EECS 16A Designing Information Devices and Systems I
Spring 2023 Homework 12

This homework is due April 14, 2023, at 23:59.
Note: Slip days will NOT be allowed on this HW in order to release solutions before Midterm 2.

Self-grades are due April 21, 2023, at 23:59.

Submission Format
Your homework submission should consist of **one** file.

- `hw12.pdf`: A single PDF file that contains all of your answers (any handwritten answers should be scanned).

Submit the file to the appropriate assignment on Gradescope.

1. **Reading Assignment**

   For this homework, please read Notes 19 and 20. They will provide an overview on the "golden rules" of op-amps, various op-amp configurations (non-inverting, inverting, buffers, etc), and designing circuits using op-amps. You are always encouraged to read beyond this as well.

   (a) What are the two "golden rules" of ideal op-amps? When do these rules hold true?

   (b) What is the effect of "loading" and how can op-amps be used to mitigate this effect?

2. **Op-Amp in Negative Feedback, Round #2**

   In this problem we will analyze the same op-amp circuit in Problem 3 of last week's Homework 11. However, this time the op-amp is assumed to have infinite gain, $A \to \infty$, and we will analyze the circuit directly with KCL, KVL, and the op-amp Golden Rules.

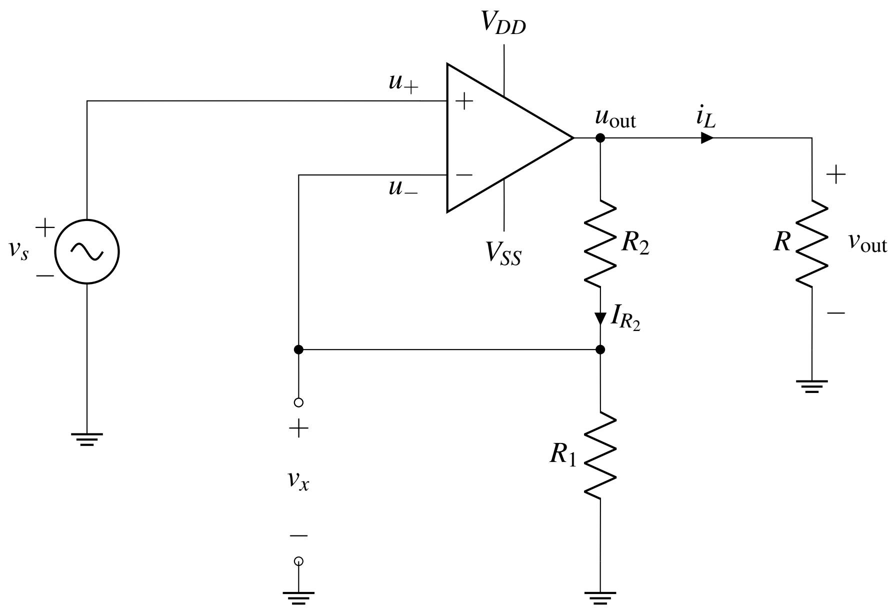


Figure 1: Non-inverting amplifier circuit using an op-amp for feedback

(a) Is the circuit in Fig. 1 in negative feedback?

Hint: Turn off all independent sources, wiggle the output voltage, and check if the feedback in the loop will counteract the wiggle.

(b) What is $u_+ - u_-$?

Note: Since in part (a) we confirmed the circuit is in negative feedback, we can apply both op-amp Golden Rules.

(c) Find v_x as a function of v_{out}. *Hint: What is the current into the negative terminal u_- of the op-amp?*

(d) Now use the results of part (b) and (c) to find v_{out} as a function of v_s.

(e) Does the value of the load resistor R affect the output voltage v_{out}? Why or why not?

