MODULE 03

OP-AMPS I

PREREQUISITES: MODULE 02: INTRODUCTION.

OUTLINE OF MODULE 03:

What you will learn about in this Module:

- Most important & commonly used Op-Amp performance characteristics
- Ideal Op-Amp behavior
- Basic Op-Amp circuits & applications

What you will build in the lab:

You will build several basic Op-Amp circuits, then you will test them using a signal generator and an oscilloscope.

INTRODUCTION:

Operational Amplifiers (Op-amps) have revolutionized the design of analog circuits because of the range of applications to which they can be applied. Op amps have become one of the most common and inexpensive components in analog circuitry due to their versatility.

What is an amplifier? Like many things in the engineering world, amplifiers are defined by their function. Amplifiers in general, and op-amps in particular, can perform many useful electronic functions. They can increase the *amplitude* of a signal, for example, a low-voltage signal from a microphone can be amplified to any desired voltage level. The amount of amplification is referred to as the *gain*. It is easiest to think of the gain as simply the ratio of the output to the input signal of an amplifier:

$$gain: \quad A_0 = \frac{Output}{Input}$$

In the simplest case, the output and input have the same units (such as voltage), so the gain is just a dimensionless number. If the low-level microphone signal was a sine wave with peak-to-peak amplitude of 1 mV, for example, and you amplified the signal by a gain of -2000, then the resulting output signal would be a sine wave with a peak-to-peak amplitude of 2 V, and the sine wave itself would be inverted with respect to the original signal due to the negative value of the gain. It is common for amplifiers to have either positive or negative gains, and gain factors of millions or even billions are easily achieved with modern amplifiers. Typically, an amplifier will have a |gain| ≥ 1, but this is by no means always the case.

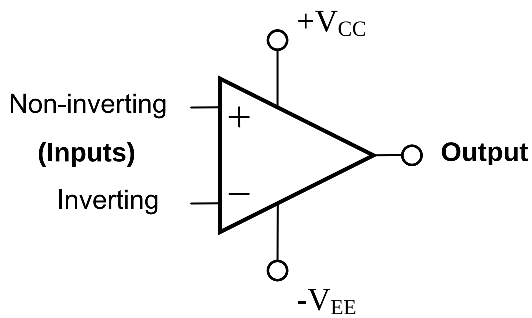
The thing that makes op-amps so tremendously useful is their functional versatility. In addition to simply functioning as a linear multiplier to increase the amplitude of a signal, op amps can easily be configured to perform many other functions:

- Simply follow a signal; output = input (called a *follower* or *buffer*, for signal isolation)
- Add a constant voltage to a signal (called *offset*)
- Add two or more voltages together (called a *summing* amplifier, can add + & - signals)
- Amplify the difference between two signals (called a *difference* amplifier)
- Change the input or output characteristics of a circuit (impedance or capacitance)
- Filter the signal to exclude certain frequency components (*low*, *high*, or *band-pass* filters)
- Integrate a signal over time (*integrator*, very useful in feedback control)
- Differentiate a signal (*differentiator*, also useful in feedback control, edge detection)
- Increase the power output capability of a circuit (called a *power* amplifier)
- Generate waveforms, such as sine waves (called an *oscillator* or *function generator*)
- Compare two signals and indicate which is greater (called a *comparator*)
- Compare two signals with an added hysteresis, to exclude noise spikes (*Schmidt trigger*)
- Mathematical transformations, such as linear input to log scale output (*log converter*)
- Detect the maximum (or minimum) value of a signal (called a *peak detector*)
- Detect and hold the maximum or minimum value of a signal (*sample-and-hold*)
- Determine when the amplitude of a signal is zero (called a *zero crossing detector*)
- Convert a current signal to a voltage (called a *transimpedance* amplifier)
- Convert a voltage signal to a current (called a *transconductance* amplifier)

The really powerful thing about op-amps is that they can often combine two or more of the above functions into a single amplifier stage, so that a great deal of sophisticated analog signal processing can take place without using up too much space, power, or money. They are so versatile that it is even possible to build an analog computer using op-amps. Prior to the maturation of digital computing, analog computers composed chiefly of precision op-amps (before the days of large-scale integration) were used to model very complex dynamic systems, such as aircraft (e.g. the Harrier AV-8 jump jet). One reason that analog computers eventually lost out to digital computers is that analog memory remained expensive and cumbersome.

