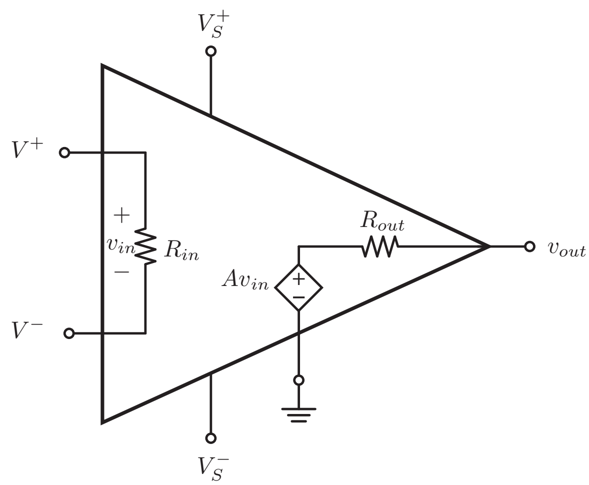
This homework is due November 2, 2015, at Noon.

1. **Homework process and study group**

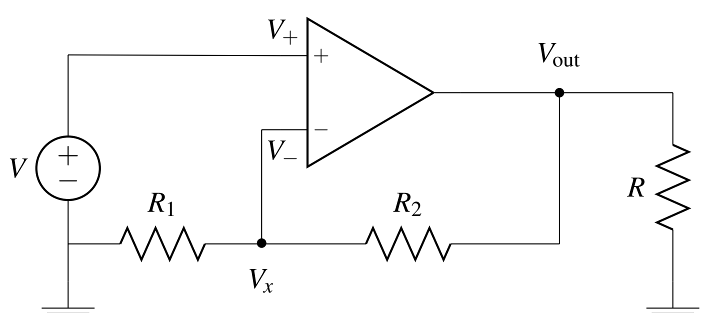
   Who else did you work with on this homework? List names and student ID's. (In case of hw party, you can also just describe the group.) How did you work on this homework?

2. **Op-Amp Golden Rules**

   In this question we are going to show that the golden rules for op-amps hold by analyzing equivalent circuits and then taking the limit as the open-loop gain approaches infinity. Below is a picture of the equivalent model of an op-amp we are using for this question, where we are assuming $R_{in} \to \infty$ (open circuit) and $R_{out} \to 0$ (short circuit).



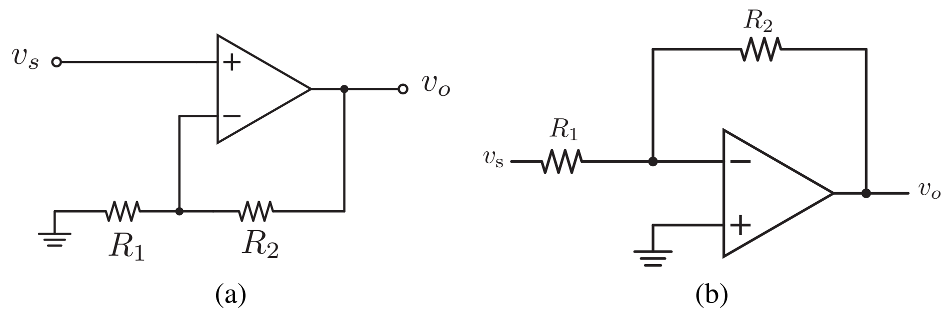
   (a) Now consider the circuit below. Assume that no current flows into the "+" and "-" terminals of the op-amp, and $v_{\text{out}} = Av_{\text{in}} = A(V_+ - V_-)$. Given these facts, draw a equivalent circuit using the op-amp model described above and calculate v_{out} and v_x in terms of A, V, R_1, R_2 and R. Is v_x larger or smaller than V? Do these values depend on R?



(b) Calculate v_{out} and v_x in the limit as $A \to \infty$. Do you get the same answers if you apply the golden rules ($V_+ = V_-$ when there is negative feedback)?

3. 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) Derive the voltage gain of the non-inverting amplifier using the Golden Rules. Explain the origin of the name of the amplifier. