Overview
In this lab we introduce the operational-amplifier (op-amp), an active circuit that is designed for certain characteristics (high input resistance, low output resistance, and a large differential gain) that make it a nearly ideal amplifier and useful building-block in circuits. In this lab you will learn about DC biasing for active circuits and explore a few of the basic functional op-amp circuits. We will also use this lab to continue developing skills with the oscilloscope.

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Background Information

**Dual-in-Line (DIP) Integrated-Circuit Packaging**

All the integrated-circuits (ICs) we will use in ECE 2 use the dual-in-line package (DIP). This is a very common IC package, although many manufacturers are now migrating towards surface-mount technologies using smaller packages with a greater density of pins. The solderless breadboards were designed specifically for use with DIP components.

Figure 4-1 shows an image of some DIP packages along with an internal cross-section and numbering scheme for the pins. Internally the semiconductor chip is connected to the external package leads via tiny gold bond-wires. There is always a notch on one end of the package that serves as an indexing mark for the pin numbers, often accompanied by a small dimple which indicates pin #1. The pins are then numbered sequentially in a counter-clockwise pattern from pin #1. DIP packages can be made with anywhere from 6 pins for simple ICs to 40+ pins for more complex ICs.

**The 741 Op-Amp**

Your textbook and lecture notes will be the key references for this lab as far as the basic operation of ideal op-amps and circuit configurations. Here we will just focus on the specifics of the “741” and relevant practical issues that will come up in the lab.

![741 Op-Amp Pin Diagram](image)

Figure 4-1 – Dual-in-line (DIP) packages and pin numbering.

![741 Schematic](image)

Figure 4-2 – The 741 op-amp pin diagram (8-pin DIP) and schematic.

Op-amps were first developed in the vacuum tube era and then later adapted to transistors. The 741 is a classic design, first introduced in 1968. There are much better op-amps on the market today, but for a long time it was considered the op-amp of choice for most generic
applications. Because if its widespread use and popularity it has one really great feature for ECE 2: it is cheap! We can get them for 27 cents or less in quantities of 100.

The 741 pinout (for 8-pin DIP package) is shown in Figure 4-2, along with a schematic. This information is taken straight from the component data-sheet; you should always review the datasheet before using any IC (the data sheet for the National Semiconductor version of the 741, the LM741, can be found on the course website). Obviously you are not expected to understand the detailed schematic at this stage, nor many of the other details in the datasheet. We are including it here just to illustrate the point that even an old IC like the 741 is not trivial (20 transistors, 11 resistors, and 1 capacitor) though of course it is quite primitive in comparison to modern microprocessors (billions of transistors). The great thing about op-amps is that the external behavior is modeled by some very simple equivalent circuits.

The most important practical fact for beginning students to remember is that **OP-AMPS ALWAYS REQUIRE DC POWER.** Sometimes the power-supply connections are omitted in circuit diagrams just to avoid clutter, but that doesn’t mean they aren’t needed! It is simply impossible for op-amp circuits to work without DC biasing, and most errors in prototyping are simply due to incorrect biasing. Many (but not all) op-amps require both positive and negative supply voltages—that is, a “bipolar” power supply. In the 741 the positive supply voltage is attached to pin-7, and the negative supply voltage is attached to pin-4. Information on the maximum power-supply voltages can be found in the datasheet. For our device it is ±18V max. Although most op-amp circuits can be understood based on the characteristics of an ideal op-amp, the non-idealities of real op-amps are always present to some extent. In this experiment we will discuss two important non-idealities: output saturation and slew rate. Output saturation simply means the op amp cannot force the output voltage beyond the supply voltages. We will be using ±15V in most of the circuits, so the output will not be able rise above +15V or fall below -15V.

**Pre-lab Preparation**

**Before Coming to the Lab**

- Read through the details of the lab experiment to familiarize yourself with the components and testing sequence.
- One person from each lab group should obtain a parts kit from the ECE Shop.

**Required Equipment**

- Provided in lab: Bench power supply, Function Generator, and Oscilloscope
- Student equipment: Solderless breadboard, and jumper wire kit

**Parts List**

<table>
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<tr>
<th>Qty</th>
<th>Description</th>
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<tbody>
<tr>
<td>1</td>
<td>1 k-Ohm 1/4 Watt resistor</td>
</tr>
<tr>
<td>2</td>
<td>4.7 k-Ohm 1/4 Watt resistor</td>
</tr>
<tr>
<td>2</td>
<td>10 k-Ohm 1/4 Watt resistor</td>
</tr>
<tr>
<td>2</td>
<td>LM741CN</td>
</tr>
<tr>
<td>2</td>
<td>Ceramic capacitor, 0.1uF (radial lead, Z5U, 50V)</td>
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In-Lab Procedure

4.1 Op-Amp Basics

First Step: DC Biasing

Op-amps always require DC biasing and therefore it is advisable to configure the bias connections first before adding any other circuit elements. Figure 4-3 shows one possible biasing arrangement on a solderless breadboard. Here we use two of the long rails for the positive and negative supply voltages, and two others for any ground connections that may be required later. Also shown are so-called “bypass” capacitors attached between the power-supply and ground rails. It is too early to discuss the purpose of these capacitors in any great detail, but they are useful to improve the immunity to noise on the supply-lines and avoid parasitic oscillations. It is considered good practice in analog circuit design to always include bypass capacitors close to the supply pins of each op-amp in your circuit.

