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

This homework is due April 9, 2018, at 23:59.
Self-grades are due April 12, 2018, at 23:59.

Submission Format
Your homework submission should consist of **two** files.

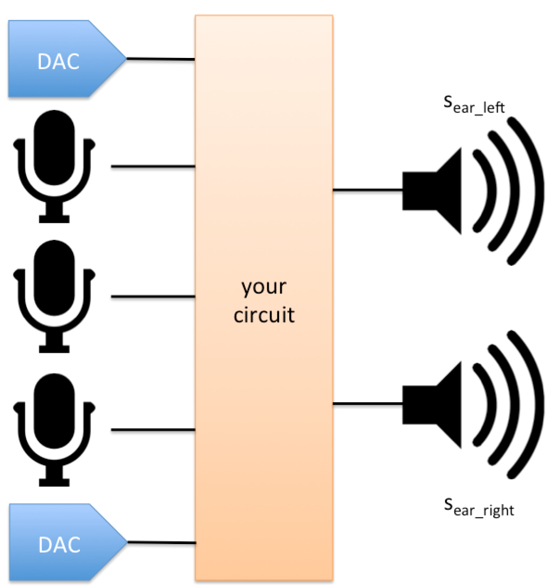
- `hw10.pdf`: A single PDF file that contains all of your answers (any handwritten answers should be scanned)

Submit each file to its respective assignment on Gradescope.

1. **Noise Cancelling Headphones Part 2**

Almost everyone has tried "noise cancelling" headphones at some point. The basic goal of noise cancelling headphones is for the user to hear only the desired audio signal and not any other sounds from external sources. In order to achieve this goal, noise cancelling headphones include at least one microphone that listens to what you might have otherwise heard from external sources and then feeds a signal in to your speakers that cancels (subtracts out) that externally-generated sound.

(a) In discussion, we had just one speaker and one microphone, but almost all headphones today have two speakers (one for each ear). Adding an extra speaker that can be driven by a separate audio stream typically makes things sound more real to us. For similar reasons, having multiple microphones to pick up ambient sounds from multiple different locations can help us do a better job of cancellation, if we can use that information in the right way.



Let's now assume that our system has 3 microphones and 2 speakers, and that the source of our audio is stereo – i.e., we have two different audio streams s_{left} and s_{right} (produced by two different DACs) that represent the ideal sounds we would like the user to hear in their left and right ear. We have three microphone audio signals s_{mic1}, s_{mic2}, and s_{mic3}, and let's assume that without any active noise cancellation, some fraction of the signal picked up by each microphone would be heard by the user in each of their ears. For example, $a_{1\text{left}}$ would represent the fraction of the signal picked up by microphone 1 that will be heard in the user's left ear, $a_{2\text{right}}$ would represent the fraction of the signal picked up by microphone 2 that will be in the user's right ear, etc.

Let the vector $\vec{s}_{\text{noise}}$ represent the noise heard in each ear and $\vec{s}_{\text{mic}}$ represent the sound in each mic. Find a matrix $\mathbf{A}$ such that $\vec{s}_{\text{noise}} = \mathbf{A}\vec{s}_{\text{mic}}$.

(b) Assume no noise canceling, find an equation for $\vec{s}_{\text{ear}}$, the sound heard in each ear in terms of the two audio streams and $\vec{s}_{\text{noise}}$.

(c) In order to cancel the noise, we want to create a signal that is the inverse of $\vec{s}_{\text{noise}}$. Let $\vec{s}_{\text{cancel}}$ be the vector representing the cancel signal in each headphone. Find a matrix $\mathbf{B}$ in terms of the matrix $\mathbf{A}$ such that $\vec{s}_{\text{cancel}} = \mathbf{B}\vec{s}_{\text{mic}}$.

