Lab 4: Introduction to Operational Amplifiers

Objective:

This lab explores the characteristics of operational amplifiers and investigates several simple circuits.

- Basics of how to hook up and use op amps.
- Voltage amplifiers (inverting and non-inverting).
- The follow/buffer amplifier.
- The Transimpedance amplifier (current-to-voltage converter).

Reading Assignments:

- National Semiconductor Application Note (AN-20):
  In particular, the following sections:
    - Introduction
    - The Inverting Amplifier
    - The Non-Inverting Amplifier
    - The Current-to-Voltage Converter

- Skim the LF356 OpAmp Data Sheets
- "Detectors.pdf"

PreLab Questions:

[PL1] What are the roles of each of the 8 pins on the LF356 chip?

[PL2] What is the expected voltage gain of Figure 1? Show the equations for this.

[PL3] What is the expected voltage gain of Figure 2? Show the equations for this.

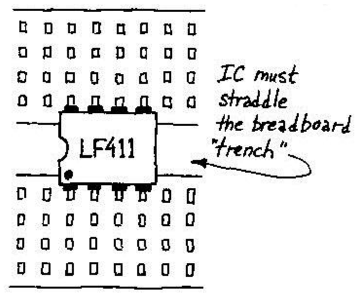
[PL4] "Design" a Transimpedance (TIA) op amp circuit to produce an output voltage of 1V for an input current of 100nA, from a photodiode. Draw the complete circuit, including 0.1 μf capacitors that bypass each power supply pin to ground, and a 100pf capacitor in parallel with the feedback resistor.

Lab Exercises:

A. Basic Operational Amplifier Circuits

Two points before we begin:

1. First, note how the IC package goes into the breadboard. The chip is called "DIP" for dual-inline package. It straddles the trench or gap.



2. A point that may seem to go without saying, but sometimes needs a mention: the op amp always needs power, applied at two pins; nearly always that means ±15V. We remind you of this because circuit diagrams ordinarily *omit* the power connections. On the other hand, many op amp circuits make no direct connection between the chip and ground. Don't let that rattle you; the circuit always includes a ground—in the important sense: common reference called zero volts.

Note: Use an LF356 op amp for all of the circuits below.

1. **Inverting Amplifier** (30 min. estimated amount of time):

Construct the inverting amplifier shown in Figure 1. Drive the amplifier with a 1kHz sine wave.

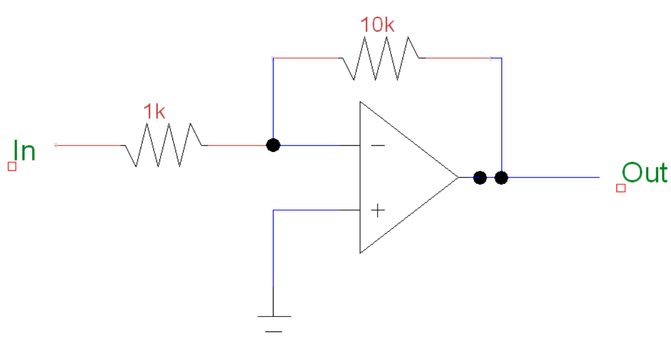


Figure 1. Inverting Amplifier

[Q1] What is the measured gain of this circuit? How does this value compare with the pre-lab?

2. Non-inverting Amplifier (15 min. estimated amount of time):

Wire up the non-inverting amplifier shown in Figure 2.

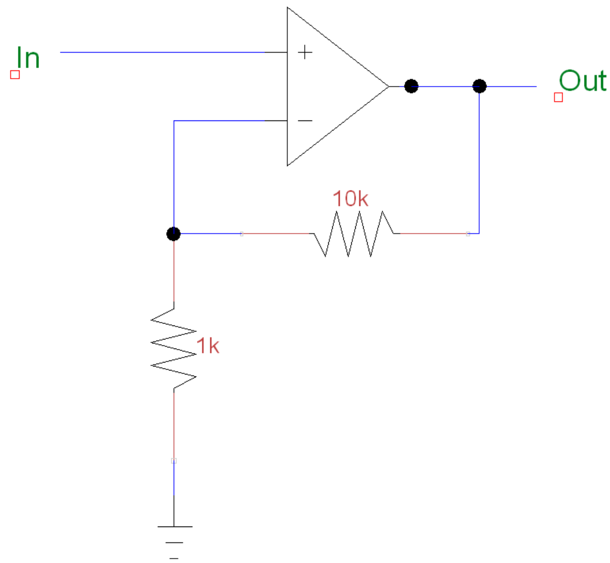


Figure 2. Non-Inverting Amplifier

- **[Q2]** What is the measured gain of this circuit? How does this value compare with the pre-lab?
- **[Q3]** Sketch the input and output voltage waveforms for a 1 kHz input sine wave with 1 volt amplitude.
- **[Q4]** Repeat for a 1 kHz input square wave with 1 volt amplitude. Is there evidence that the output is being limited by the slew rate of the op-amp? Increase the frequency until you begin to see this.