- Insert the op-amp in your breadboard and add the wires and bypass capacitors as shown in Figure 4-3. To avoid problems later you may want to attach a small label to the breadboard to indicate which rails correspond to $+V_s$, $-V_s$, and ground.

- Next, set the power-supply to produce ±15V and attach the supply and COM connections to the terminals on your breadboard. The use jumper wires to power the rails as shown. Remember, the power-supply COM terminal will be our circuit “ground” reference. Once you have your bias connections, monitor the output current on the power-supply to be sure that there aren’t any inadvertent short-circuits. You may wish to use a DMM to probe the IC pins directly to insure that pin 7 is at +15V and pin 4 is at -15V.

Unity-Gain Amplifier (Voltage Follower)

Our first op-amp circuit is a simple one, shown in Figure 4-4. This is called a unity-gain buffer, or sometimes just a voltage follower, defined by the transfer function $V_{out} = V_{in}$. At first glance it may seem like a useless device, but as we will show later it finds use because of its high input resistance and low output resistance.

- Using your breadboards and the lab bench power supply, construct the circuit shown in Figure 4-4. Note that we have not explicitly shown the power connections here; it is implicitly understood that those connections must
be made in any real circuit (as you did in the previous step), so it is unnecessary to show them in the schematic from this point forward. Use short jumper wires to connect input and output to the generator and oscilloscope alligator clip leads. Don’t forget to ground the scope leads (ground connections are not shown in the schematic).

- Use the function generator at the bench as source $V_g$ to provide a 1 V amplitude (2 V pk-pk), 1 kHz sinewave excitation to the circuit, and observe the output on the oscilloscope. Configure the scope so that the input signal is displayed on channel 1 and the output signal is displayed on channel 2. Make a plot of the two resulting waveforms in your lab notebook, noting the descriptive parameters of the waveforms (peak values and the fundamental time-period or frequency). Your waveforms should confirm the description of this as a “unity-gain” or “voltage follower” circuit.

**Slew Rate Limitation**

Ideally the output will follow the input signal precisely for any input signals, but in a real amplifier the output signal will never respond *instantaneously* to the input signal. This non-ideality can be observed when the input signal is a rapidly varying function of time. For large-amplitude signals this limitation is quantified by the *slew rate*, which is the maximum rate-of-change (slope) of the output voltage that the op-amp is capable of delivering. The units of slew-rate are usually expressed as $V/\mu s$.

- Set the function generator to a square wave signal with a 5 V amplitude (10 V p-p) and increase the frequency until you see a significant departure from ideal behavior, that is, when the output starts looking more like a trapezoid than a square wave. You will probably need to adjust the time scale (Sec/Div) to see this. Make a plot of the output waveforms at this point and measure its 10-90% rise time as defined in Figure 4-5. Also note the peak-to-peak voltage of the output signal. Compute and record the slew rate according to your measurements.

**Buffering Example**

The high input resistance of the op-amp (zero input current) means there is no loading on the generator; *i.e.*, no current is drawn from the source circuit and therefore no voltage drops on any internal (Thevenin) resistance. Thus in this configuration the op-amp acts like a “buffer” to shield the source from the loading effects of the circuit. From the perspective of the load circuit the buffer transforms a non-ideal voltage source into a nearly ideal source. Figure 4-6 describes a simple circuit that we can use to demonstrate this feature of a unity-gain buffer. Here the buffer is inserted between a voltage-divider circuit and some “load” resistance:
□ Turn off the power and add the resistors to your circuit as shown in Figure 4-6 (note we have not changed the op-amp configuration here, we’ve just inverted the schematic relative to Figure 4-4).

□ Turn on the power and set the function generator to a 1 kHz sinusoidal signal with a 2 V amplitude (4 V p-p). Use the scope to simultaneously observe $V_g(t)$ and $V_{out}(t)$ and record the amplitudes in your notebook.

□ Remove the 10 kΩ load and substitute a 1 kΩ resistor instead. Record the amplitude.