For the latter two functions of op-amps (*transimpedance* and *transconductance* amplifiers), note that the gain is no longer unitless, but rather has units of V/I (volts per amp) or I/V, respectively. The terms *transimpedance* and *transconductance* arise from Ohms law (refer to Modules #1 and #2), where V/I = R (impedance), and I/V = R^{-1} (*conductance*, the inverse, more or less, of impedance). This type of signal conversion is exceedingly useful for engineers and scientists, since many sensors will generate a small electrical current (micro or nano amps, or less) in response to a signal, but our data acquisition systems generally require the input of a relatively large voltage signal (often ± 10.0 V). Often the required signal conversion and amplitude gain can be achieved with only one or two op-amps and a few external components to tune the circuit appropriately, as we will shortly discuss in detail.

Op-amps are represented by the symbol shown in the figure below. It is common for op-amps to be supplied on a single integrated circuit chip, with either one, two, or four op-amps on a single IC, where each op-amp cam be operated independently. Each op-amp has two inputs and one output. The inputs are designated inverting (-) and non-inverting (+). The figure can be drawn with either input on top, so it is necessary to label the inputs accordingly (+ or -) on each op-amp in a circuit. The power supply terminals (+V_{CC} and –V_{EE}) must always be connected on the physical integrated circuit chip, but they are often not shown on the circuit drawing (they are implied).



The basic idea when using an op-amp is that one generally connects the output to one of the inputs using resistors or capacitors to provide feedback. The feedback components allow the output to be scaled to the input. Most op-amps use voltage feedback, but there are also a few current feedback op-amps available, which are also known as *Norton amplifiers*. Because they are by far the most commonly used type of op-amp, the remainder of this module will deal only with voltage-feedback op-amps. We will discuss Norton Amplifiers in a later module.

Op-amps adhere to the following two rules (ideally):

1- No current flows into either of the inputs
2- The op amp will adjust its output to try to keep both inputs at the same voltage

Real op-amps do not perfectly adhere to this “ideal” behavior, but they are close enough that you can use these two rules to simplify your initial designs.

The number of possible uses of op-amps is so large that many books have been published on just this topic. These books are often called “op-amp cook books”, since they can contain hundreds of useful circuits. In most cases the circuits are based upon the assumption that the op-amps behave ideally (as defined above), which for many practical applications is a good approximation of the truth. As a result, many people use op-amps every day without having any knowledge of the inner workings of these fiendishly clever devices. Although it is always best to know exactly how a device works, the best place to begin learning about op-amps is simply to identify a technical problem involving analog signals (i.e., pick a project), crack open a “cookbook”, follow the directions (i.e., build the circuit), then test and characterize the performance of the circuit you built. As your confidence and skill increase, you’ll see opportunities to use op-amps in more sophisticated and challenging applications, and you’ll discover that the manufacturer's datasheets are in fact NOT just filled with useless reams of meaningless numbers, but actually are often not quite replete with the technical minutiae that you need to select the best op-amp for your specific needs. There are op-amps that have been devised for every conceivable application. Soon you will discover to your simultaneous delight and horror that the world of electronics has about a trillion different op-amps to sell to you (just go to www.digikey.com, and search for "op-amp", then lash yourself to the mast for a rocky ride).

To ease you into the limitless world of op-amps, for the laboratory we will select only two op-amps that we have found to be generally useful for a wide range of applications (the LM324 and the LF444).

READINGS FROM HOROWITZ AND HILL (H&H): *ART OF ELECTRONICS*

Browse through Chapter 4, but pay close attention to the following sections: Introduction, 4.01-4.06, 4.08
Read carefully the section "Impedances of sources and loads" on pages 65-66.