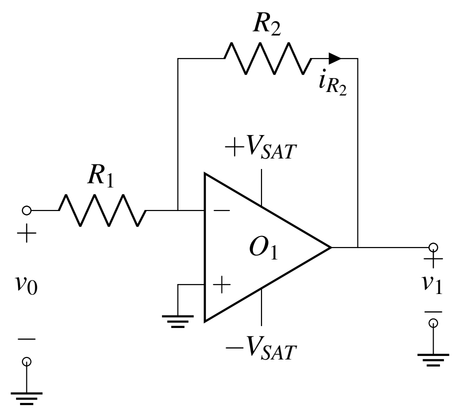
3. Integration using Op-amps

Analog circuits can be used to implement many different mathematical functions. In this problem, we will see how we can use an op-amp to create an integrator. An integrator circuit takes a time-varying voltage input $v_0(t)$ and integrates it over a time period. In other words, we want to build a circuit where the output is of the form

$$v_1(t) = K \int_0^t v_0(\tau) d\tau$$

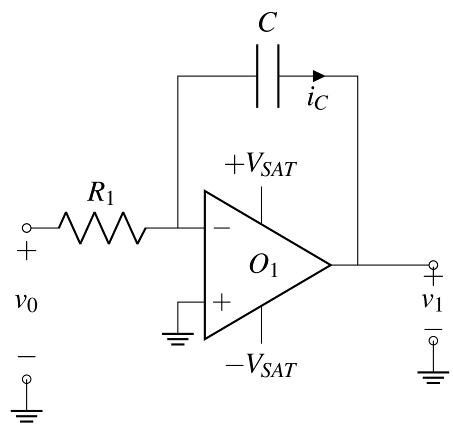
for some constant K.

(a) Let's analyze the inverting op-amp configuration shown below. For this problem, we will assume that the op-amp is ideal and apply the op-amp golden rules.



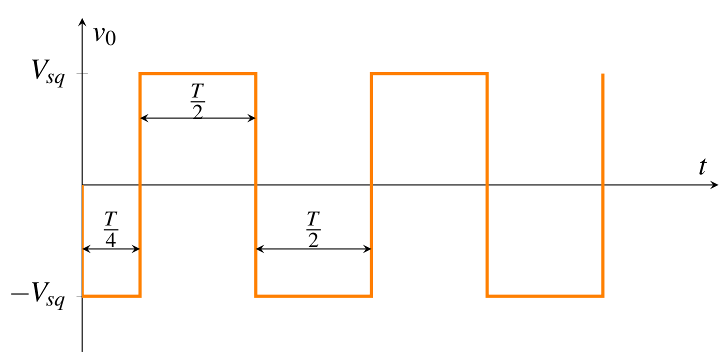
What is the current i_{R_2} flowing through resistor R_2? Write your answer in terms of v_0, R_1, and R_2.

(b) What happens if we replace the resistor in feedback R_2 with a capacitor C instead? Analyze the circuit to find the current through the capacitor i_C and express your answer in terms of v_0, R_1, and C. How does this current differ from the previous part?



(c) Assume that the capacitor starts uncharged at $t = 0$ and that $v_0(t)$ varies with time. Solve for the output voltage $v_1(t)$ as a function of time t. Express your answer in terms of $v_0(t)$, R_1, and C.
Hint: You may leave your answer as an integral of $v_0(t)$ as shown in the initial problem statement.

(d) If v_0 varies with time as shown in the following diagram, plot v_1 for $t = 0$ to $t = 1.5T$. In your plot indicate an algebraic expression for the slope (as a function of R_1, C and V_{sq}) and add tick marks on the x and y axis indicating the time and voltage values where the ramp slope changes. You may assume again that capacitor C has 0V across it at time $t = 0$.



