| YOUR NAME: | YOUR SID: |
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| YOUR PARTNER'S NAME: | YOUR PARTNER'S SID: |

Pre-Lab Score: ___/40
In-Lab Score: ___/60
**Total: ____/100**

# Operational Amplifiers

LAB 3: Operational Amplifiers

ELECTRICAL ENGINEERING 40

INTRODUCTION TO MICROELECTRONIC CIRCUITS

University Of California, Berkeley

Department of Electrical Engineering and Computer Sciences

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Lab Contents:

## Lab Objectives

This lab will familiarize you with the properties and operation of operational amplifiers. In this lab we will use the TLC227 operational amplifier to implement several different practical configurations of the operational amplifier. In the next lab, we will build up an instrumentation amplifier from discrete parts so that you can add it to your final project.

In the pre-lab, you will first simulate the different configurations for the operational amplifier: inverting, non-inverting, comparator mode, and Schmitt trigger. Make sure to bring your circuit schematics with you to the lab.

During the lab, you will build the circuits that you simulated in the pre-lab and explore the non-idealities of real world implementations.

## Pre-Lab Component

In this lab we will be working with a strange device known as the operational amplifier. The operational amplifier is used extensively in circuit applications throughout the field of electrical engineering, and so it is worth your while to master the art of using the operational amplifier. Unfortunately, understanding the internal circuitry of the operational amplifier is beyond the scope of this course (see EE140) so we will just focus on the basics.

Operational amplifiers are (obviously) used to amplify electrical signals by a certain factor known as the gain. In theory operational amplifier have infinite gain; however, practical operational amplifiers have very large gain, which is sufficient for a majority of DC applications. Later in the course we will learn about the limitations and finite gain bandwidth for AC applications, but we're not concerned about that at the moment.

Because the gain of the operational amplifier is very large, we use negative feedback to control the gain of a given configuration.

Once again we will be using Multisim for our simulation purposes in the pre-lab.

Before we start, however, we're going to take a peek at the datasheet for the operational amplifier we will be using throughout this lab, the TLC277.

You can find the datasheet here. Datasheets contain information pertaining to the functionality, limitations, and practical applications of the IC chip and are indispensible.

### Datasheet

Now that you have the datasheet, we want to make sure you actually take a peek at it.

We will be using the Dual-In-Line package version of the TLC277 in the lab. Draw the pin diagram of the TLC277 below (i.e. just copy it from the datasheet to the space below). Notice that it has two op amps and is hence a "dual" package.

**Score __/2**

On some pin diagrams, there are pin outs labeled "NC". What does "NC" stand for? (The LM6482 does NOT have a NC but ICs that you encounter in the future may. **(1pt)**

In the pin diagram, which pin numbers and labels are the positive and negative power supply connections of the TLC277? **(1 pt)**

Positive supply label: Pin:

Negative supply label: Pin:

NOTE: The operational amplifier is an active component and requires power. If you fail to connect the power connections for circuit components that require power, they will not work.

## The Inverting Amplifier

One of the uses of an operational amplifier that you will repeatedly encounter throughout this course is the inverting amplifier configuration. The inverting amplifier amplifies a signal input by a gain but also inverts the polarity of the signal. Recall that the open loop gain of an ideal operational amplifier is given by $A = \infty$ and the output voltage is given by $V_{out} = A(v_+ - v_-)$ or $V_{out} = \pm\infty$.

So clearly we can see that in the open loop configuration for the operational amplifier, we can only obtain $\pm\infty$ as the output or, more practically, the high or low bounds of the supply voltage (since in practice we cannot create infinite potential).

In order to solve this problem, we implement a negative feedback loop shown in the figure below which will allow us to construct a system with a finite closed loop gain.