3. Follower/Buffer Amplifier (15 estimated amount of time):

Build the follower shown in Figure 3. Check out its performance.

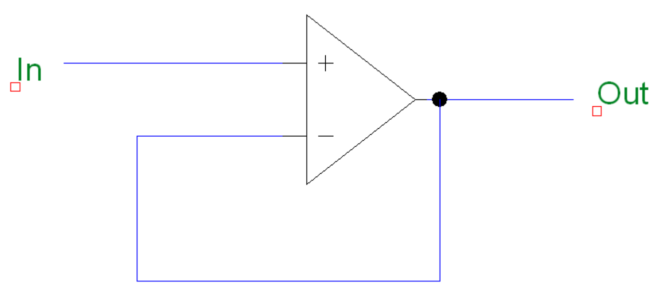


Figure 3. Follower/Buffer Amplifier

- **[Q5]** What is its behavior at DC?
- **[Q6]** What is its behavior at AC?
- **[Q7]** Why would you ever want to use this circuit?

B. Powering an LED : Constant Current Source

4. Voltage-to-Current Amplifier (30 estimated amount of time):

Build the voltage-to-current amp shown in Figure 4. Choose R2 so that an input voltage V_{in} = 0 to +10 VDC delivers a current I_{out} = 0 to +100 mA. Measure I_{out} as a function of V_{in} from 0 to +10VDC.

[Q8] Plot your measured values of I_{out} vs. V_{in}.

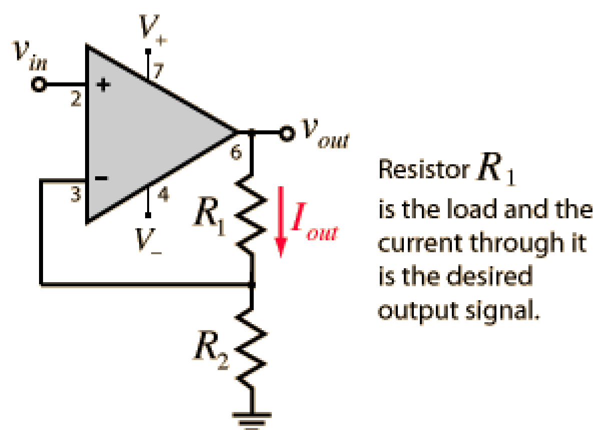


Figure 4. Voltage-to-Current Amplifier

$$V_{pin3} = V_{pin2} = V_{in} \quad \text{(op-amp voltage rule)}$$

$$V_{in} = V_{out} \frac{R_2}{R_1 + R_2}$$

$$so\ V_{out} = V_{in} \frac{R_1 + R_2}{R_2}$$

$$also: \quad I_{out} = \frac{V_{out}}{(R_1 + R_2)} \quad \text{(op-amp current rule: no current flows into pin 3)}$$

Therefore: $$\boxed{I_{out} = \frac{V_{in}}{R_2}} \qquad (4.1)$$

As the last equation implies, the output current that flows through the load R1 is determined by the input voltage Vin and R2, and not R1. Hence the name of the circuit: a voltage-to-current converter. For a given load resistance R1 (whatever its value), the output voltage of the op amp will reach a value such that equation 4.1 is satisfied. In other words, the current flowing through the load R1 is not dependent on the actual value of its resistance, but rather the (independently-controlled) values of Vin and R2. In this manner, this circuit functions as a current source, and not a voltage source.

It is important to note that Ohm's law is still satisfied for the load resistance R1—for a pre-set current I_{out}, the op amp effectively adjusts its output voltage Vout until the voltage drop across the load R1 equals $I_{out} x R_1$. Said another way, the circuit supplies ("forces") a current I_{out} to flow through the load resistance R1, by adjusting the voltage drop across the load until Ohm's law is satisfied.

