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

Operational Amplifiers

LAB 3: Operational Amplifiers

ELECTRICAL ENGINEERING 43/100

ELECTRONIC TECHNIQUES FOR ENGINEERING

University Of California, Berkeley

Department of Electrical Engineering and Computer Sciences

Professor: Kris Pister

Lab Contents:

Lab Objectives

This lab will familiarize you with the properties and operations of operational amplifiers. In this lab we will use the TLC277 operational amplifier to implement several different practical configurations of the operational amplifier.

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

The operational amplifier is used extensively in circuit applications all throughout the field of electrical engineering, so it would be worth your while to master the art of using it. 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 for a majority of DC applications is sufficient. Later in the course we will learn about the limitations and finite gain bandwidth for AC applications.

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.

Pre-Lab Assignment

1. Read lectures notes on amplifiers posted on Piazza.
2. Complete the prelab questions over the next few pages (**40 points**).
3. Familiarize yourself with the rest of this document before arriving in lab!
4. Watch the online lab lecture videos related to this lab. It may help to watch them before you attempt the pre-lab questions.
5. Read notes on oscilloscope usage on Piazza.

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 on Piazza or on google. 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, 8 pin version of the TLC277 in the lab. Draw the circuit diagram of the TLC277 below (i.e. just copy it from the datasheet on page 3 to the space below). This tells us the pin references on the IC with respect to our circuit. Notice that it has two op amps and is hence a "dual" package. Please draw the high-level diagram with the pins labeled, not the transistor-level circuit.

Pre-Lab Score __/3

On some pin diagrams, there are pin outs labeled "NC". What does "NC" stand for? (The TLC277 does NOT have a NC but ICs that you encounter in the future may. **(Pre-Lab 1pt)**

In the circuit diagram, which pin numbers and labels are the positive and negative power supply connections of the TLC277? **(Pre-Lab 4 pts)**

Positive supply label: ________ Pin : ____

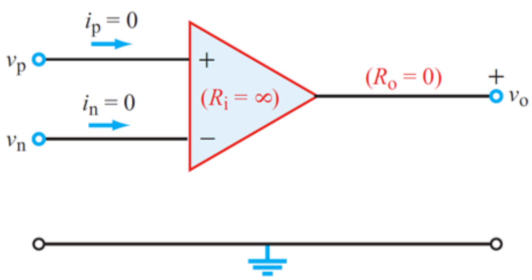
Negative supply label: ________ Pin: ____

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, it will not work.

Operational Amplifier Basics

The two main characteristics of an ideal op-amp are the following: Infinite gain (ie, a change in even a fraction of a millivolt in the input will swing the output over its full range), and infinite input impedance (absolutely zero current will flow into the inputs). To apply circuit analysis with ideal op-amps, use nodal analysis but with these "golden rules" shown below: (1) no current flows into the op-amp and (2) the input voltages are identical if the op-amp is in a **negative feedback configuration**. Please see the lecture notes posted on Piazza for more information on amplifiers.

Circuit Analysis With Ideal Op Amps



Ideal Op Amp

- Current constraint $i_p = i_n = 0$
- Voltage constraint $v_p = v_n$
- $A = \infty$ $R_i = \infty$ $R_o = 0$

- Use nodal analysis as before, but with these "golden rules":
- $v_p = v_n$ (Ideal op-amp model). Both inputs are at the same voltage
- $i_p = i_n = 0$ (Ideal op-amp model). No current into op amp
- Do not apply KCL at op amp output

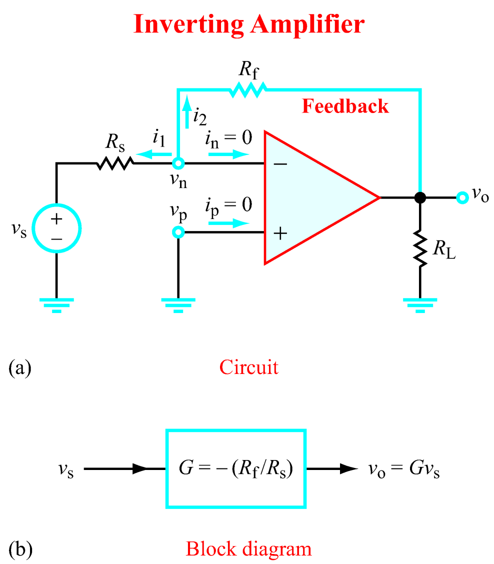
$V_p = V_n$ only for negative feedback configurations

Here are some helpful Wikipedia articles about op-amps and the applications we study below:

http://en.wikipedia.org/wiki/Operational_amplifier#Operation
http://en.wikipedia.org/wiki/Inverting_amplifier#Inverting_amplifier
http://en.wikipedia.org/wiki/Inverting_amplifier#Non-inverting_amplifier
http://en.wikipedia.org/wiki/Schmitt_trigger#Non-inverting_Schmitt_trigger

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 parity of the signal. Recall that the open loop gain of any ideal 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]

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.)