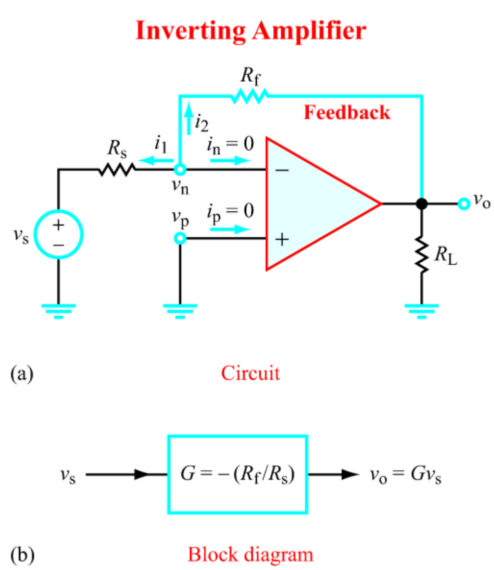



Figure 4-9: Inverting amplifier circuit and its block-diagram equivalent.[1]

[1] Ulaby and Maharbiz, Circuits. Figure 4-9

The above figure shows a simple inverting amplifier configuration with negative feedback. Given the assumptions of an ideal operational amplifier, show that the relationship between $V_o$ and $V_s$ is given by:

$$V_o = -\frac{R_f}{R_s} V_s$$

*We want you to mathematically **prove** this statement in the space below. (Hint: Use the summing point constraint)

**Score __/5**

Now fire up Multisim and simulate this circuit. Use a DC voltage source as $V_{in}$ and connect the power supplies to $V_{cc} = 5V$ and $V_{ss} = -5V$. Attach a printout of your simulation to this lab report. **(5 points)**

Now using the equation you derived for the output voltage of an inverting amplifier, pick a pair of values for $R_f$ and $R_{in}$ such that $V_{out} = -5V_{in}$. Verify in Multisim that $V_{out} = -5V_{in}$ by varying $V_{in}$ and probing the output.

$R_f =$ ☐ $R_{in} =$ ☐ **(1 point)**

**The Non-Inverting Amplifier**

The inverting configuration has a negative gain (hence the inverted polarity) but suppose we wanted a positive gain. We use the non-inverting configuration to accomplish this.

Below is one of the standard implementations of the non-inverting amplifier. Notice we still use a negative feedback loop but we configure the feedback loop such that the output voltage is not inverted as shown in the figure below.

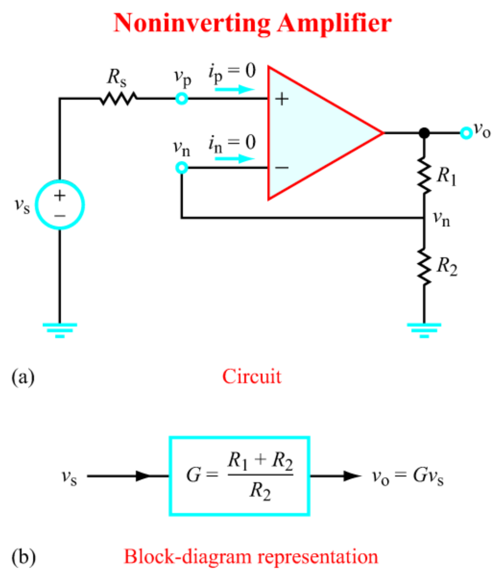



Figure 4-8: Noninverting amplifier circuit: (a) using ideal op-amp model, and (b) equivalent block-diagram representation.

Once again, using the assumptions about ideal operational amplifiers, **prove** that the relationship between $V_{out}$ and $V_{in}$ is given by:

$$V_{out} = \left(1 + \frac{R_1}{R_2}\right) V_{in}$$

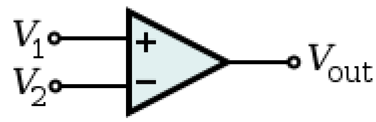
**Score __/5**

Now **simulate this configuration** in Multisim and verify that the gain is in fact positive for all voltages. Also attach a print out of this schematic to your lab report. **(5 points)**

**The Comparator**

The inverting and non-inverting amplifiers are both configured with a negative feedback loop in order to amplify the input signal by a reasonable gain factor. But what if we simply wanted the output to be high or low? Would we still use a negative feedback loop?