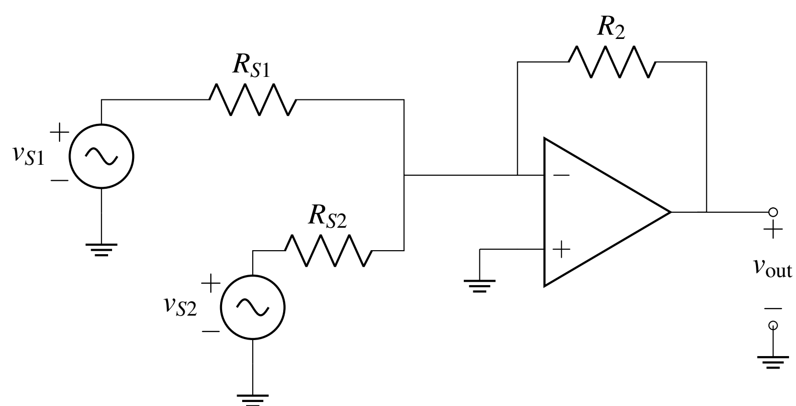
4. Cool For The Summer

You and a friend want to make a box that helps control an air conditioning unit based on both your inputs. You both have individual dials which you can use to control the voltage. An input of 0 V means that you want to leave the temperature as is. A **negative voltage input** means that you want to **reduce** the temperature. (It's hot out, so we will assume that you never want to increase the temperature – so no, we're not talking about a Berkeley summer...)

Your air conditioning unit, however, responds only to **positive voltages**. The higher the magnitude of the voltage, the stronger it runs. At zero, it is off. You also need a system that **sums up** both you and your friend's control inputs.

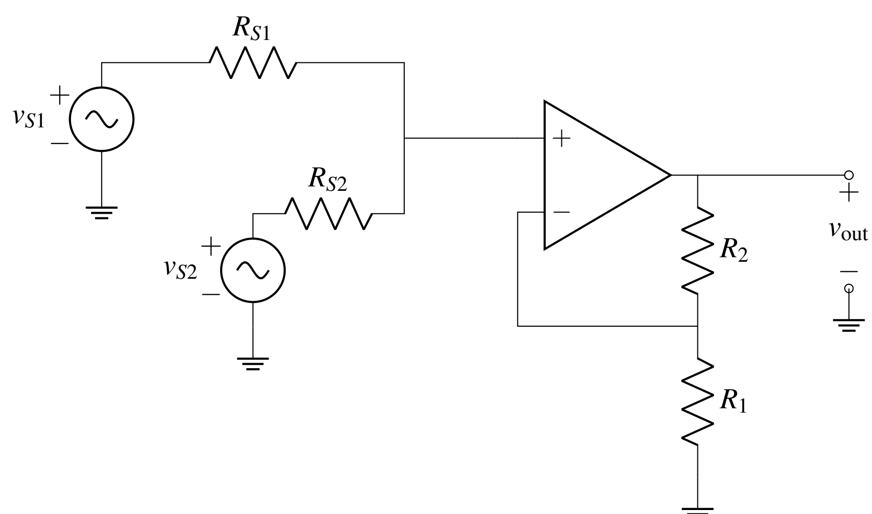
Therefore, you need a box that acts as an **an inverting summer** – *it outputs a weighted sum of two voltages where the weights are both negative*. The sum is weighted because one room is bigger, so you need to compensate for this.

(a) You suggest the circuit below, essentially an inverting amplifier with two inputs. Find v_{out} in terms of v_{S1}, v_{S2}, R_{S1}, R_{S2} and R_2.
Hint: You can solve this problem using either superposition or our tried-and-true KCL analysis.



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

(c) Your friend has a different circuit idea. He proposes the following circuit below.



Find v_{out} in terms of v_{S1}, v_{S2}, R_{S1}, R_{S2}, R_1, and R_2. Can we also use this circuit to control our AC system? Why or why not?
Hint: How does this circuit relate to the one in question 2?

5. Island Karaoke Machine

Learning Goal: *The objective of this problem is design a circuit that calculates the difference between two signals and amplifies the result.*

You're stuck on a desert island and everyone is bored out of their minds. Fortunately, you have your EECS16A 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.

In our case, 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_{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.

The equivalent circuit model of the iPhone audio jack and speaker is shown in Figure 2. We model the **audio signals and jack** as v_{left} and v_{right} with **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 $R_{\text{speaker}} = 4\,\Omega$.

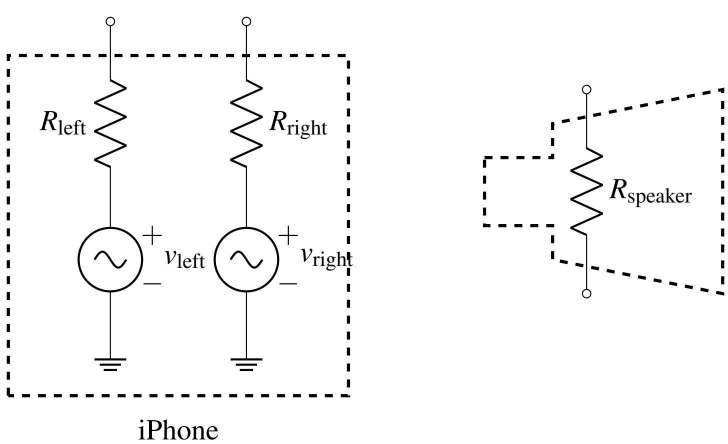


Figure 2: Audio jack and speaker of an iPhone.

(a) One of your island survivors suggests the circuit in Figure 3 to do this. **Find the expression for the voltage across the speaker R_{speaker} as a function of v_{vocals} and $v_{\text{instruments}}$.**

Does the voltage across the speaker depend on v_{vocals}? In other words, what do you think the islanders will hear – vocals, instruments, or both?

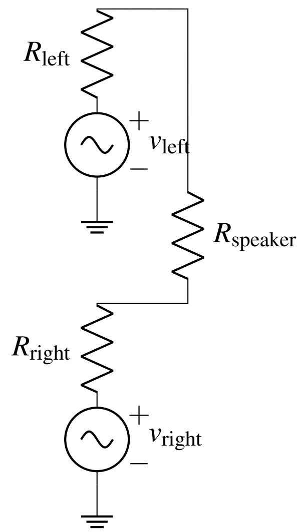


Figure 3: Circuit for part (a).

(b) We need to boost the sound level to get the party going. To this end, we want a range of $\pm 2\,\text{V}$ across the speaker. Design a circuit by completing the Figure 4 below that takes in $\{v_{\text{left}}, R_{\text{left}}\}$ and $\{v_{\text{right}}, R_{\text{right}}\}$ combos as inputs and outputs an **amplified version of $v_{\text{instrument}}$ across R_{speaker}**. Consider all op-amps to be **ideal** for this problem.

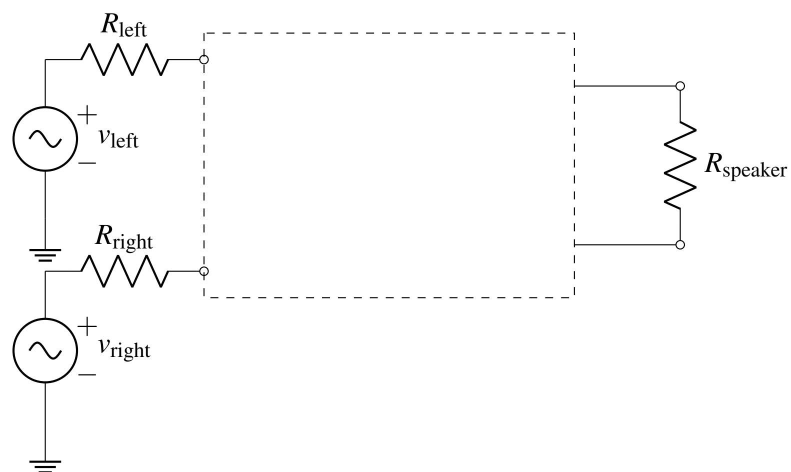


Figure 4: Circuit for part (b).

