Name: ______________________________

Hands-on Introduction to Electrical Engineering
Assignment 6: Operational Amplifiers

1 Topics

In this assignment, you will review the following topics:

- Operational amplifier (op-amp) basics,
- Simple op-amp amplifiers,
- Op-amp as comparator; digital light detection.

Please make sure that you are familiar with these topics prior to the lab session.

2 Basic op-amp circuits

The operational amplifier (op-amp) is a simple and easy-to-use building block for analog electronics. The schematic symbol for the op-amp is shown in Fig. 1(a), and the basic behavior is given by the equation

$$v_{\text{OUT}} = A \cdot (v_+ - v_-)\,,$$

where v_+ and v_- represent the voltages at the two input terminals of the op-amp, and A is a very large gain on the order of 10^6. In addition, the op-amp inputs draw no current, so Fig. 1(b) represents a valid circuit model for the operational amplifier.

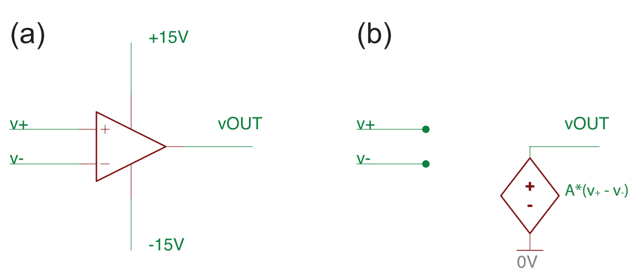

Figure 1: (a) Schematic symbol of the opamp, which has two input ports v_+ and v_-, one output port v_{OUT}, and two supply voltages which we take to be ±15 V. (b) Circuit model for the operational amplifier.

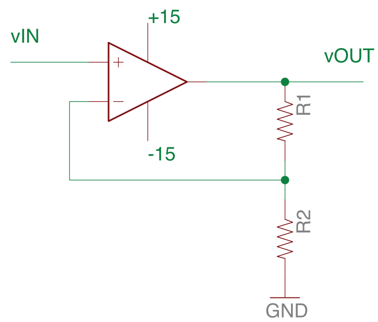

Figure 2: Non-inverting op-amp amplifier.

2.1 Noninverting amplifier

2.1.1 Analysis

Consider the op-amp circuit shown in Fig. 2. Use the node method and the op-amp circuit model of Fig. 1(b) to determine the output v_{OUT} as a function of the input v_{IN} in terms of R_1, R_2 and A. What is the result in the limit $A \to \infty$?

$$v_{\mathrm{OUT}}/v_{\mathrm{IN}} =$$

2.1.2 Construction

We will use the "411" op-amp to construct the noninverting amplifier of Fig. 2 using $R_1 = 4\text{k}$ and $R_2 = 1\text{k}$. What is the expected gain? Confirm the input-output relationship by applying a 1 V amplitude, 10 kHz sinusoid at the input. The pinout of the 411 op-amp is shown in Fig. 3.

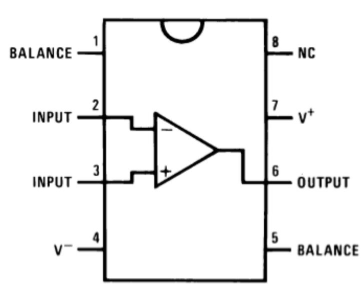

Figure 3: Pinout of the 411 op-amp. You may ignore the "BALANCE" inputs (*i.e.* leave it unconnected). However, do not forget to connect the power lines: V^+ to +15 V, and V^- to −15 V.

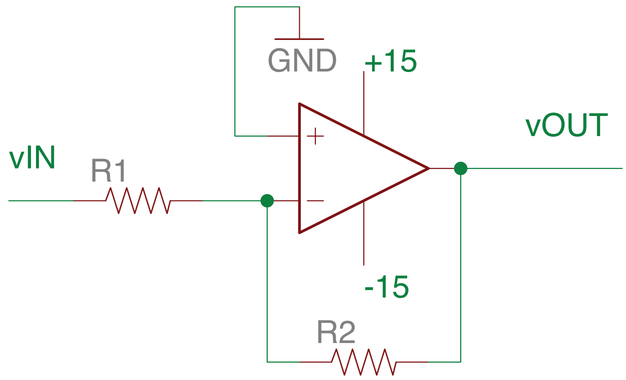

Figure 4: Inverting op-amp amplifier.

2.2 Inverting amplifier

2.2.1 Analysis

Next, consider the amplifier configuration of Fig. 4. Again, compute the input-output relationship as a function of R_1, R_2 and A. What is the result in the limit $A \to \infty$?

