividers, one with a source of v_{in}, and one with a source of v_{out}.

$$v_- = \frac{v_{in}R_2}{R_1 + R_2} + \frac{v_{out}R_1}{R_1 + R_2} = 0V \tag{6}$$

Rearranging this equation will give us the same relationship shown in Equation 5. Both methods have their pros and cons, but will get you to the same answer. Use the method that works best for you and works for the application you are working with.

There are a few important things to realize with the gain of an inverting amplifier. The first part, which can be implied by the name, is that the signal gets inverted. Since the gain is negative, we are flipping v_{in} over $0V$. Depending on the application, this is not a big deal, and sometimes can be very useful. If one is wanting to remove a superimposed signal from a source, flipping the signal (shifting the signal by 180^o) and adding it back to the original source would allow that signal to be reduced. Think back to the superposition lab to convince yourself of this. In audio production, our ears cannot tell the difference between a negative and positive voltage; we only interpret power, so having an inverted signal on a speaker is not a big deal as long as it isn't reducing the power of another signal.

Since the resistor values are the only part of the circuit that impact the gain in this system, we can adjust our gain to be essentially whatever we want. We can even get the gain to be below 1, which means that we can reduce and amplify the signal from v_{in} as we see fit. Making R_2 a potentiometer would turn this into an adjustable gain amplifier. Picking R_1 to work well with R_2 will depend on your application.

An important side effect of the inverting amplifier is that our v_{in} is technically attached to our v_{out}. This means that loading can become an issue if your resistors are too small. That said, if your resistors are too large, the feedback from the circuit can become ineffective. Determining your resistors properly in an inverting amplifier is really important. In Figure 4, we are just using a voltage divider, just like many applications of the inverting amplifier. Keep in mind rules and states of a voltage divider to make this as effective as possible.

4.1.3 The Non-Inverting Amplifier

If we can set up an inverting amplifier, it would make sense that we can setup a non-inverting amplifier. The only difference here is that we will attach our input voltage to our non-inverting input, and ground the input of our inverting input, as seen in Figure 5.

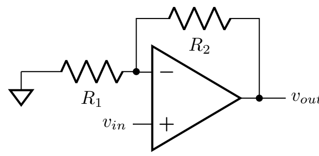

Figure 5: Non-Inverting Amplifier

The good news is that the isolation is back! With v_{in} back on its own input, we can effectively isolate our input from our output, but how does this affect the gain? We still have negative feedback, so $v_- = v_+$ still holds. R_1 and R_2 are still in a voltage divider, but we only have to worry about v_{out} affecting the voltage at v_-.

$$v_- = \frac{v_{out} R_1}{R_1 + R_2} = v_{in} \ , \quad \frac{v_{out}}{v_{in}} = 1 + \frac{R_2}{R_1} \tag{7}$$

Depending on the application, the non-inverting amplifier is helpful, but can be tedious at times. If you want to fully isolate your input from your output, having a non-inverting amplifier will help you do this. That said, we are not able to reduce the gain below 1 using a non-inverting amplifier. Depending on the application, if you have a set gain or do not need to adjust your gain below 1, a non-inverting amplifier allows you to get an isolated, in-phase signal on the output compared to your input.

4.2 Useful Negative Feedback Circuits

As mentioned in the intro of this lab, a full course could probably be used to talk about op-amps and how we can use them. Negative feedback allows us to stabilize the output based on the idea that the inputs will be driven to equal each other. Using our inverting and non-inverting amplifiers, we can make summing and differential amplifiers.

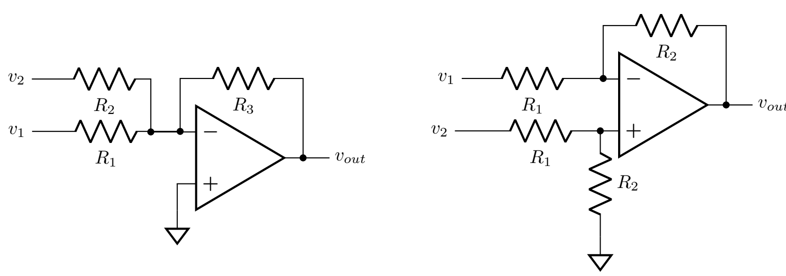

Figure 6: Left: Summing Amplifier. Right: Differential Amplifier

4.2.1 The Summing Amplifier

As mentioned in numerous labs at this point, combining signals is something that happens quite frequently. Using a summing amplifier allows us to combine waves, amplify them based on our negative feedback rules, and potentially isolate our signals as well. As you might be able to assume, before even doing any math, that the summing amplifier that is in Figure 6 is an inverting summing amplifier since the input signals are attached to the inverting input. While it does multiply the sum of the inputs by -1, it does come with other perks. If all of the resistors in the summing amplifier are equal to each other, our output voltage is equal to the inverted sum of our inputs, and this will work for any number of inputs with this amplifier.

$$v_{out} = -(v_1 + v_2 + ... + v_n) \text{ when } R_1 = R_2 = R_3 ... = R_n \tag{8}$$

It is worth your time to verify this using superposition, voltage division, and Kirchhoff's Current Law. You can make a non-inverting summing amplifier as well in the same fashion you would make a non-inverting amplifier if isolation is important for your system, and attach your input signals to your non-inverting input, but the above equation will only work with two inputs. With three or more signals, your resistors will have to be adjusted to maintain the same summing relationship; do the math to figure out why! One solution to keep the math nice would be to use an inverting summing amplifier with as many signals as you need, and then send v_{out} to another inverting amplifier with a gain of -1 to make the output the actual sum instead of inverted, and then buffer the output with a gain of 1 to isolate the amplifier. Trade-offs such as making math easier at the expense of a more complex circuit will become a regular topic of discussion in future projects and experiments!

4.2.2 The Differential Amplifier

If we have easy ways to combine signals with an op-amp, we should have easy ways to subtract them, too. Taking a look at the differential amplifier in Figure 6, we can see we have a classic inverting amplifier setup, but instead of our non-inverting input being directly attached to a ground, we have a reference voltage provided by v_2. Remember the fundamental equation of op-amps, where the output voltage is always going to end up being the difference of the two inputs. We can stabilize this using our negative feedback, and now take an actual difference measurement with a controlled gain.

$$v_{out} = \frac{R_2}{R_1}(v_2 - v_1) \tag{9}$$

Wait, isn't this the definition of a voltmeter? Yes! In fact, a lot of commercial digital voltmeters will use a system like this to take voltage measurements instead of a galvanometer like discussed in the earlier labs. Sending this voltage difference to a microcontroller or a device handling a display screen can allow for quick displays of voltage differences.

4.2.3 Op-Amp + Filter = ?

You might have noticed that every feedback circuit we have looked at besides the buffer uses some form of voltage divider to adjust the gain of the op-amp and modify the usability of the op-amp. As you learned in the filters lab, a filter is just a fancy voltage divider that changes its response based on the frequency of the source, so can we use a filter with an op-amp? Of course! In fact, we can have the op-amp do calculus for us! (sort of...) Looking at our inverting amplifier in Figure 4, replacing R_2 with a capacitor will give us an integrator circuit, where the input signal gets integrated at the output, essentially providing a rolling average of the input. Replacing R_1 with a capacitor will give a differentiator circuit, displaying the rate of change of the input.

Just like other inverting op-amp circuits, these will give inverted signals, but it is not recommended to use these with a non-inverting amplifier setup due to the increased complexity of the math to figure out the values needed, and the circuit will get more complex since you will have to put another filter on the non-inverting input. Instead, just apply the same approach as your non-inverted summing amplifier; start with an inverting circuit, then invert it again.

You will also find that your circuits are more susceptible to noise when using a filter to setup your op-amp, which sounds a bit ironic since we often use filters to reduce noise, but it is true, especially for the differentiator. For a differentiator, add a capacitor in parallel with R_2 (known as a compensation capacitor) to help reduce noise. Adding a [compensation] resistor in series with the R_1 capacitor will also help with this. A similar approach can be taken with the integrator, but since your circuit is essentially taking a continuous average of your circuit, noise becomes less of an issue, especially if you are sampling a very slow signal or taking a very long measurement.