ADDITIONAL READINGS & INTERNET RESEARCH:

Go to the National Semiconductor web page and locate Applications Note 4 (AN-4): "Monolithic Op-Amp: The Universal Linear Component"

For the laboratory exercises, you will need to go to the National Semiconductor web page and find the datasheet for the LM324 (or LM324A) Op-Amp, in the "Plastic DIP" package. You will need this to figure out the pinout of the IC, so that you know where to connect the positive and negative power, and how to connect to each amplifier on the IC (one IC has 4 separate Op-Amps on it, so it is called a "Quad Op-Amp"). You will eventually also need the datasheet for the LF444, so you should find that also.

1- See if you can find any "Op-Amp Cookbooks" posted on the Web.

2- Do any of the following manufacturers have Applications Notes that are collections of Op-Amp circuits?

- National Semiconductor
- Texas Instruments (Burr Brown)
- Motorola
- Maxim-ic (Dallas Semiconductor)
- Microchip

3- Is there such a thing as a book that is essentially nothing more than a collection of Op-Amp Circuits? (try amazon.com)

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SELF QUIZ

1: Without looking back at the text you just finished reading, list as many different functions as you can remember that an op-amp can perform in a circuit.

2. Use the datasheets for the LM324 and the LF444 to find the input impedance of each of these types of amplifier. Which has the larger input impedance, and how big is the difference between these two?

3. Going back to Module 2, compare the input impedance of these amplifiers with that of the oscilloscope, both with and without a 10X probe. How large is the difference?

4. Why is input impedance an important thing to pay attention to for amplifiers and test equipment?

PLEASE ANSWER THE ABOVE QUESTIONS AND E-MAIL TO THE INSTRUCTOR
"I have neither given nor received aid on this examination, nor have I concealed any violation of the Honor Code"

X____

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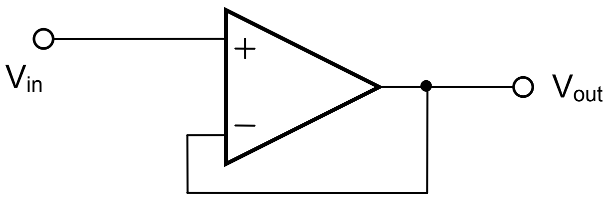
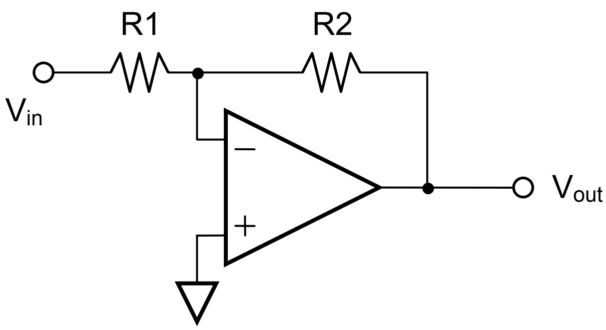
LABORATORY PROJECTS

1- Use ExpressSCH to draw the circuits shown below (use the LM324 component).

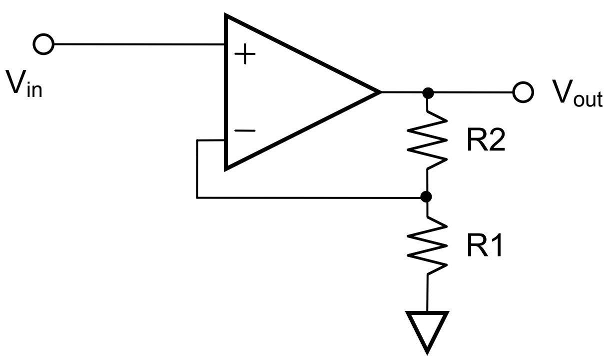
2- Use an LM324A Quad Operational Amplifier to build the following circuits. You should begin with a Vector Prototyping Board and a 14-pin DIP Socket (with gold-coated contacts). Place the socket so that it straddles one of the long power busses on the prototype board, and so that each pin on the socket will connect with a patch that will allow additional components to be soldered to the same patch.



Buffer (voltage follower)
Gain = 1
Output = Input
Useful for isolating analog signals, for example, to achieve improved output impedance.



Inverting Amplifier
Gain = -R2/R1
Output = Input * gain
This is the most basic Op-Amp application. Note that the output will be "inverted", since the gain is negative.



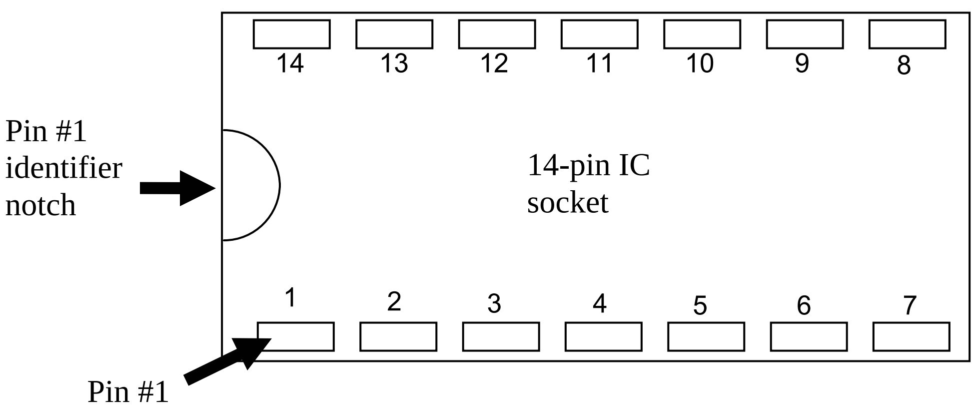
Non-Inverting Amplifier
Gain = 1 + (R2/R1)
Output = Input * gain
This is another common Op-Amp application. Note that the output will not be inverted since the gain is positive.

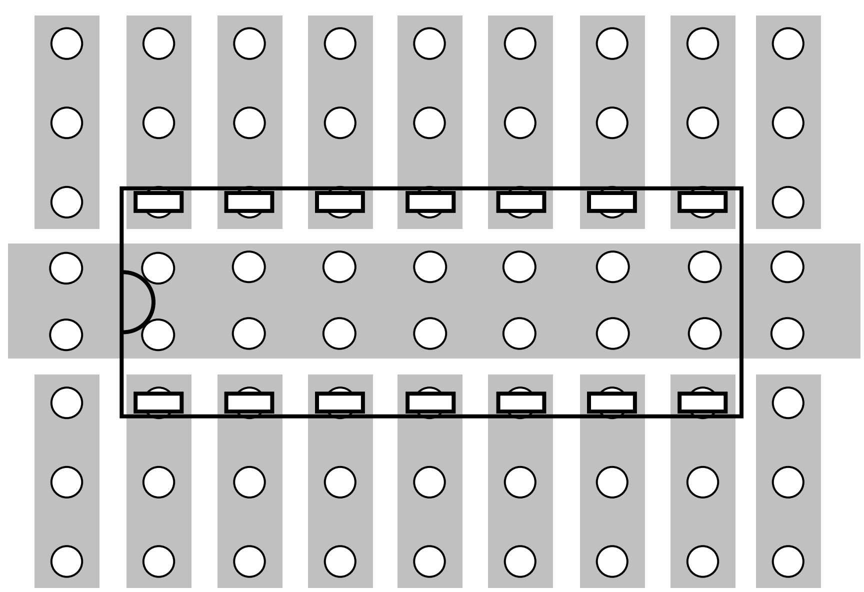
Set the resistor values such that the gain of the inverting amplifier is about -2, and the gain of the non-inverting amplifier is approximately 2.

Hints: The little downward-pointing triangle means "ground". There are several other symbols for ground (see H&H). For the resistors, generally you want to use resistors in the range of 1K to 1M. Lower resistor values tend to allow unnecessarily large currents to flow and larger values allow such a small amount of current that the circuit becomes more vulnerable to noise.

First, you will want to use an IC socket. It is a little plastic socket that allows you to plug in and remove ICs without having to solder and de-solder the IC directly. Use a 14-pin IC socket from the parts cabinet.

The figure below is a Top view of a 14-pin IC socket: you will plug your op-amp into this socket later, when you have finished building your circuit. Note from the sketch below that the IC socket will have a notch in one end to identify Pin #1. This will help to keep you from plugging in the IC backwards. Plugging in an IC backwards and applying power usually results in the IC being destroyed, and is often accompanied by interesting hissing sounds, the generation of prodigious amounts of heat, and occasionally even smoke. Rule of thumb: if you can *smell* your circuit, something is probably wrong.