NOTE on Power Supplies:

<u>Voltage Source</u>: A standard power supply allows you to set the output voltage to a determined value, and then supplies the necessary current so that Ohm's law is satisfied for the load resistance connected across the output terminals of the power supply. A battery operates the same way (to the extent that it's an ideal Thevenin source….!). Both function as a <u>voltage source</u>—the power supply and the (ideal) battery maintain a constant voltage at their output terminals, and supply a current that satisfies Ohm's law for the load resistance.

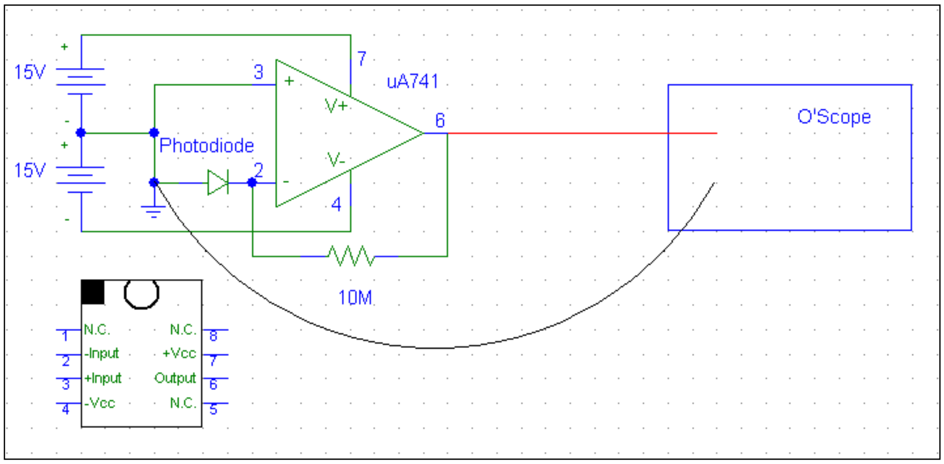
<u>Current Source</u>: A current source, on the other hand, maintains a constant current flowing out of and back into its output terminals, and varies its output voltage to satisfy Ohm's law for the load resistance. This can happen up to a point, namely the maximum voltage that the current source can supply. This is called the compliance voltage.

5. Current to Voltage Converter (TIA)

Build the following circuit. Use an LM741 op-amp, and arrange the dual-output power supply to supply +15 VDC to pin 7, -15 VDC to pin 4, and ground to pin 3.

Add the following components to this circuit. Note that they are non-polarized, so it does not matter which they are installed.

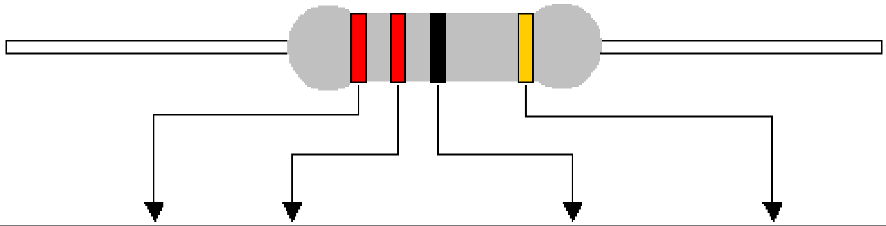
--a 10 kohm resistor between the output (pin 6) and ground (pin 3).
--a 470 pf capacitor (small yellow disk marked "47 1") in the feedback loop. Place the capacitor in parallel with the feedback resistor, between pins 2 and 6.



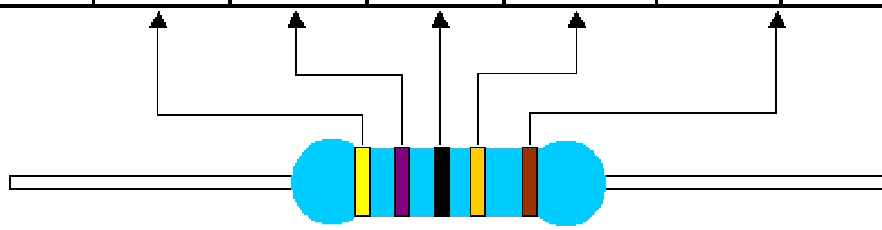
Transimpedance Amplifier (TIA) circuit.