Just like filters and other RC circuits, your cutoff frequency plays a role in how effective your integrator or differentiator will work. Do some research to better understand how to use these circuits (extra credit task in lab).

4.3 Positive Feedback

Positive feedback on an op-amp is when you attach the output voltage to the non-inverting input of the op-amp. Thinking back to Equation 1, where $v_{out} = A_o(v_+ - v_-)$, we can setup the function where v_+ is a function of the the output voltage, $v_{out} = A_o(f(v_{out}) - v_-)$. This means that the output voltage, or at least part of it, is getting added to the equation instead of being subtracted like in negative feedback. This is going to cause the op-amp to be driven to the supply voltages, either to the positive or negative supply, depending on the initial conditions from when voltage is applied to the non-inverting input. Other lingo you will hear with this phenomenon will be "railing" or "driven to the rails," which just means you are maximizing or minimizing the output based on your supplies. In electronics, positive feedback is often considered a bad thing and sometimes dangerous if not handled properly, since we usually want to be able to effectively control the gain of a device like in negative feedback, but positive feedback does have its uses if it is managed properly.

4.4 The Comparator

A comparator is an op-amp with positive feedback that allows us to control when the voltage is driven to a specific supply. This circuit will look almost identical to an inverting amplifier, but it will be setup with positive feedback instead of negative feedback.

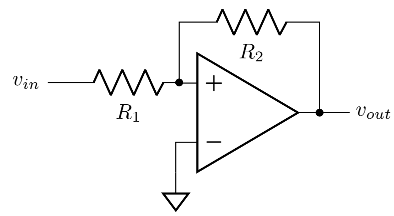

Figure 7: Comparator circuit with positive feedback.

Similar to a voltage divider, we will need to think of this in states depending on which supply is driving the output. For this, let's make $R_1 = 1k\Omega, R_2 = 10k\Omega$ with our supplies being $\pm 5V$.

Let's start with the positive supply driving the op-amp output, meaning that $5V$ is being sent at v_{out}. If $v_{in} = 0V$, or the input is off for now, the voltage at v_+ would be $0.45V$ using the voltage divider equation. Nothing too crazy so far. Let's try with the negative supply driving the output. Doing the same math with $v_{in} = 0V$, our voltage at v_+ is now $-0.45V$, nearly a full volt difference between the two. This means that our circuit has two possible outcomes when $v_{in} = 0V$. When this happens, we say that the circuit has a **hysteresis voltage**, meaning that the end results of the circuit will depend on previous states of the circuit.

With positive feedback circuits, we cannot assume $v_+ = v_-$. Instead, we have to work with the idea that v_+ and v_- can be adjusted independently. That said, we can still assume that there is no current flow between v_+ and v_-, so we essentially have two independent circuits that impact v_{out}. Thinking back to Equation 1, when $v_+ \approx v_-$, our output becomes inconsistent, but with the voltage divider on the positive feedback it is stabilized a bit. Starting with v_{out} driving at $+5V$, as we adjust v_{in} to when $v_+ - v_- < 0V$, our output will switch from $+5V$ to $-5V$. This will happen at a specific threshold that we can calculate using Kirchhoff's Current Law and our voltage divider equations. In fact, the same equation we used with the inverting amplifier, Equation 6, will work here. The only difference is we are setting $v_+ = v_-$ instead of assuming they are equal in the first place. Solving for v_{in}, we can make the equation below:

$$v_{in} = -v_{out} * R_1/R_2 \tag{10}$$

Using an output voltage of $5V$, we can calculate that an input voltage of $-0.5V$ will give us a $0V$ difference between our inputs, and reducing the input voltage further will start driving the output of the op-amp to $-5V$. On the other side, if we start with $-5V$, we can calculate that proving an input voltage larger than $0.5V$ will start driving the op-amp to $+5V$. This is very useful as this allows us to reduce noise in a signal, and only cause a change if a threshold is met and if the change is happening in the proper direction. The other interesting thing here is that we have two threshold voltages, not just one like with negative feedback. This means that we can monitor two voltages at one time, which comes in use with sensors. One example is in household thermostats, where we would like to turn on a a heater if it gets too cold in a room, and then turn it off once the temperature in the room reaches a certain value.