Below is a diagram of the comparator. At first glance, we find that the comparator will saturate to the high voltage supply or the low voltage supply because the open loop gain of the operational amplifier is very large.




Also we recall that the output voltage is given by:

$$V_{out} = A(V_+ - V_-)$$

In this case, $V_+ = V_1$ and $V_- = V_2$.

In practice, the output voltage of the operational amplifier is limited by the range of the positive and negative power supply voltages. If the output voltage $V_{out}$ falls into the range outside the supply voltages, we obtain a condition known as saturation. In this case, the operational amplifier will simply output the highest or lowest voltage available, which are the values of the high and low supply voltages[2].

It is fairly simple to see that the output voltage would be given by the following ($V_{supply} = V_{cc} = -V_{ss}$):

$$V_{out} = V_{supply}\ if\ V_1 > V_2$$

$$V_{out} = -V_{supply} if\ V_1 < V_2$$

Keeping this in mind, suppose we wanted to design a circuit which would output high or $V_{supply}$ if the input voltage $V_1 > \alpha V_{supply}$ (and low or $-V_{supply}$ otherwise), where $\alpha$ is a constant and $-1 < \alpha < 1$. Draw the circuit below using ONLY one comparator, two resistors $R_a$, and $R_b$, and supplies $V_{cc}$, and $V_{ss} = -V_{cc}$. Clearly label the positive and negative supply voltages, the input voltage $V_1$, and the output voltage $V_{out}$. Also find a relationship between $R_a$, $R_b$, and $\alpha$.

| |
|---|
| **Score __/5** |

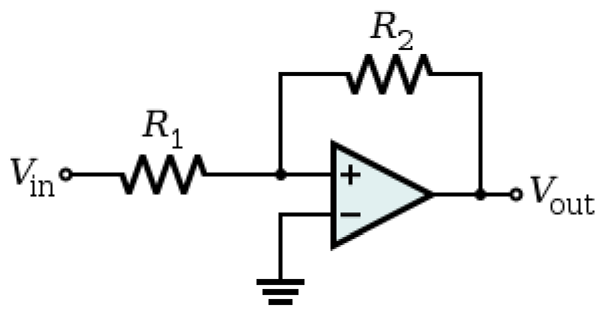
[2] Not all op-amps are capable of driving the output all the way to the supply voltage. While some op-amps, such as the LMC6482 have a so-called “rail-to-rail” output, an op-amp without this feature may only be able to drive the output to within a volt or two of the supply. In our case, the TLC277 does not have a rail-to-rail output.

**The Schmitt Trigger**

One of the most common uses of a comparator is on-off control. Suppose we would like to build an electronic thermostat that switches a heater on and off to maintain a constant room temperature. This could be built out of a comparator: just connect a temperature sensor to the (+) input, a constant voltage to the (-) input, and the heater to the output (perhaps through a relay). There is only one problem: a tiny decrease in temperature will turn the heater on, and a similarly tiny increase will turn it off. This very rapid cycling will be very annoying and will quickly wear out the heater.

A practical thermostat operates somewhat differently from the simple comparator circuit. If it is set to 68 degrees, it might turn on the heater when the room temperature drops below 67 degrees, and only turn it off when the temperature goes above 69 degrees. This behavior is known as hysteresis: rather than being fixed, the thermostat's setpoint changes depending on whether the heater is on or off. How could we add this feature to our comparator circuit?