Pre-Lab Score __/5

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

Now fire up Multisim and simulate the inverting amplifier circuit. Use a DC voltage source as V_{in} and connect the power supplies to $\boldsymbol{V_{cc} = 5V}$ **and** $\boldsymbol{V_{ss} = -5V}$. Use the TLC277CP (or TLC272CP for older versions of Multisim) op-amp in the Analog component category. Attach a print out of your simulation to this lab report. **(Pre-Lab 5 points)**

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

$R_f =$ ☐ $R_s =$ ☐ **(Pre-Lab 1pt each)**

The Non-Inverting Amplifier

The inverting configuration has a negative gain (hence the inverted parity) 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.

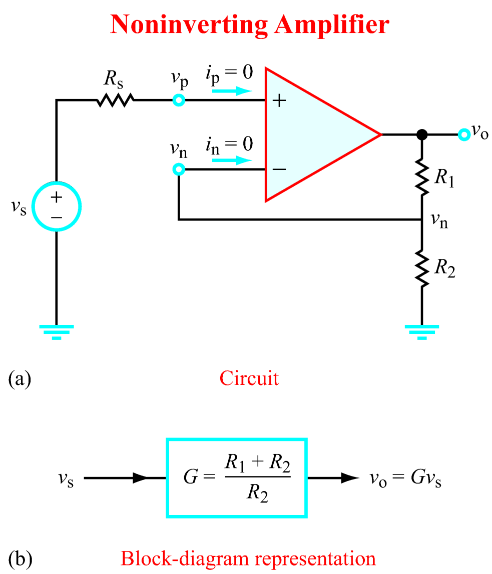


Figure 4-8: Noninverting amplifier circuit: (a) using ideal op-amp model, and (b) equivalent block-diagram representation.

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

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

Pre-Lab Score __/5

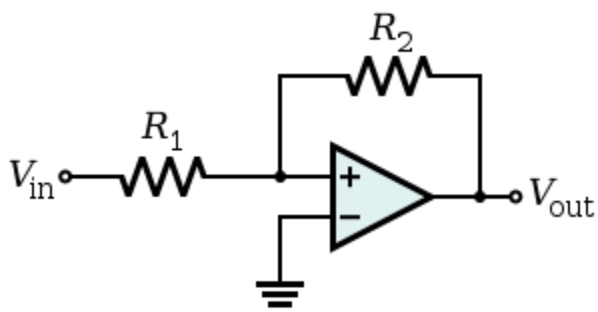
Now **simulate this configuration** in Multisim and verify that the gain is in fact positive for all voltages. Also attach a print out of this schematic to your lab report. **(Pre-Lab 5 points)**

The Schmitt Trigger

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?

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. At first glance, we find that the Schmitt trigger will saturate to the high voltage supply or the low voltage supply because the closed loop gain of the operational amplifier in the positive feedback configuration is very large. **Note, V_p is not equal to V_n, in the positive feedback configuration.**



Non-Inverting Schmitt Trigger[i]

Also we recall that the output voltage is given by:

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

In practice, the range of the positive and negative power supply voltages limits the output voltage of the op-amp. 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.

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+}. To completely understand the derivation behind the threshold voltages requires some background into the internal circuitry of operational amplifiers, so we will just provide you with the end result.[2]

The positive threshold voltage V_{thr+} and negative threshold voltage V_{thr-} are given by:

[2] We recommend you take EE140, which covers transistors and operational amplifiers, for further details if you're interested.

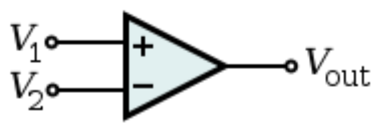
$$V_{th+} = \frac{R_1}{R_2} V_{supply} \; AND \; V_{th-} = -\frac{R_1}{R_2} V_{supply} \quad (V_{supply} = V_{cc} = -V_{ss})$$

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 $R_2 > R_1$. Label all relevant points in terms of the given variables and briefly explain your reasoning.