5 Real Op-Amps

Just like every component we use, the math only gets us so far, and we need to face the realization that the components in real life will not work quite as perfectly as we would hope. We will discuss some of the limitations of real op-amps in this section. All of these specifications can be found in the data sheet of the op-amp that you are using. Make sure that the op-amp will work for your applications!

5.1 Open Loop Gain and frequency

As mentioned at the beginning of the reading, an op-amp has an open loop gain that is ideally infinite, but at the least very large, often on the order of 10^6 or larger. This actually only holds true up to a specific frequency due to limitations of the internals of the op-amp known as the **gain-bandwidth product or unity-gain frequency**. Once you surpass this frequency, the open loop gain will start dropping below 1 almost instantaneously, and the principles of the op-amp discussed throughout this entire document will no longer hold. Depending on the op-amp, this limitation is usually at least past $1MHz$, but make sure to check the datasheet to be certain. If you are planning on working on very high frequency projects, you will need to make sure your op-amp can handle those frequencies.

5.2 Common Mode Voltages and Voltage Swing

It would be great if we could put in whatever voltages we wanted into an input of an op-amp and it would output appropriately, but sadly, that is not the case. Every op-amp has a **common mode voltage** range which will instruct you on the range of voltages that you can send into your op-amp inputs. These are almost always defined as a function of the supply voltages, so if you are supplying $\pm 5V$ and the data sheet says that the max common mode voltage is $V_+ - 1.5V$ and a minimum of $V_- - 0.1V$, your common mode voltage range is $-5.1V < v_{in} < +3.5V$. If you move outside of this range, the op-amp will not work in a linear fashion, as in all of the equations we discussed in this reading will not apply. The LF356 and LM324N, op-amps we will be using in lab, have wide common-mode voltage ranges, especially at lower voltages. Because of this, voltage ranges will not be a huge concern for this lab, but make sure to keep this in mind for future labs and projects.

Just like our inputs, our outputs also have limitations, known as the voltage swing of the op-amp. The voltage swing will tell us how much of the supply voltage we can actually output, often no more than a half of a volt inside the supply voltage. This will often be described in the same location as the common-mode voltages on the data sheet and will also be defined with the supply voltages. If you are supplying $\pm 5V$ and the data sheet says that the maximum voltage swing is $V_+ - 0.2V$ and a minimum of $V_- + 0.2V$, your voltage swing is $-4.8V < v_{out} < +4.8V$. So, we can get close to our supply voltage on the output, but not quite there. This becomes a larger issue when you are working with small supply voltages, but you will also see some datasheets give different ranges of swing voltages at different supply values. Make sure you keep this in mind when choosing an op-amp for an application. If you are trying to get out the entire supply voltage, you will likely see clipping, or your signal not quite making it to the supply due to your swing voltage.

5.3 Input Currents

Like a voltmeter, we like to think an op-amp has no current flow between the inputs, but we also know that is not the case. There will be a very small amount of current that flows through the inputs, known as the **input bias current** which can cause a small voltage drop between resistors helping with feedback, which will lead to some error on the output. Fortunately, this is usually in the nano-amp range, which will have virtually no effect in this lab, but can become really important in low-voltage and low-current applications. When discussing the input currents between the two inputs, we are now discussing the **input offset current**, which is the difference between the two biases. Due to the internals of an op-amp, your inputs will likely draw slightly different amounts of current even if they are attached to the same source. Higher-precision op-amps will often have a pin that will allow you to adjust your offset current to a more precise level if you need to.

5.4 Slew Rate

Throughout this document, we have been talking as if these shifts in voltage happen instantaneously, and to us they might seem to. In reality, these changes happen over the course of a few microseconds, known as the **slew rate**. The slew rate changes based on the op-amp. For example, the LF356 can change at $12V/\mu s$, which is fine for our applications, but other applications might need a faster rate, such as the ZL40120, which has a slew rate of over $1000V/\mu s$! In reality, this will mean that our output will be slightly delayed compared to our input. Depending on your applications, especially in fast-switching applications, this can become a big deal.