In turns out that we can use positive feedback using a configuration called a Schmitt trigger to accomplish this. Below is a diagram of the Schmitt trigger:




Non-Inverting Schmitt Trigger[i]

We know that the relationship between the input voltages and output voltages is once again:

$$V_{out} = A(V_+ - V_-)$$

Now consider the Schmitt trigger schematic more carefully. At first glance it would appear that if $V_{in}$ is positive, then $V_{out}$ is saturated to $V_{cc}$ ($V_{cc} > 0$), and if $V_{in}$ is negative, then $V_{out}$ is saturated to $V_{ss}$ ($V_{ss} < 0$). This is mostly correct, except for when $V_{in}$ changes from positive to negative voltage, and from negative to positive voltage.

The transition from $V_{cc}$ to $V_{ss}$ occurs at a negative threshold $V_{thr-}$ and the transition from $V_{ss}$ to $V_{cc}$ occurs at a positive threshold voltage $V_{thr+}$. The difference between these thresholds is the hysteresis. These voltages are given by the following equations: (don't worry, you'll get to derive them yourself in a little bit)

$$V_{th+} = \frac{R_1}{R_2} V_{supply} \qquad V_{th-} = -\frac{R_1}{R_2} V_{supply} \qquad (V_{supply} = V_{cc} = -V_{ss})$$

Given this information, let's perform a brief thought experiment. Suppose the input voltage $V_{in}(t)$ is given by $V_{cc}\sin(\omega t)$. In the space provided below, draw the waveform $V_{out}(t)$. Assume that $R_2 = 2R_1$. Label all relevant points in terms of the given variables and briefly explain your reasoning.

**Score __/5**

Now derive the above equations for $V_{thr+}$ and $V_{thr-}$. (Hint: start with the output at $V_{cc}$ or $V_{ss}$; what input voltage will make the comparator switch to the other state?)

**Score __/5**

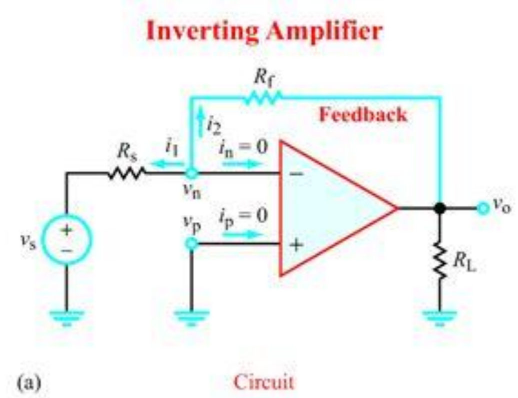
# Lab Section

## The Inverting Amplifier

So now that we've analyzed and analyzed each configuration in the pre-lab, it is now time to actually build these circuits to compare the theory against actual practice.

We will start first with the inverting amplifier. Recall from the pre-lab that the gain for the inverting amplifier configuration is given by:

$$G = -\frac{R_f}{R_{in}} \text{ and } V_{out} = GV_{in}$$




Let's start by attempting to build an inverting amplifier circuit with a gain of your choosing. Fill in the table for the given values of $R_{in}$ and $R_f$ using $\pm 5V$ as your supply voltages to the operational amplifier.

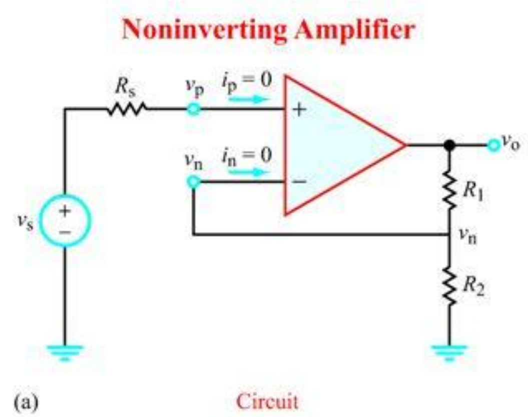
Use a digital power supply as $V_{in}$ so that you can pin point the input voltage and record the output voltage $V_{out}$ for each gain and input. Record your data in the space provided below. **(7 pts)**

