EECS 16A    Designing Information Devices and Systems I
Fall 2018                                                                 Homework 10

**You should plan to complete this homework by Thursday, November 1st. Everything in this homework is in scope for the midterm, but you do not need to turn anything in. There are no self-grades for this homework.**

## 1. Op-Amp in Negative Feedback

In this question, we are going to show that the second golden rule applies for op-amps in negative feedback. We will analyze circuits containing op-amps by first replacing the op-amp with our model, and then taking the limit as the open-loop gain ($A$) approaches infinity.

Figure 1 shows the equivalent model of the op-amp. We can simplify further, by setting $V_{DD} = -V_{SS}$ and assuming that the inputs ($v_{in}$) are small enough for the output to not saturate to $V_{DD}$ or $V_{SS}$. These assumptions result in the model in Figure 2 (Note 18, pg. 4).
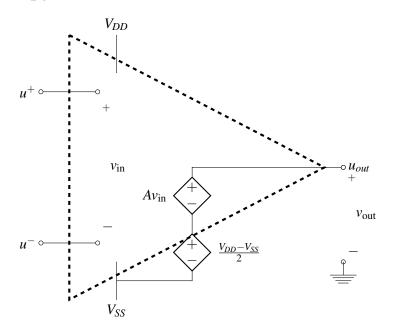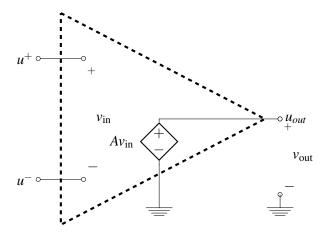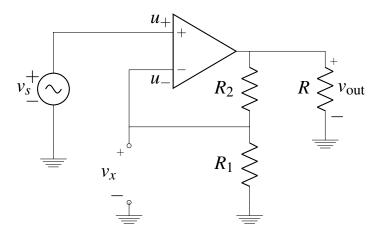


Figure 1: Op amp model

Figure 2: Op-amp model with the simplifying assumptions
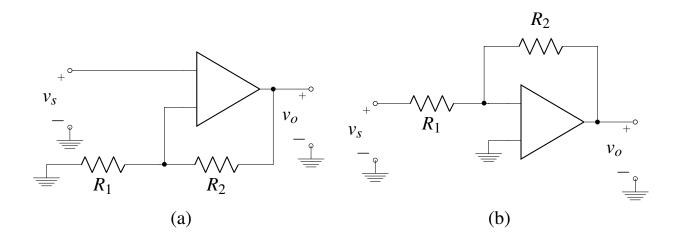
(a) Now consider the circuit below.

Draw an equivalent circuit by replacing the op-amp with the op-amp model shown above (Figure 2) and calculate $v_{\text{out}}$ and $v_x$ in terms of $A$, $v_s$, $R_1$, $R_2$ and $R$. Is the magnitude of $v_x$ larger or smaller than the magnitude of $v_s$? Do these values depend on $R$?



(b) Using your solution to part (a), calculate the limits of $v_{\text{out}}$ and $v_x$ as $A \to \infty$. Do you get the same answers if you apply the fact that $u_+ = u_-$ when there is negative feedback?

## 2. Basic Amplifier Building Blocks

The following amplifier stages are used often in many circuits and are well known as (a) the non-inverting amplifier and (b) the inverting amplifier.

(a)                                                              (b)

(a) Label the input terminals of the op-amp labeled (a), so that it is in negative feedback. Then derive the voltage gain ($A_v = \frac{v_o}{v_s}$) of the non-inverting amplifier using the Golden Rules. Explain the origin of the name of the amplifier.

(b) Label the input terminals of the op-amp labeled (b), so that it is negative feedback. Then derive the voltage gain ($A_v = \frac{v_o}{v_s}$) of the inverting amplifier using the Golden Rules. Explain the origin of the name of the amplifier.
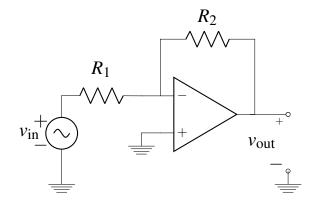
## 3. Cool For The Summer

You and a friend want to make a box that helps control an air conditioning unit. You both have dials that display a voltage: 0 means that you want to leave the temperature as it is. Negative voltages mean that you want to reduce the temperature. (It's hot, so we will assume that you never want to increase the temperature – so, we're not talking about a Berkeley summer...)