When soldering your IC socket into place, you should put the pins into the PCB so that they line up with the solder patches as shown in the diagram above. Imagine for a moment that you have X-Ray vision, and can see through the PCB while soldering…it should look like the figure above. The light gray areas are the solder patches (they are actually covering a thin copper film on the PCB underneath). You connect components, such as resistors, to your IC by soldering them into the patches that connect to the IC pins. Note that the components, including the IC socket, are usually placed on the blank side of the PCB (the opposite side from the solder). Thus, every PCB has two sides: a *component* side, and a *solder* side. This is not always true…sometimes we need to place components on the solder side, and frequently you will see that there are conductive traces on both sides of a modern PCB. This is called a "two-sided" board. In fact, many modern computer PCBs are "multi-layer" boards, with conductive traces on both the top and bottom, and on several distinct layers within the board itself. You can easily find multilayer boards with up to 7 layers of conductive traces. This is common in computers, aircraft electronics, and spacecraft (to save space and weight).

We will use IC sockets in this course as a convenience, mostly to allow you to easily replace ICs after you test (and sometimes destroy) them. If you decide to use IC sockets in your future circuit designs, you should consider the suggestions below:

<u>Notes about IC sockets:</u>

1. Use IC sockets with gold-plated contacts, they are *much* more reliable (less likely to form oxides on the contacts), and don't cost too much more.
2. IC sockets are a good Idea for prototyping, but for large-scale production boards you should only use them if you know you will probably remove and replace the ICs. Often, the IC socket will cost more than the IC itself! (this should tell you something about how wonderfully inexpensive ICs have become).
3. You should be careful not to bend the IC leads when inserting and removing ICs from the socket. Use a tool to carefully pry the IC, pull it out as straight as possible, try not to tilt it.
4. Some very high speed circuits will not work as well if you use IC sockets because you need to keep the lead length for the IC pins as short as possible. For most circuits you will ever build, this will not be a problem.
5. Make sure to always align the Pin 1 identifier notch on the IC when you are inserting it into the IC socket. All IC sockets have a similar identifier notch.

When inserting an IC into an IC socket, you may need to use an IC insertion tool to bend all of the legs in slightly during the insertion. Alternatively, you can *carefully* bend the legs in slightly by pressing first one row of pins, then the other, of the IC against the table surface before insertion.

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While you are building this circuit, please adhere to the color code for wires that we will use throughout this course:

GREEN = Ground
YELLOW = +5 Volts
RED = +15 Volts (or the highest regulated positive voltage, other than +5 V)
BLACK = -15 Volts (or the highest regulated negative voltage)

We will power the Op-Amps using +15 V for the positive supply, and -15V for the negative supply. Thus, we refer to +15V and -15V as the "supply rails". The op-amp can not generate output values outside of this range. Usually the output range of an Op-Amp will be somewhat less that the "rail-to-rail" voltage, often by a volt or more. Some modern Op-Amps are designated "rail-to-rail outputs", which means that if you feed them +/- 15 volts of power, the output swing from each amplifier can go as high as 15 Volts, or as low as -15 Volts.

After soldering the IC socket into place, you should run wires to the appropriate pins to supply power. Refer to the datasheet for the LM324A Op-Amp (that you found on the web) and wire the power to the op-amp appropriately.

Finally, you should "decouple" the power supplies by adding capacitors between each power pin and ground. Place a 0.1 μF ceramic capacitor between the +15V power pin on the op-amp and ground, using the shortest possible lead lengths on the capacitor. Do the same thing for the -15V supply pin. The trick is to place the capacitors as close to the op-amp as possible. This power supply decoupling will tend to improve the performance of your op-amp circuits because it smoothes out the power supply to the IC.