Your parts bins contain resistors with values of 100, 1k, 10k, 100k, 1M, and 10M ohms. The color code for resistors works as follows:

TOKEN RESISTOR COLOR CODE



COLOR	1ST BAND	2ND BAND	3TH BAND	MULTIPLIER	TOLERANCE	
BLACK	0	0	0	1		
BROWN	1	1	1	10	± 1%	F
RED	2	2	2	100	± 2%	G
ORANGE	3	3	3	1K		
YELLOW	4	4	4	10K		
GREEN	5	5	5	100K	± 0.5%	D
BLUE	6	6	6	1M	± 0.25%	C
VIOLET	7	7	7	10M	± 0.10%	B
GREY	8	8	8		± 0.05%	A
WHITE	9	9	9			
GOLD				0.1	± 5%	J
SILVER				0.01	± 10%	K
PLAIN					± 20%	M



Look at the output of the TIA on the oscilloscope. What do you see? The circuit might be oscillating at a very high frequency, which is not a good thing!

[Q9] Measure the frequency of oscillation, in MHz.

To get rid of this oscillation, place 0.1µF capacitors from the supply pins to ground (from pin 7 to ground, and from pin 4 to ground). These capacitors are small yellow disks marked "104M". They are non-polarized—it doesn't matter which way they are installed.

Look at the output on the oscilloscope. Has the high frequency oscillation disappeared?

<u>Cover the photodiode with a black cloth</u> to block all of the light.

[Q10] What do you observe on the oscilloscope?

[Q12] What DC voltage V_o do you measure?

<u>Expose the photodiode to light from the overhead fluorescent lights</u>. Replace the feedback resistor with other values to make sure that the output voltage is less than ± 15VDC.

[Q13] What do you observe on the oscilloscope?

[Q14] What is the frequency of oscillation?

[Q15] What DC voltage V_o do you measure?

[Q16] What is the value of the feedback resistor that you used?

[Q17] What is the photocurrent, I_{ph} in µA?

<u>Expose the photodiode to light from the portable fluorescent light</u>.

[Q20] What do you observe on the oscilloscope?

[Q21] What is the frequency of oscillation?

[Q22] What DC voltage V_o do you measure?

6. Output Voltage V_o vs. Light Level

Replace the power supply with two 9-volt batteries.

Replace (if necessary) the feedback resistor with a 10 kohm resistor.

Take the breadboard, detector, and batteries over to the optical table.

Position the detector so that red He-Ne laser beam hits the center of the detector's active area.

Turn off the overhead fluorescent lights and work in dim light (using just the LED flashlight).

Cover the end of the laser with the black cloth. Record V_{dark}. It may or may not be quite equal to 0. This is the <u>dark reading</u>.

Remove the black cloth. Record V_o as you vary the light level Φ on the detector, using the various Neutral Density (ND) filters provided. Even though we can't measure the absolute value of Φ, we can know the <u>relative light levels</u>:

$$\boxed{\begin{aligned} ND &= -\log(\tau) \\ \tau &= 10^{-ND} \end{aligned}}$$

where τ is the transmission of the ND filter ($0 \le \tau \le 1$). Note that $\tau = 0$ corresponds to ND = ∞ (beam totally blocked), and $\tau = 1$ corresponds to ND = 0 (transmission of 100% of the laser power to the detector, using no Neutral Density filter at all). <u>*The values of τ are also equal to the normalized power of the laser beam incident on the detector*</u>

Use the Excel spreadsheet to process your data as follows:

- Label the columns as follows:
    - Column A: "ND"
    - Column B: "Normalized Laser Power"
    - Column C: "Detector Output"
    - Column D: "Dark-Corrected Detector Output"
    - Column E: "Normalized Detector Output"

- Enter the values of ND that you used, in column A.

- Calculate the corresponding values of τ in column B. Note that these values are also equal to the normalized power of the laser beam incident on the detector (τ = 1 corresponds to the full power from the laser, whatever that happens to be in actual milliwatts).

- Enter the values of V_o in column C.

- Subtract V_{dark} from each value of V_o, placing the new values in column D.

- Divide these dark-corrected values by their maximum value. This turns the output voltages into relative values (no units), and normalizes the output readings to cover the range 0-1. Place these normalized values in column E.

[Q23] Make a plot of the Normalized Detector Output (column E, y-axis) vs. the Normalized Laser Power (column B, x-axis).

[Q24] Is the detector output linear with laser power? If not, where does the non-linearity occur (low light levels, or high light levels)?

[Q25] Over the range of linear output, calculate the slope of the line. Is it equal to 1? (In other words, if the laser power doubles, does the detector output increase by a factor of 2?)