□ Now move the 1 kΩ load between pin 3 and ground, so that it is in parallel with the 4.7 kΩ resistor. Record how the output amplitude has changed. Can you predict the new output amplitude?

### 4.2 Simple Amplifier Configurations

**Inverting Amplifier**

Figure 4-7 shows a textbook inverting amplifier with a 10 kΩ “load” resistor at the output. Note that the pin numbers have now been omitted from the diagram. This is often the case with op-amp schematics because pin assignments are too component-specific.

□ With reference to the LM741 pinout diagram in Figure 4-2, write in the pin assignments directly onto the schematic in Figure 4-7.

□ Now assemble the inverting amplifier circuit shown in Figure 4-7 using $R_2 = 4.7\, \text{kΩ}$ . Remember to shut off the ±15 V supply before assembling a new circuit. Cut and bend the resistor leads as needed to keep them flat against the board surface, and use the shortest jumper wires for each connection (as in Figure 4-3). Remember, the breadboard gives you a lot of flexibility. For example, the leads of resistor $R_2$ do not necessarily have to bridge over the op-amp from pin 2 to pin 6; you could use an intermediate node and a jumper wire to go around the device instead.

□ Turn on the power supply and observe the current draw to be sure there are no accidental shorts. Now adjust the generator to produce a 1 volt amplitude, 1kHz sine wave at the input ($V_g$), and again display both the input and output on the oscilloscope. Measure and record the voltage gain of this circuit, and compare to the theory discussed in class. Make a plot of the annotated input/output waveforms in your notebook.

Now is an appropriate time for a comment on circuit debugging. At some point in ECE 2 you are likely to have trouble getting your circuit to work. That is to be expected—nobody is perfect. However, don’t simply assume that a non-working circuit must imply a malfunctioning part or bench instrument. That is almost never true; 99% of all circuit problems are simple wiring or biasing errors. Even experienced engineers can make such mistakes, and consequently, learning how to “debug” circuit problems is a very important part of your learning process. It is NOT the TA’s responsibility to diagnose errors in your circuit, and if you find yourself relying on others in this way then you are missing a key point
of the lab and you will be unlikely to succeed in later coursework. Unless smoke is issuing
from your op-amp or there are brown burn marks on your resistors or your capacitor has
exploded, your components are probably fine—in fact most of them can tolerate a little abuse
now and then! The best thing to do when things aren’t working is to just turn off the powersupply and look for simple explanations before blaming parts or equipment. The DMM is a
valuable detective tool in this regard.

**Output Saturation**

- Now change the feedback resistor $R_2$ in Figure 4-7 from 4.7 kΩ to 10 kΩ. What is the
gain now? Slowly increase the amplitude of the input signal to 2 volts, and carefully
sketch and annotate the waveforms in your notebook.

The output voltage of any op-amp is ultimately limited by the supply voltages, and in many
cases the actual limits are slightly smaller than the supply voltages due to internal voltage
drops in the circuitry. Quantify the internal voltage drops in the 741 based on your
measurements above.

**Summing Circuit**

The circuit of Figure 4-8 is a basic inverting
amplifier with an additional input, called a
“summing” amplifier. Using superposition we
find that the output is a linear sum of signals
from the two sources, each with their own
unique gain:

- With the power off, modify your inverting
amplifier circuit as shown in Figure 4-8.
Use the remaining output of the power
supply for $V_{dc}$. Turn that output all the way
down so that you can adjust up from zero
during the experiment.

- Now apply a 1 volt amplitude sinewave for $V_g$ and 2 volt DC for $V_{dc}$. Observe and record
the input/output waveforms on the oscilloscope screen. Pay close attention to the ground
signal level of the output channel on the oscilloscope screen (note: make sure both
channels are set for DC coupling). When used in this way, such a circuit could be called a
level shifter.

- Pull out the DC offset knob of the function generator and adjust the DC offset until $V_{out}$
has zero DC component. Estimate the required DC offset by observing the input
waveform on the scope (note: it is not $-V_{dc}$, be sure to understand why).

- Push the DC offset knob back in to reset the offset to zero. With channel 2 of the scope
(the channel connected to the op-amp output) set for 5V/div, turn up $V_{dc}$ slowly to +18V.
What happens to $V_{out}$? Record the DC voltage of the output.

- Return $V_{dc}$ to approximately +2V. Set the scope to 1V/div, AC coupled, and adjusted so
you can see the complete $V_{out}$ waveform. Turn $V_{dc}$ back up to 18V. What does the
oscilloscope trace for $V_{out}$ look like? Does the amplifier appear to be amplifying?

The last step is an important lesson: sometimes things don’t appear to be working simply
because we aren’t looking at them in the right way. In this case, with the scope on AC
coupling we can’t see why the output is saturating. No amplifier will function properly if there is a large DC offset that causes the output to saturate.