Your air conditioning unit, however, responds to positive voltages. The higher the magnitude of the voltage, the stronger it runs. At zero, it is off.
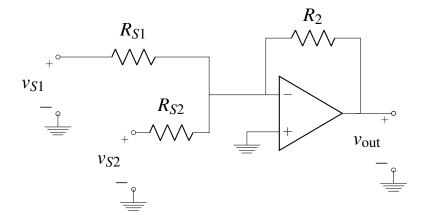
Therefore, you need a box that is an inverting summer – it outputs a weighted sum of two voltages where the weights are both negative. The sum is weighted because each of you has your own subjective sense of how much to turn the dial down, so you need to compensate for this.

This problem walks you through this using an op-amp.

(a) As a first step, find $v_{\text{out}}$ in terms of $R_2$, $R_1$, $v_{\text{in}}$.

(b) Now we will add a second input to this circuit as shown below. Find $v_{\text{out}}$ in terms of $v_{S1}$, $v_{S2}$, $R_{S1}$, $R_{S2}$ and $R_2$.



(c) Let's suppose that you want $v_{\text{out}} = -\left(\frac{1}{4}v_{S1} + 2v_{S2}\right)$ where $v_{S1}$ and $v_{S2}$ represent the input voltages from you and your friend. Select resistor values such that the circuit implements this desired relationship.

(d) Now suppose that you have another AC unit that you want to add to the same room. This unit however, functions opposite to the already existing unit; it responds to negative voltages. You want to run both units at the same time. Add another op-amp based circuit to the circuit in part (b), so that you invert the output of the circuit from part (b).

## 4. Island Karaoke Machine

You're stuck on a desert island and everyone is bored out of their minds. Fortunately, you have your EE16A lab kit with op-amps, wires, resistors, and your handy breadboard. You decide to build a karaoke machine. You recover one speaker from the crash remains and use your iPhone as your source. You know

that many songs put instruments on either the "left" or the "right" channel, but the vocals are usually present on both channels with equal strength.

The Thevenin equivalent model of the iPhone audio jack and speakers is shown below. We assume that the audio signals $v_{\text{left}}$ and $v_{\text{right}}$ have equivalent source resistance of the left/right audio channels of $R_{\text{left}} = R_{\text{right}} = 3\,\Omega$. The speaker has an equivalent resistance of $R_{\text{speaker}} = 4\,\Omega$.
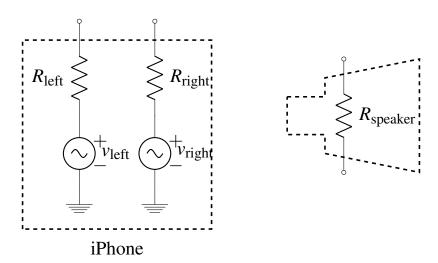
For this problem, we'll assume that the vocals are present on both left and right channels, but the instruments are only present on the right channel, i.e.
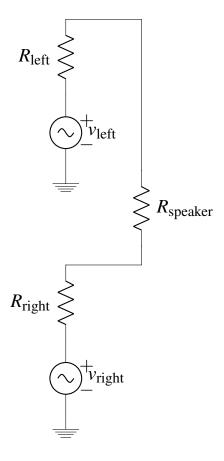
$$v_{\text{left}} = v_{\text{vocals}}$$
$$v_{\text{right}} = v_{\text{vocals}} + v_{\text{instrument}},$$

where the voltage source $v_{\text{vocals}}$ can have values anywhere in the range of $\pm 120\,\text{mV}$ and $v_{\text{instrument}}$ can have values anywhere in the range of $\pm 50\,\text{mV}$.
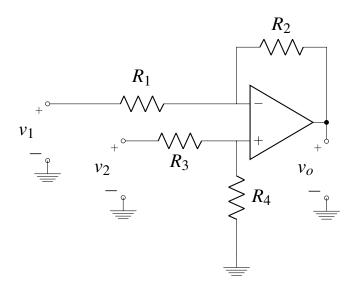
What is the goal of a karaoke machine? The ultimate goal is to *remove* the vocals from the audio output. We're going to do this by first building a circuit that takes the left and right audio outputs of the smartphone and then calculates its difference. Let's see what happens.



iPhone

(a) One of your island survivors suggests the following circuit to do this. Calculate the voltage across the speaker as a function of $v_{\text{vocals}}$ and $v_{\text{instruments}}$. Does the voltage across the speaker depend on $v_{\text{vocals}}$? What do you think the islanders will hear – vocals, instruments, or both?