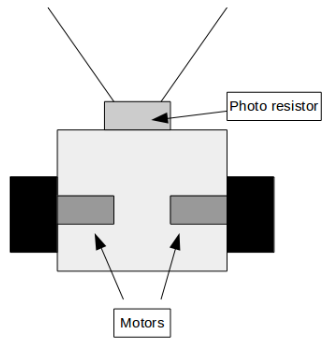
(d) Assume that the microphones can be modeled as voltage sources, whose value v_{micn} is proportional to s_{micn}, design and sketch a circuit that would implement the cancellation matrix $\mathbf{B}$. You should assume that this circuit has three voltage inputs v_{mic1}, v_{mic2}, and v_{mic3} and two voltage outputs $v_{\text{cancel\_left}}$ and $v_{\text{cancel\_right}}$ (corresponding to the voltages that will be subtracted from the desired audio streams in order to cancel the externally-produced sounds). In order to simplify the problem, you can assume that all of the v_{mic} voltages are already centered at $0\,\text{V}$ (relative to the DAC ground). Furthermore, assume all entries of the $\mathbf{A}$ matrix are positive. You may use op-amps and resistors to implement your circuit. You do not have to pick specific resistor values, but write expressions for each resistor value.

(e) **PRACTICE:** Building upon your solutions to all previous parts, and otherwise making the same assumptions about the relative voltage ranges of v_{mic1}, v_{mic2}, and v_{mic3} and available supply voltages, sketch the complete circuit you would use to create the stereo audio on the two speakers while cancelling the noise picked up by the three microphones.

2. 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 V far away from the flashlight. When far away from the flashlight, the photoresistor value will be $10\,k\Omega$ and dropping toward $100\,\Omega$ as it gets closer to the flashlight.

In your design, you may use any number of resistors and op-amps. You also have access to voltage sources of 10 V and −10 V. Based on your circuit, derive an expression for the motor voltage as a function of the circuit components that you used.

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

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

In your design, you may use any number of resisitors and op-amps. You also have access to voltage sources of 10 V and −10 V. Based on your circuit, derive an expression for the motor voltage as a function of the values of circuit components that you used.

3. Island Karaoke Machine

After a plane crash, 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_{left} and v_{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 $4\,\Omega$.

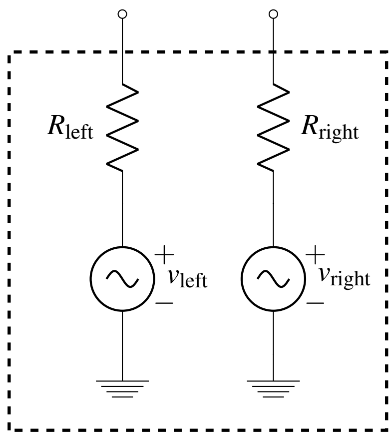
For this problem, we'll assume that

$$v_{\text{left}} = v_{\text{vocals}}$$
$$v_{\text{right}} = v_{\text{vocals}} + v_{\text{instrument}},$$

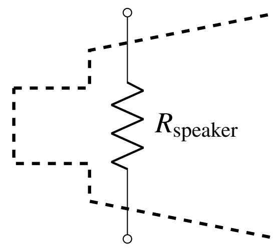
where the voltage source v_{vocals} can have values anywhere in the range of $\pm 120\,\text{mV}$ and $v_{\text{instrument}}$ can have values anywhere in the range of $\pm 50\,\text{mV}$.

That is, the vocals are present on the left and right channel, but the instrument is present only on the right channel.

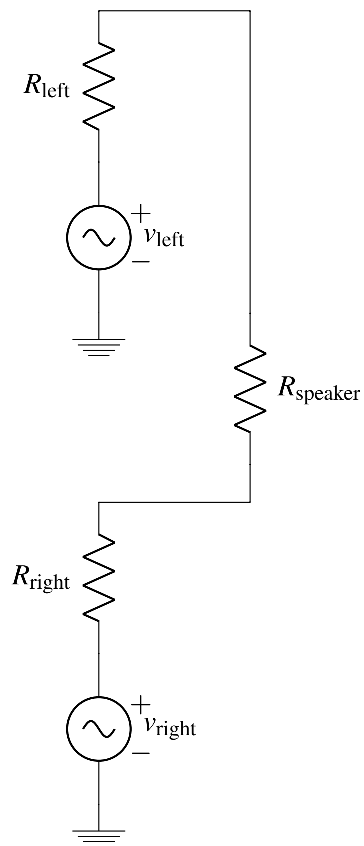
What is the goal of a karaoke machine? The ultimate goal is to *remove* the vocals from the audio output. We're going to do this by first building a circuit that takes the left and right outputs of the smartphone audio output and then takes its difference. Let's see what happens.



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_{vocals} and $v_{\text{instruments}}$. What do you notice? Does the voltage across the speaker depend on v_{vocals}? What do you think the islanders will hear – vocals, instruments, or both?