Once you have built the three amplifiers shown above, you will be connecting the inputs to each amplifier to the Test Points of the signal generator box from Module 02. In order to do this you will need a cable with a BNC connector on one end, and a means to connect to the wired within the BNC cable on the other end. You can use a BNC cable with test clips, or you can use a BNC adapter that has screw post adapters to allow connection to wires. The black clip will always be GROUND, the red clip will always be the signal. You may wish to add small wire loops (using solid wires that have no insulation on them) to your op-amp inputs so that you can easily clip the cable to your circuit. So, for example, you would connect the black clip from the signal generator to a ground point somewhere on your PCB (you may want to solder a bare wire loop into a hole on your PCB connecting to GROUND to make this easy). Then you would connect the red clip from the signal generator to Vin (the input) of one of your amplifiers. You can use a "T" sitting at the signal generator on the BNC terminal so you can also connect to Ch-1 of the O-scope. Finally, you connect the output of the amplifier to Ch-2 of the O-scope, and compare the two signals.

3- The remainder of this Laboratory is simple: Once you have built the three Op-Amp circuits shown above, connect the Test Points from the signal generator (used in Module-02) to the input of each amplifier circuit, one at a time. Then, look at the output from the same amplifier circuit. You should monitor the signals on the O-Scope: input signal on Ch-1, and output signal on Ch-2, for each Test Point on the signal generator. Record what you see below, noting the signal amplitude and other features that you may notice. Feel free to sketch what you see.

TP1:____

TP2:____

TP3:____

TP4:____

TP5:____

TP6:____

TP7:____

TP8:____
(note: try disconnecting the input signal on Ch-1, but leave Ch-2 connected. Does the signal at Ch-2 change when you do this?)

Lastly, compare these with your results from Module-02. In particular, compare the results for TP-8. What are the differences? Why do you see different waveforms at TP-8 if you use a coaxial cable, a 10X probe, and an op-amp buffer? Why is it OK to use a standard test clip to measure the output from the op-amp, but when you do this with the raw output from TP-8 the signal looks much smaller? The simple answer to all of these things is related to the impedances of sources and loads, described in your readings in H&H. Before going on, try to describe it in your own words.

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THE CONCEPT OF INPUT IMPEDANCE:

The concepts of input and output impedance are critical in electronics. If you have not already done so, be sure to carefully read the section "Impedances of sources and loads" on page 65 of H&H. Now that you have read this section, look very closely at the input connectors on the oscilloscope. Right next to the BNC connectors, you will see some tiny writing that tells you the electrical characteristics of the o-scope. In this case, the Tektronix scope reads: "1MΩ, 25 pF"

What this means is that when you connect it to a circuit the oscilloscope will behave as if it were a 1MΩ resistor and a 25 pF capacitor connected from the input point to ground. Sometimes this can have a very significant effect on the signal you are trying to measure as you will see in just a minute. For now, just ignore the capacitor (the 25 pF), and focus on the 1MΩ resistor.

Now go ahead and carefully look at the waveform from TP8 again by hooking the test point output directly to the oscilloscope. Be sure to set your oscilloscope to 1V/division so that you can see the difference in the signal that will happen. You should note the amplitude and offset of the waveform.

Now, disconnect the o-scope from the test point, and use a test clip to connect from TP-8 to the input of the buffer amplifier that you just built. This is the first circuit in the Laboratory Projects above. Be sure to connect the red clip to the op-amp buffer input, and the black clip to a ground point somewhere on your circuit board. Now, connect the output from your buffer back to the o-scope, and again carefully study the measured waveform. Describe the difference quantitatively:

Draw a circuit diagram below showing how the 1MΩ resistor input of the o-scope changes the circuit of TP-8 (hint: this will form a voltage divider with a 10MΩ and a 1MΩ resistor). Does this explain the difference in the two measured signals for TP-8?

It is very important that you understand the concepts of *input impedance* and *output impedance*. These factors will explain about 90% of the "weird" behavior of devices when they apparently work, but then act strangely when you test them.

MODULE 03

FEEDBACK

Was this Module useful and informative?

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Is there a topic that should get more or better coverage?

____

In what way can this Module be improved?

Content: ____

Depth of Coverage: ______________________________________

Style: ____

Any additional comments that will help us to improve this course:

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If you prefer, you may e-mail comments directly to Bob Dennis: yoda@umich.edu