6 Integrated Circuits

Op-Amps and many other types of circuits we like to combine into one device, such as timers, microcontrollers, and even processors, are rather complex and often require a lot of precision when making in order for the circuits to work properly. To save time and make the circuits a bit more approachable, integrated circuits, or the little black chips you see on circuit boards, are manufactured to have the internals of the circuit already setup with the inputs and outputs assigned to different pins coming out of the integrated circuit.

6.1 Reading a Datasheet of an Integrated Circuit

Whenever you use an integrated circuit (IC, or often just called a chip), make sure you have the datasheet for it on hand. Every IC that is manufactured commercially should have a datasheet, and if you cannot find one for the IC, it is recommended to not use it. Datasheets can often be found by doing a simple web search for "[IC name] Datasheet," and a datasheet from a reputable source, such as the manufacturer or distributor, will likely be one of the first links. Searching for a "LF356 Op-Amp datasheet" will likely bring up a datasheet from Texas Instruments, who designed the op-amp chip.

Not all datasheets are created equal, but the vast majority will at least have a general description of the IC, a pin-out diagram, a data table with voltage and power recommendations and limits, and often a general block diagram of operation.

6.2 Setting Up an Integrated Circuit on a Breadboard

All DIP (dual in-line packages) IC's (rectangular chips with pins on the left and right) follow an international standard on how the pins on the chip are numbered and marked, unless **very clearly mentioned** in the datasheet. This makes it easy for us to ensure that the chips are setup properly in our circuits and allows for standardization across the industry. Looking at the top of the IC, you will find the type of chip, along with manufacturer information. You will also see a dot near one of the edges or a notch on one end of the chip. The notch or dot represents the top of the chip. The top left pin is pin 1, and work your way around the chip counter-clockwise to count the pins. For the LF356, pins 1-4 are on the left side going top to bottom. Once you reach the bottom of the left side of the chip, move directly across to the bottom right side, and work your way back up. The bottom right pin for the op-amp is pin 5, and the top right is pin 8. The LM324 has 14 pins, 7 on each side. This may take some getting used to, but once you work with many different chips, this counting becomes second nature.

Once you know the layout of the pins on your IC, you can add it to your breadboard **over a bridge on your breadboard**, or the gap that separates the rows of 5 pin holes on each side. This allows you to have 4 pin holes allocated to each pin of the IC to attach different wires and components to.

Prelab

7 Understanding Real Op-Amps

In this lab, we will be using the LF356 single op-amp and the LM339 quad comparator. For each of these chips, find the below values and explain what limitations they introduce into our experiments:

- Maximum supply voltages, or how far away from 0V we can go (both positive and negative supply)
- Minimum supply voltages, or how close we can get to 0V (both positive and negative supplies)
- Common Mode Voltage Range
- Voltage Swing Range

Note: Some datasheets are better than others, and formatting is not standard, even if you get the datasheets from the same manufacturer. Sometimes the values will be in a table, graph, or even just stated in a paragraph. Using the find function on a PDF will make quick work of this!

Another note: When looking up the datasheets for these chips, you will find that the datasheets actually cater to multiple chips, such as the LM324N, LM224N, and the LM124N. The changes in the chip numbers or letters denote slight modifications in the chip that change some of the application settings, but are not worth making a separate datasheet for. Make sure you are looking at the right data for the right chip.

8 AC vs DC input to an Op-Amp

1. Design an op-amp circuit with the LF356 op-amp that will have a gain of -1.5.
2. If the op-amp is supplied with $\pm 5VDC$, what is the maximum and minimum voltages we can input into the op-amp and still receive a full signal? Determine a positive and negative DC, and an AC signal in V_{pp}. Assume an ideal Op-Amp.
3. Design an op-amp circuit with the LF356 op-amp that will have a gain of +10.
4. If the op-amp is supplied with $\pm 5VDC$, what is the maximum and minimum voltages we can input into the op-amp and still receive a full signal? Determine a positive and negative DC, and an AC signal in V_{pp}. Assume an ideal Op-Amp.
5. Simulate both of these circuits in Spice and test your input voltages at each state to verify your math. Do your values match up? If no, why might this be? Do some research if you need to. **Note:** You will likely not find the LF356 or LM324 in LTspice. You can use a generic "JFET-input operational amplifier" in the simulation.