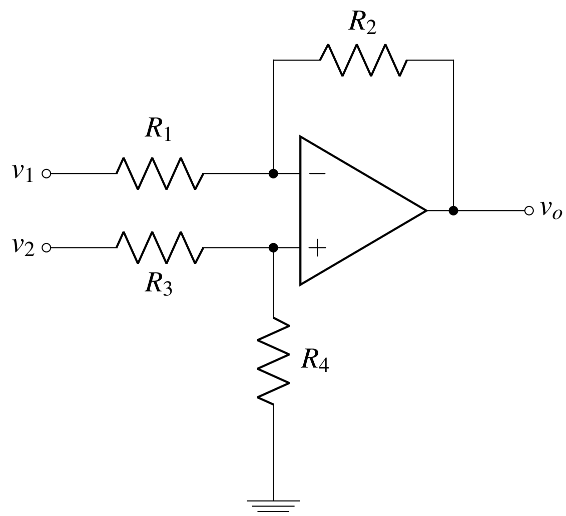


(b) Clearly, we need to boost the sound level to get the party going. We can do this by *amplifying* both v_{left} and v_{right}. Keep in mind that we could use inverting or non-inverting amplifiers.

Let's assume, just for this part, that we have already implemented circuits that amplify v_{left} and v_{right} by some factor G. We now have two voltage sources, v_{Gl} and v_{Gr} that are v_{left} multiplied by G and v_{right} multiplied by G. Use these voltage sources to get $G \times v_{\text{instruments}}$ across R_{speaker}.

(c) Now, design a circuit that takes in v_{left} and v_{right} and outputs an amplified version of $v_{\text{instrument}}$ across the speaker load. You want $\pm 2\,\text{V}$ across the speaker to get the party going. You can use up to three op-amps, and each of them can be inverting or non-inverting.

(d) The trouble with the previous part is the number of op-amps 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!



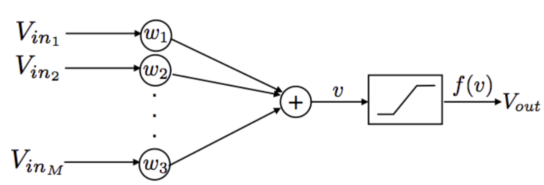
If we set $v_2 = 0\,\mathrm{V}$, what is the output v_o in terms of v_1? (This is the inverting path.)

(e) If we set $v_1 = 0\,\mathrm{V}$, 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 $\pm 2\,\mathrm{V}$ across it.

4. Brain-on-a-Chip with 16A Neurons

Neurelic Inc, is a hot new startup building chips that emulate some of the brain functions (for example associative memory). As an intern, fresh out of 16A you get to implement the neural network circuits on this chip. The neural network consists of neurons that consist of the following blocks shown on the figure below.

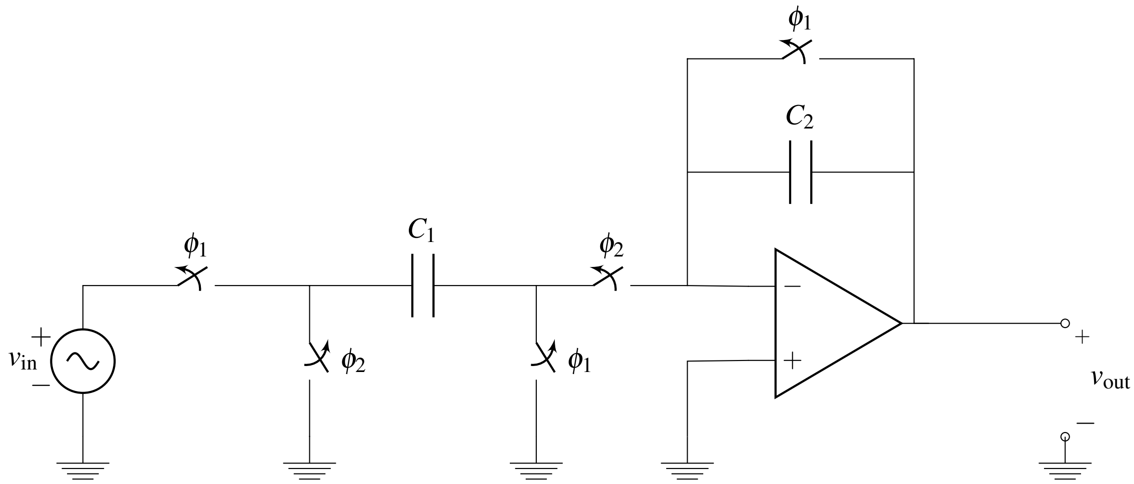


Input signals v_{in_i} are voltages from other neurons, which are multiplied by a constant weight w_i in each synapse and summed in the neuron. Each neuron also contains a nonlinear function (called a sigmoid) which is defined as