| $R_{in}$ | $R_f$ | Theoretical Gain | $V_{in}$ | $V_{out}$ | Actual Gain |
|---|---|---|---|---|---|
| $1k\Omega$ | $1k\Omega$ | | $1V$ | | |
| $1k\Omega$ | $1.8k\Omega$ | | $1V$ | | |
| $1k\Omega$ | $4.7k\Omega$ | | $1V$ | | |
| $1\text{k}\Omega$ | $10k\Omega$ | | $1V$ | | |
| $4.7k\Omega$ | $1k\Omega$ | | $-3V$ | | |
| $4.7k\Omega$ | $4.7k\Omega$ | | $-3V$ | | |
| $4.7k\Omega$ | $20k\Omega$ | | $-3V$ | | |

**The Non-Inverting Amplifier**

Recall that the gain for a non-inverting amplifier is given by:

$$V_{out} = \left(1 + \frac{R_1}{R_2}\right) V_{in}$$




Once again build the circuit and use the programmable power supply as the input voltage given the following values for $V_{in}$ and $V_{out}$, and using $\pm 5V$ as the operational amplifier supplies. **(7 pts)**

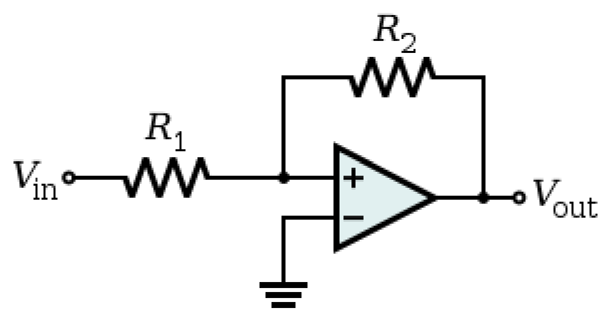
| $R_1$ | $R_2$ | Theoretical Gain | $V_{in}$ | $V_{out}$ | Actual Gain |
|---|---|---|---|---|---|
| $1k\Omega$ | $1k\Omega$ | | $1V$ | | |
| $1k\Omega$ | $1.8k\Omega$ | | $1V$ | | |
| $1k\Omega$ | $4.7k\Omega$ | | $1V$ | | |
| $1k\Omega$ | $10k\Omega$ | | $1V$ | | |
| $4.7k\Omega$ | $1k\Omega$ | | $-1V$ | | |
| $4.7k\Omega$ | $4.7k\Omega$ | | $-1V$ | | |
| $4.7k\Omega$ | $20k\Omega$ | | $-1V$ | | |

**The Schmitt Trigger**

From the pre-lab, we determined that the Schmitt trigger in theory will switch from high to low at different voltages depending on whether the input voltage goes from high to low or from low to high. Now all we have to do is see it in action.

Below is the Schmitt trigger from the pre-lab:

$$V_{th+} = \frac{R_1}{R_2} V_{supply} \; AND \; V_{th-} = -\frac{R_1}{R_2} V_{supply}$$




Non-Inverting Schmitt Trigger[ii]

First, we want a quick way of verifying whether this threshold voltage switching behavior exists. To do this, we will simply use a function generator and input a sine wave into the Schmitt trigger.

Build the Schmitt trigger given above and use the function generator as the input voltage. Make sure to the set the peak-to-peak voltage to 10V for the function generator. Frequency is set to be 1 kHz.

Choose the values of $R_2$ and $R_1$ such that the threshold voltages $V_{th+} = 1V$ and $V_{th-} = -1V$. Once again use $\pm 5V$ as supply voltages to the operational amplifier. Probe the input and output voltages with the oscilloscope.