9 The Adjustable Gain Amplifier

1. Design an op-amp circuit with the LF356 op-amp and a 10K potentiometer that will have an adjustable gain from -1 to as close to 0 as possible.
2. What limitations, such as input voltage range, will this amplifier have? What are some ways we can accommodate for those limitations? Will these limitations change depending on the gain of the op-amp? If yes, how?
3. Redesign the circuit so the largest gain (farthest away from a gain of 0) the op-amp can produce is -5. What is the smallest gain (as close to 0) that the op-amp can produce using the 10K potentiometer?
4. What limitations, such as input voltage range, will this amplifier have? What are some ways we can accommodate for those limitations? Will these limitations change depending on the gain of the op-amp? If yes, how?

In Lab

General Note with Op-Amps: Op-amps like a stable supply voltage. Any fluctuations in their supply voltage will cause them to act erratically, and it makes it difficult to get a stable output. Our bench power supplies and even the USB power outputs in your computer fluctuate, so plugging your supplies directly to your op-amp without any additional assistance will make it a difficult task to get good data. To compensate for this, add a **decoupling capacitor** to both your positive and negative supply. For our labs, 0.1uF capacitors will work just fine. Reference the below diagram for guidance. You will want to keep the capacitors close to the op-amp electrically if possible. This is to say, the less wire you have between the decoupling capacitors and the op-amp, the better.

NOTE: Set current limit at 0.1A to prevent chips from burning.

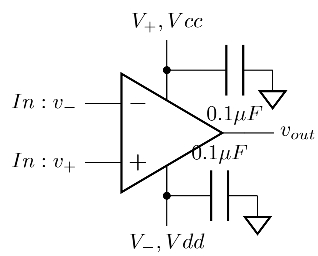

Figure 8: General schematic for an Op-amp with decoupling capacitors

10 AC vs DC input to an Op-Amp

1. Construct the circuit you designed in prelab task 8.1, powered with $\pm 5VDC$. Don't forget about supplying power to V_+ and V_-! Op-amps are **active components,** meaning they need external power to work properly. Remember that **your input voltages are different than your supply voltages.** Do not connect v_+ and V_+!

2. Measure the output voltages by manually sweeping from -5V DC to +5V DC by at most 0.5V divisions (use your function generator if you only have one negative supply on your power supply). Calculate your percent error. Do these output values match what you would expect based on the gain of your op-amp? Why or why not? Try changing some parameters of the circuit to get a more desired output. What did you change? Why do you think the changes worked?

3. Measure the output voltages sweeping from amplitudes of 0Vp to 5Vp by at most 1Vp divisions (remember the difference between Vp and Vpp). Capture a screenshot from the oscilloscope that effectively shows the gain between the input and the output of the op-amp. Do these output values match what you would expect based on the gain of your op-amp? Why or why not?

4. Complete the above steps for the circuit you designed in prelab task 8.3. Use Voltage Steps of at most 0.1V between necessary ranges to properly show the effective gain.

5. Based on the data you collected, develop a statement that describes how an op-amp acts with AC and DC input voltages. Defend your statement, and explain what should be kept in mind moving forward in future labs and experiments.

11 The Adjustable Gain Amplifier

1. Construct the circuit you designed in prelab task 9.1 powered with $\pm 5VDC$. Use an input of 2.5Vpp at 440Hz (Concert A4, or the A above middle C on a piano).

2. Capture screenshots from the oscilloscope showing your maximum, minimum, and moderate gain from your circuit with cursors or measurements showing the input and output voltage values. What does the output represent in this situation?

3. Instead of the oscilloscope, attach your circuit output to a speaker, and verify your circuit acts the way you think it does in reference to the above question.