**Non-Inverting Amplifier**

The non-inverting amplifier configuration is shown in Figure 4-9. Like the unity-gain buffer, this circuit has the (usually) desirable property of high input resistance, so it is useful for buffering non-ideal sources:

- Assemble the non-inverting amplifier circuit shown in Figure 4-9. Remember to shut off the ±15 V supply before assembling a new circuit. Use the decade resistor box for $R_2$ and start with $R_2 = 1k\Omega$.

- Apply a 1 volt amplitude, 1 kHz sine wave at the input, and display both input and output on the oscilloscope. Measure the voltage gain of this circuit, and compare to the theory discussed in class. Make an annotated plot of the waveforms in your notebook.

- Increase the feedback resistance ($R_2$) from 1 kΩ to about 9 kΩ. What is the gain now?

- Increase the feedback resistance further until the onset of clipping, that is, until the peaks of the output signal begin to be flattened due to output saturation. Record the value of resistance where this happens. Now increase the feedback resistance to 99 kΩ. Describe and draw waveforms in your notebook. What is the theoretical gain at this point? How small would the input signal have to be in order to keep the output level to less than 10V given this gain? Try to adjust the function generator to this value. You may need to use the 0.2V button on the function generator, which reduces the output amplitude. Describe the output achieved.

The last step underscores an important consideration for high-gain amplifiers. High-gain necessarily implies a large output for a small input level. Sometimes this can lead to inadvertent saturation due to the amplification of some low-level noise or interference, for example the amplification of stray 60Hz signals from power-lines that can sometimes be received. Amplifiers will amplify anything at the input terminals…whether you like it or not!

### 4.3 The Op-Amp as a Comparator

The high intrinsic gain of the op-amp and the output saturation effects can be exploited by configuring the op-amp as a comparator as in Figure 4-10. This is essentially a binary-state decision-making circuit: if the voltage at the “+” terminal is greater than the voltage at the “−” terminal, $V_g > V_{ref}$, the output goes “high” (saturates at its maximum value). Conversely if $V_g < V_{ref}$ the output goes “low”. The circuit compares the voltages at the two inputs and generates an output based on the relative values. Unlike all the previous circuits there is no feedback between the input and output; we say that the circuit is operating “open-loop”.

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Comparators are used in different ways, and in ECE 2B and 2C we will see them in action in several labs. Here we will use the comparator in a common configuration that generates a square wave with a variable pulse width:

- Start by reducing the op-amp supply voltages to \( \pm 5V \) as shown in Figure 4-10, then shut off the power and assemble the circuit. As with the summing circuit earlier, use the remaining output of the power supply for the DC source \( V_{ref} \), and turn that output all the way down so that you can adjust up from zero during the experiment.

- Again configure the function generator \( V_g \) for a 2V amplitude sinewave at 1kHz. With the power supply on and \( V_{ref} \) at zero volts, record the output waveform.

- Now slowly increase \( V_{ref} \) and observe what happens. Record the output waveform for \( V_{ref} = 1V \). Keep increasing \( V_{ref} \) until it exceeds 2V and observe what happens. Can you explain this?

- Repeat the above for a triangular input waveform and record your observations.

**Extra Credit**

For students who finish early or want an extra challenge, see if you can modify the comparator circuit using your yellow and green LEDs (from the last lab) at the output so that the yellow LED lights for negative voltages and the green LED lights for positive voltages. Turn down the frequency to 1Hz (or less) so you can see them turn on-and-off in real time. Don’t forget that the LEDs will need a current-limiting resistor so that the current through it is no more than 20mA.

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**Congratulations!**

You have now completed Lab 4

As noted in the previous lab: keep all your leftover electrical components!

**Specific Discussion Items for Lab Report**

Some specific ideas for the report might be as follows:

- Slew rate: discuss how you measured and computed the slew rate in the unity-gain buffer configuration, and compare this with the value listed in the 741 data sheet.

- Buffering: explain why the buffer amplifier in Figure 4-6 allowed the voltage divider circuit to function perfectly with differently load resistances.

- Output saturation: explain your observations of output voltage saturation in the inverting amplifier configuration and your estimate of the internal voltages drops. How close does the output come to the supply rails in this experiment and also later when used as a comparator with different power-supply voltages? Can you guess what the output voltage swing would be for an op-amp that is advertised as a “rail-to-rail” device?

- Summing circuit: using superposition, derive the expected transfer characteristic for the circuit of Figure 4-8; that is, find the output voltage in terms of \( V_g \) and \( V_{dc} \). Compare the predictions of the ideal relationship with your data.

- Comparator: discuss your measurements and what would happen if the polarity of \( V_{ref} \) is reversed.