Which of the following output waveforms did you observe (Circle one)? Hint: Pick C **(1 free pt)**

A. Sine B. Sawtooth C. Square D. DC Constant

We will now construct the hysteresis curve of the Schmitt trigger. A hysteresis curve is a graph of the input voltages versus output voltages for any given circuit system. In our case for the Schmitt trigger the hysteresis curve is the input voltage $V_{in}$ versus the output voltage $V_{out}$.

Before we move on, show your Schmitt trigger to your TA. Make sure to have it set up so that you can see both the input sinusoidal waveform and the output waveform at the same time on the scope.

Your TA Signs Here **(15 pts)**

In the space below, graph two periods of the input waveform superimposed with the output waveform of the Schmitt trigger. Clearly mark any relevant values such as trigger voltages and distinguish the two waveforms.

**Score __/5**

Now let's analyze this graph. If we look at the voltages at which the output waveform switches from low to high and from high to low, we should find that the voltage on the input waveform at the switch corresponds to one of the threshold voltages we calculated in the pre-lab.

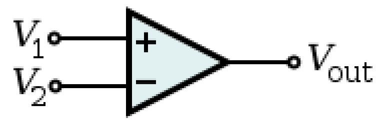
Now suppose we want to graph the hysteresis curve of our trigger. Let's consider one period of the sinusoidal input wave. During this one period, we sweep all possible voltages in the range from low to high and from high to low. Let's say that the input voltage sweeps from high to low first. From the pre-lab, we know that the output will remain at $V_+$ until we arrive at the threshold voltage $V_{th-}$ where it will change to $V_-$. The Schmitt trigger has a similar behavior when it sweeps from low to high.

Using this information and your observations from your oscilloscope, graph the hysteresis curve of the Schmitt trigger in the space provided below clearly labeling the axis, threshold voltages, and increments. If there are asymptotes, indicate them with a dotted line. Remember you must consider two cases, when the input goes from low to high and when the input goes from high to low. **Identify and indicate the direction** of each curve with an arrow in your graph, especially in the areas where the curves do not have the same value.

**Score __/5**

**The Comparator**

Since you've solved the Schmitt trigger section above, this section should be relatively easy. The hysteresis curve of the comparator if similar to that of the Schmitt trigger except the threshold voltages are the same.




Comparator[iii]

In addition, we know that the threshold voltage can be set by connecting the threshold voltage to either the inverting or non-inverting terminals of the operational amplifier. Recall from the pre-lab that the positive and negative threshold voltages are the same for a comparator.

Connect the positive and negative power supplies to the operational amplifier as before.

Connect the function generator to the non-inverting terminal of the operational amplifier – once again make sure the peak to peak value of the waveform is 10V.

Connect the programmable power supply to the inverting terminal of the operational amplifier and set it to zero.

Now probe the output of the operational amplifier with an oscilloscope.

What you should observe is yet again a square wave with a peak to peak value of $V_+ - V_-$ and a duty cycle of 50%.

Now play with the value of the programmable power supply.

In the space provided below, explain how changing the DC input at the inverting terminal affects the output waveform and explain how your conjecture agrees with the derivations in the pre-lab. Also notice that the comparator is just a Schmitt trigger with an infinite feedback resistor (hence an open circuit).

**Score __/5**

Once again, show your setup to your TA and demonstrate the changing duty cycle of the output waveform on your oscilloscope.

Your TA Signs Here **(15 pts)**

## Lab Report Submissions

This lab is **due at the beginning** of the next lab section. Make sure you have **completed all questions** and **drawn all the diagrams** for this lab. In addition, **securely** attach any loose papers specified by the lab and submit them with this document.

These labs are designed to be completed in **groups of two.** Only one person in your team is required to submit the lab report. Make sure the names and student IDs of **BOTH** team members are on this document (preferably on the front).

### Image Citations

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[i] http://en.wikipedia.org/wiki/Schmitt_trigger

[ii] http://en.wikipedia.org/wiki/Schmitt_trigger

[iii] http://en.wikipedia.org/wiki/Comparator