4. Repeat the above steps for the circuit you designed in prelab task 9.3.

5. What do you notice about the outputs of your circuit at high gains? Why is this happening? How can we accommodate for this phenomenon?

12 The Comparator

Comparators (op-amps with positive feedback) are very useful if used properly, so helpful that there are integrated chips that already setup a platform for very fast and stable state switching. In that spirit, we will be using the LM339 comparator in the below tasks.

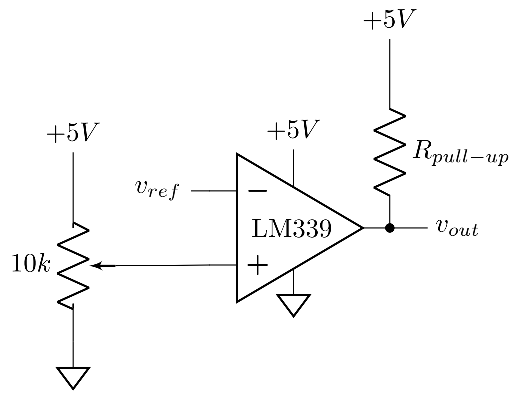

Figure 9: General integrated comparator setup

1. Construct the circuit seen in Figure 9 using a triangle wave with a .5Hz, 2.5Vpp signal with a +2.5V DC offset, and a pull-up resistor value of $1K\Omega$. Set the 10K potentiometer to have a 2.5V output on the wiper.
   Note: Notice that we are not using a negative supply here. Op-amps/comparators do not need to have both a positive and a negative supply, they will work with only one or the other.
   Important! The LM339 has a very different pinout compared to the LM324. Make sure you have the datasheet available so you are attaching everything properly!

2. Capture a screenshot of an oscilloscope showing the input signal and the output of the comparator with cursors showing the voltage at which the output switches with both states.

3. Remove the pull-up resistor from the circuit. What happens? Why is the pull-up resistor necessary?

4. Pull-up resistors are a standard practice in digital circuits, such as with buttons and other 2-state devices. Based on your observations here, why would a pull-up resistor be helpful in these situations?
   Note: Pull-down are also used by attaching the output to a ground instead of a voltage source. Take a moment to think about why we would use both of these and where each situation might be useful.

5. Reattach the pull-up resistor to the output of the LM339. Adjust the potentiometer so that a significantly different voltage is being sent to the non-inverting input. How did this change the behavior of the comparator? Capture a screenshot of an oscilloscope showing the input signal and the output of the comparator with cursors showing the voltage at which the output switches with both states.

6. Attach a LF356 op-amp without the pull-up resistor in parallel with the LM339, such that it has the same potentiometer, and triangle wave at the inputs, and the same supply inputs. View the output of both the LM339 and the LF356 at the same time on the oscilloscope. For clarification, both the LF356 and the LM339 should be operational, with the same 10K potentiometer and the same triangle wave as inputs for both chips. The outputs should be separate.

7. Capture a screenshot of an oscilloscope showing the input signal and the outputs with cursors showing the voltage at which the output switches with both states.
8. Add noise to your triangle wave by combining the triangle wave and a noise signal with the function generator. Use a noise values of 1Vpp, and a frequency of 10KHz. Capture a screenshot of an oscilloscope showing the input signal and the outputs with cursors showing the voltage at which the output switches with both states.
9. What do you notice about the behavior of the comparator compared to a normal op-amp? Why should we use a comparator instead of just an open-loop op-amp in a situation like this?

13 Bonus Task: Modifying a Comparator (+10%)

Based on the reading, the comparator circuit that was used above does not act the way the math says it should. In order to get a 2-threshold system, positive feedback needs to be implemented with the LM339. Using the LM339, design and construct a positive feedback circuit with threshold voltages of -1.5V and 1.5V. Use XY mode on an oscilloscope to show that the thresholds are met and to visually see the hysteresis voltage.

14 Bonus Task: Integrator and Differentiator Circuits (+15%)

Do some research on integrator and differentiator circuits, more than what is provided in this reading. Design, construct, and test both a stable integrator and a stable differentiator circuit. Cite your sources and justify the design of the circuit you made.