Pre-Lab Score __/5

The Comparator

The switching thresholds of the Schmitt trigger is sometimes undesirable because there are two possible output voltage states for every input voltage. To avoid this slightly annoying aspect of the Schmitt trigger, we use a configuration called a comparator shown below. [ii]



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

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

Where in this case $V_+ = V_1$ and $V_- = V_2$.

It is fairly simply 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 configure a circuit which would output high or V_{supply} if the input voltage $V_1 > V_2 = \alpha V_{supply}$, where α is a constant between -1 and 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 and R_b. (hint: use R_a and R_b as a voltage divider to set the threshold αV_{supply})

Pre-Lab Score __/5

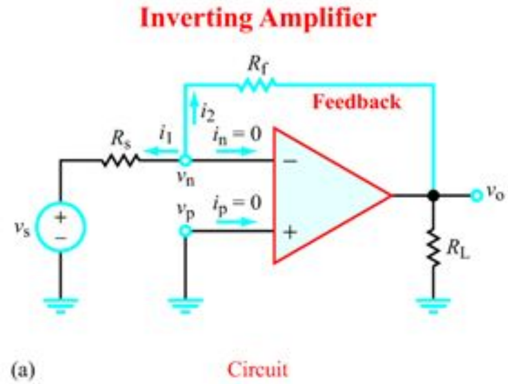
Lab Section

The Inverting Amplifier

So now that we've analyzed each configuration in the pre-lab, it is 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:

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



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

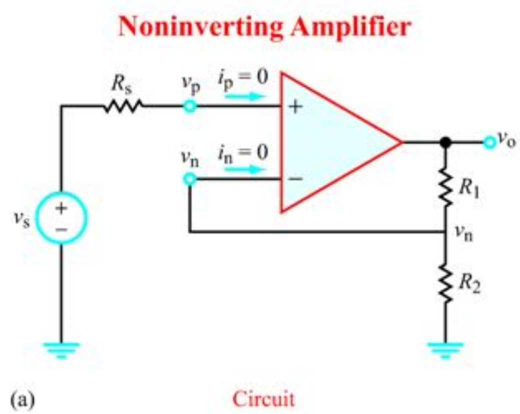
Use a digital power supply as V_{in} so that you can pinpoint the input voltage and record the output voltage V_{out} for each gain and input. Record your data in the space provided below. **(7 pts)**

R_s	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)

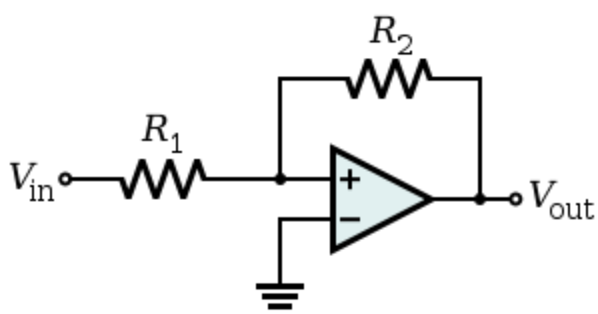
R_1	R_2	Theoretical Gain	V_{in}	V_{out}	Actual Gain
$1k\Omega$	$1k\Omega$		$1V$		
$1k\Omega$	$1.8k\Omega$		$1V$		
$1k\Omega$	$4.7k\Omega$		$1V$		
$1k\Omega$	$10k\Omega$		$1V$		
$4.7k\Omega$	$1k\Omega$		$-1V$		
$4.7k\Omega$	$4.7k\Omega$		$-1V$		
$4.7k\Omega$	$20k\Omega$		$-1V$		

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[iii]

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)? **(1 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.

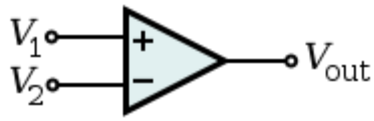
Now suppose we want to graph the hysteresis curve of our trigger. Let's consider one period of the sinusoidal input wave. During this one period, we sweep all possible voltages in the range from low to high and from high to low. Let's say that the input voltage sweeps from high to low first. From the 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 is similar to that of the Schmitt trigger except the threshold voltages are the same.



Comparator[iv]

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 end** of the lab section. Make sure you have **completed all questions** and **drawn all the diagrams** for this lab. In addition, 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). The prelab is done individually.

Image Citations

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[i] http://en.wikipedia.org/wiki/Schmitt_trigger
[ii] http://en.wikipedia.org/wiki/Comparator
[iii] http://en.wikipedia.org/wiki/Schmitt_trigger
[iv] http://en.wikipedia.org/wiki/Comparator

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