$v_{\text{OUT}}/v_{\text{IN}} =$

For the same circuit, what is the voltage v_-?

$v_- =$

Interestingly, you should find that $v_- \approx v_+ \approx 0$. Under typical conditions (specifically, op-amp circuits that employ "negative feedback"), we will find $v_+ \approx v_-$. This observation offers a shortcut in the analysis of negative feedback op-amp circuits, and the shortcut is called the "virtual short" method.

2.2.2 Construction

Please construct the inverting amplifier of Fig. 4 using $R_1 = 1\text{k}$ and $R_2 = 4\text{k}$. Confirm the expected gain by applying a 1 V amplitude, 10 kHz sinusoid at the input.

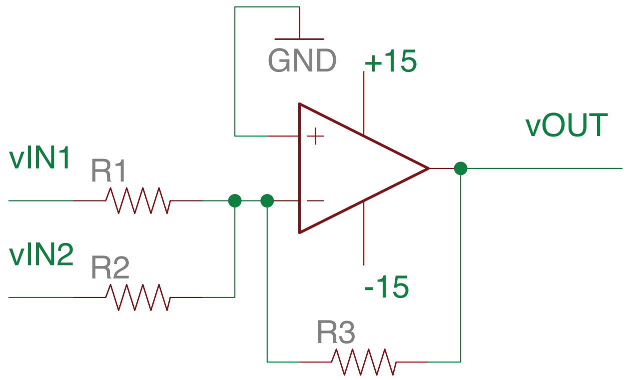

Figure 5: Summing circuit.

2.3 Summing circuit

2.3.1 Analysis

A slight variation of the inverting amplifier is the summing circuit, shown in Fig. 5. What is the output v_{OUT} as a function of v_{IN1} and v_{IN2} and circuit parameters? Note that this circuit employs negative feedback. Can you use that fact to simplify the analysis?

$$v_{\mathrm{OUT}} =$$

Note that we can weight the inputs v_{IN1} and v_{IN2} arbitrarily. This is much more convenient than our previous, resistor-network methods for adding voltage sources!

2.3.2 Construction

Construct the summing circuit using $R_1 = R_2 = R_3 = 1\mathrm{k}$. As for the inputs,

- Set v_{IN1} to a 1 V amplitude, 1 kHz triangle wave,
- Set v_{IN2} to the "TTL/CMOS" output of the function generator. This will be a square wave with the same frequency as the triangle wave.

Does the output of the summing circuit make sense as the sum of triangle and square waves?

Figure 6: A photocell has a resistance that varies with ambient light exposure. [Picture from Sparkfun.com.]

3 Ambient light detection – basic analog-to-digital conversion

Given the differential input pair and the very large gain A of an op-amp, it is natural to use the amplifier as a discriminator, *i.e.* to determine whether the voltage v_+ is above or below a *fixed* v_-. "Op amps" that are meant to be used as discriminators are known as "comparators." Here, we will use the "311" comparator to implement a basic light-detection circuit.

3.1 Light sensor

We will use a "mini-photocell" (which you've seen in Assignment 1) to detect light. The photocell, shown in Fig. 6, has a resistance that varies as a function of the ambient light exposure. Using the multimeter, measure the resistance of the photocell under light and no-light:

R (Light) =	R (Dark) =

We can use the mini-photocell as one of the resistors in a voltage divider. Design the voltage divider so that the output voltage **increases** as a function of increasing light. Draw the circuit below:

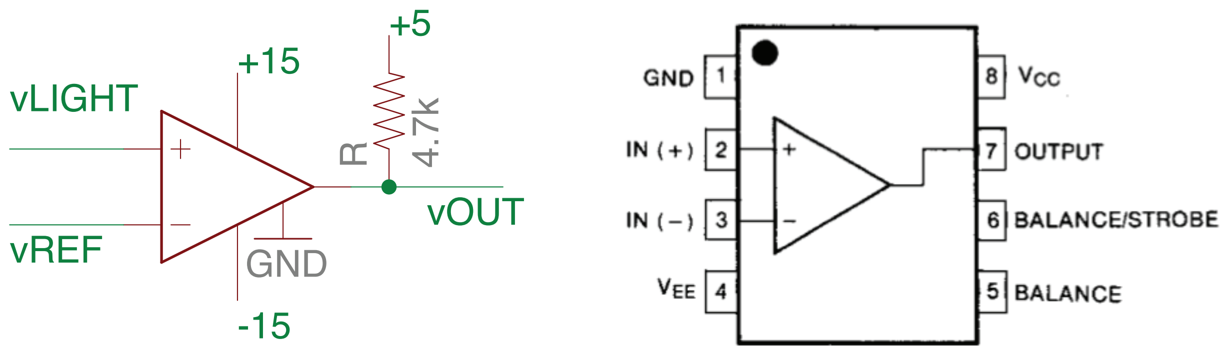

Figure 7: (Left) Comparator circuit for analog-to-digital conversion of the photocell output. (Right) Pinout of the 311 comparator IC. Note that the pinout is different from the 411 op-amp!