(b) We need to boost the sound level to get the party going. We can do this by *amplifying* both $v_{\text{left}}$ and $v_{\text{right}}$. Keep in mind that we could use inverting or non-inverting amplifiers.

Let's assume, just for this part, that we have already implemented circuits that amplify $v_{\text{left}}$ and $v_{\text{right}}$ by some factor $A_v$ (Consider $A_v = 100$ for this part). We now have two voltages, $v_{\text{Gl}}$ and $v_{\text{Gr}}$ that are $A_v \cdot v_{\text{left}}$ and $A_v \cdot v_{\text{right}}$ respectively. Use $v_{\text{Gl}}$ and $v_{\text{Gr}}$ to get $A_v \cdot v_{\text{instrument}}$ across $R_{\text{speaker}}$.

(c) Now, you want $\pm 2\,\text{V}$ across the speaker to get the party going. Using the scheme in part (b), design a circuit that takes in $v_{\text{left}}$ and $v_{\text{right}}$ and outputs an amplified version of $v_{\text{instrument}}$ across the speaker with the range of $\pm 2\,\text{V}$. You need to design both amplifiers with the right gain $A_v$ to achieve this.

You can use up to two op-amps, and each of them can be inverting or non-inverting.

(d) The trouble with the approach in part (c) is that multiple op-amps are required. Let's say you only have one op-amp with you. What would you do? One night in your dreams, you have an inspiration. Why not combine the inverting and non-inverting amplifier into one, as shown below!

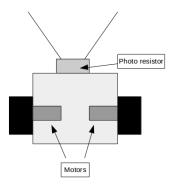If we set $v_2 = 0\,\text{V}$, what is the output $v_o$ in terms of $v_1$? (This is the inverting path.)

(e) If we set $v_1 = 0\,\text{V}$, what is the output $v_o$ in terms of $v_2$? (This is the non-inverting path.)

(f) Now, determine $v_o$ in terms of $v_1$ and $v_2$. (*Hint:* Use superposition.) Choose values for $R_1$, $R_2$, $R_3$ and $R_4$, such that the speaker has $\pm 2\,\text{V}$ across it.

## 5. PetBot Design

In this problem, you will design circuits to control PetBot, a simple robot designed to follow light. PetBot measures light using photoresistors. A photoresistor is a light-sensitive resistor. As it is exposed to more light, its resistance decreases. Given below is the circuit symbol for a photoresistor.



Below is the basic layout of the PetBot. It has one motor on each wheel. We will model each motor as a $1\,\Omega$ resistor. When motors have positive voltage across them, they drive forward; when they have negative voltage across them, they drive backward. At zero voltage across the motors, the PetBot stops. The speed of the motor is directly proportional to the magnitude of the motor voltage. The light sensor is mounted to the front of the robot.

(a) **Speed control** – Let us begin by first having PetBot decrease its speed as it drives toward the flashlight.

Design a motor driver circuit that outputs a decreasing positive motor voltage as the PetBot drives toward the flashlight. The motor voltage should be at least $5\,\text{V}$ far away from the flashlight. When far away from the flashlight, the photoresistor value will be $10\,\text{k}\Omega$ and dropping toward $100\,\Omega$ as it gets closer to the flashlight.

In your design, you may use any number of resistors and just 1 op-amp. You also have access to voltage sources of $10\,\text{V}$ and $-10\,\text{V}$. Based on your circuit, derive an expression for the motor voltage as a function of the circuit components that you used.

**Hint:** You should consider the loading effect of connecting this circuit to your motor, which has resistance. A buffer may help solve this problem.

(b) **Distance control** – Let us now have PetBot drive up to a flashlight (or away from the flashlight) and stop at distance of $1\,\text{m}$ away from the light. At the distance of $1\,\text{m}$ from the flashlight, the photoresistor has a value $1\,\text{k}\Omega$.

Design a circuit to output a motor voltage that is positive when the PetBot is at a distance greater than $1\,\text{m}$ from the flashlight (making the PetBot move toward it), zero at $1\,\text{m}$ from the flashlight (making the PetBot stop), and negative at a distance of less than $1\,\text{m}$ from the flashlight (making the PetBot back away from the flashlight.)

In your design, you may use any number of resistors and just 1 op-amp. You also have access to voltage sources of $10\,\text{V}$ and $-10\,\text{V}$. Based on your circuit, derive an expression for the motor voltage as a function of the values of circuit components that you used.

## 6. Homework Process and Study Group

Who else did you work with on this homework? List names and student ID's. (In case of homework party, you can also just describe the group.) How did you work on this homework?