Hint 1: *We need to get an output voltage with the range of* $\pm 2\,\text{V}$. *The input voltage* $v_{instrument}$ *can have values anywhere in the range of* $\pm 50\,\text{mV}$. *What gain is needed from the op-amp based amplifier circuits?*

Hint 2: *Use two op-amps in the non-inverting configuration. The non-ideal voltage source* $\{v_{left}, R_{left}\}$ *must be the input to one non-inverting amplifier and the non-ideal voltage source* $\{v_{right}, R_{right}\}$ *must be the input to the other non-inverting amplifier. Keep the gain of both amplifiers equal so the vocals still cancel out across the speaker!*

Hint 3: *Connect the speaker $R_{speaker}$ across the outputs of those two op-amps.*

(c) The trouble with the approach in part (b) is that two 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 in Figure 5!

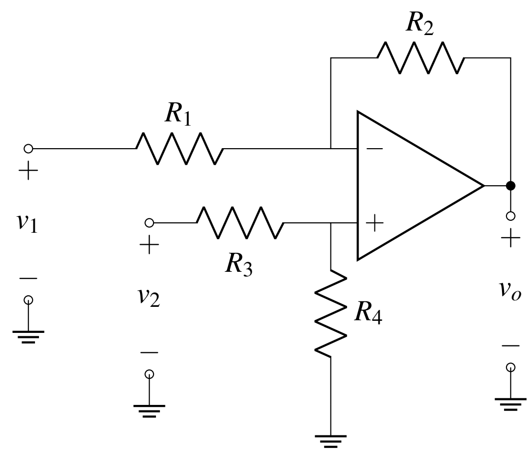


Figure 5: The new amplifier for part (c).

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

(d) Consider the circuit in Figure 5 again. 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.)

(e) Now, determine v_o in terms of v_1 and v_2 by superposing your results from the last two parts. Choose values for R_1, R_2, R_3 and R_4, such that the output range is $v_o = \pm 2\,\text{V}$ for $v_2 - v_1 = \pm 50\,\text{mV}$.

(f) We now connect our iPhone and speaker to the inputs and outputs of the circuit we designed. We realize that we forgot to account for the Thevenin resistance of the left and right channel source from the iPhone. How should we modify our resistor value choices from part(e) to account for this?
Hint: *What is the resistor configuration of R_{left}, R_1 and R_{right}, R_3? Can we combine these pairs into an equivalent resistor for each pair?*

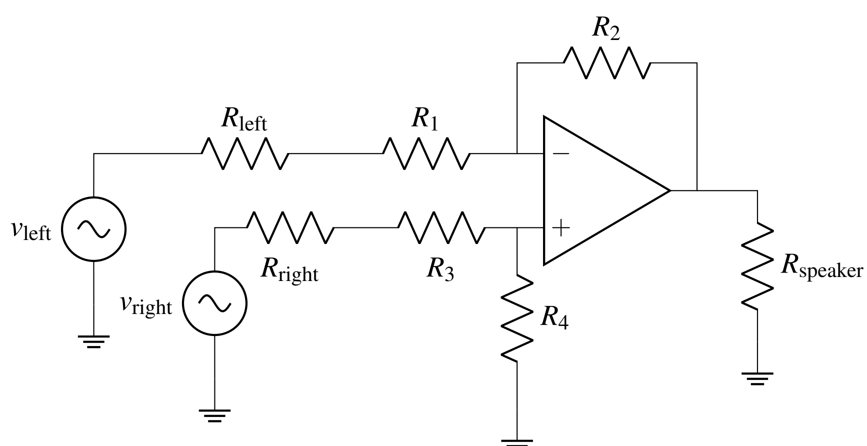


Figure 6: The differential amplifier connected to the source and speaker.

6. Homework Process and Study Group

Who did you work with on this homework? List names and student ID's. (In case you met people at homework party or in office hours, you can also just describe the group.) How did you work on this homework? If you worked in your study group, explain what role each student played for the meetings this week.