$$f(v) = \begin{cases} -1, & v \leq -1 \\ v, & -1 < v < 1 \\ +1, & v \geq +1 \end{cases}$$

where v is the internal neuron voltage after the synapse summer and $f(v)$ is the neuron voltage output.

(a) Your mentor suggests that you warm-up first by analyzing the circuit below to use as neuron with a single synapse. ϕ_1 and ϕ_2 are non-overlapping clock phases that control the circuit switches.

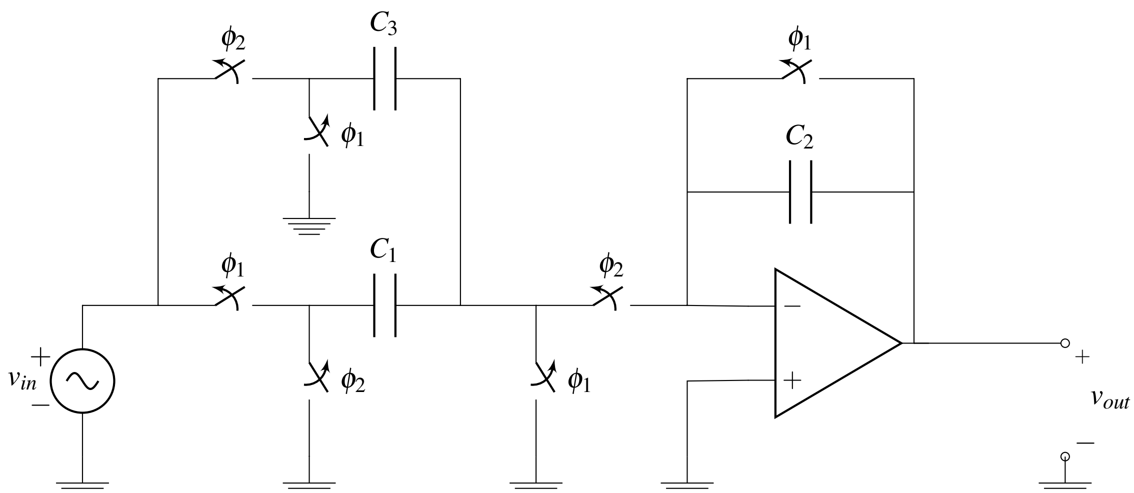


i. Draw an equivalent circuit during ϕ_1 and write an expression for v_{out} as a function of v_{in}, C_1 and C_2.

ii. Draw an equivalent circuit during ϕ_2 and write an expression for v_{out} as a function of v_{in}, C_1 and C_2.

(b) Write an equation for v_{out} during ϕ_2 as a function of v_{in} for $C_1 = C_2$ and op-amp supply voltages of ± 1 V. Briefly explain how this circuit implements the sigmoid function.

(c) Then, your mentor shows you the following neuron circuit, which can realize both positive and negative synapse weight and create $v_{out} = w_1 v_{in}$ in ϕ_2.



i. Draw an equivalent circuit during ϕ_1 and write an expression for v_{out} as a function of v_{in}, C_1, C_2, and C_3.

ii. (5 points) Draw an equivalent circuit during ϕ_2 and write an expression for v_{out} as a function of v_{in}, C_1, C_2, and C_3.

(d) Now it is your turn to implement a neuron that realizes the following function $v_{out} = w_1 v_{in_1} + w_2 v_{in_2}$. Draw the circuit, such that $w_1 = 1/2$ and $w_2 = -1/4$. Label all circuit elements appropriately. You should use a single op-amp and as many capacitors and switches as you need. All capacitors must be of size C_{unit}. Assume that the op-amp power supplies are ± 1V (no need to draw them in the circuit). The circuit should operate in 2 phases, with $v_{out} = w_1 v_{in_1} + w_2 v_{in_2}$ in the second phase (ϕ_2), and reset in ϕ_1.

5. 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?