3.2 Comparator

We can compare the output v_{LIGHT} from your photocell resistive divider to a reference voltage v_{REF} using the 311 comparator. Use a 10k potentiometer to set up a tunable v_{REF}. Construct the comparator circuit as shown in Fig. 7(a). Note that the pinout of the 311 comparator (see Fig. 7(b)) is quite different from the 411 op-amp! In particular, note:

- Set the power ports: $V_{\mathrm{CC}} = 15$ V (pin 8) and $V_{\mathrm{EE}} = -15$ V (pin 4),
- Set the ground pin: GND = 0 V (pin 1),
- "Pull-up" the output to 5 V using a 4.7k resistor,
- As before, you may ignore the "Balance" pins.

3.3 Logic

The output of the comparator is a binary value (0 V or 5 V) and can be used as inputs to digital logic. Is the output `HIGH` or `LOW` under light and no-light conditions?

Value (Light) =	Value (Dark) =

Next, build a second-pair of light-sensor/comparator circuit.

Below, design a digital logic circuit (*e.g.* NAND, NOR, AND, OR,...) that produces a logical `HIGH` when both photocells are dark.

Finally, connect an LED (with a current-limiting resistor) to the final logic output. You should now have a circuit that turns on an LED only when both photocells are dark! Such circuits are used in backlit keyboards in modern laptops that sense the ambient lighting levels, for example.

4 Sound detection (optional)

Similar to the light detection circuit of Section 3, we may build a small circuit that can detect noise and drive an indicator LED accordingly. However, as the audio output of a microphone is AC rather than DC, we have to perform slight analog preprocessing prior to the comparator stage. If you are interested in the sound detection circuit, fill out the missing circuit fragments in Fig. 8. Some hints:

1. The rectifier circuit converts the audio signal into a single-polarity signal. This can be achieved with a diode and a resistor.
2. The AC-to-DC conversion can be thought of as a lowpass filter (LPF). How can you construct a simple lowpass filter using a single resistor and capacitor?

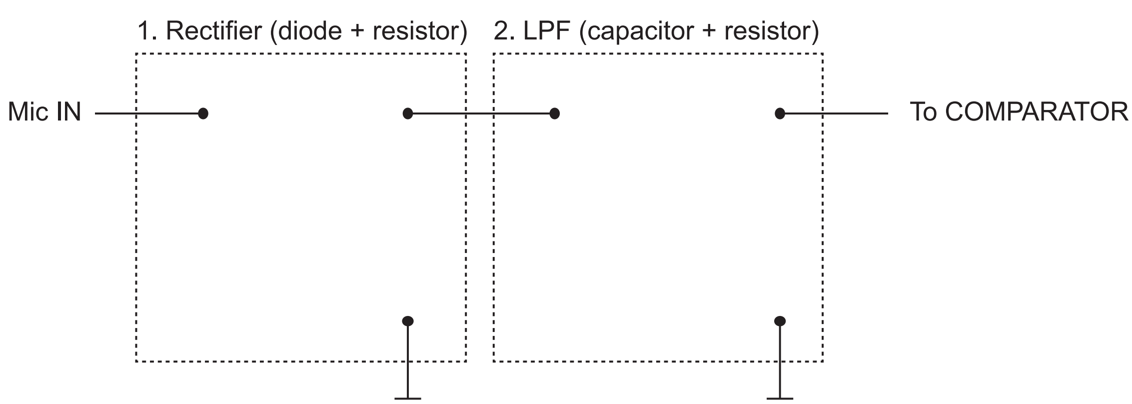

Figure 8: Circuit fragments for Audio-to-DC preprocessing.

5 Further ideas (optional)

You have now seen how to take measurements of ambient light and sound, how to convert the analog measurements into digital values, and to drive a simple LED "actuator" in response.

At the Sant school, we have additional sensors – such as temperature, proximity, and even radar devices – as well as a variety of actuators – such as wireless transreceivers, motors, speakers, light sources, and devices that allow your PC to accept measurements from your circuit board.

I hope that you will continue to create things in the future.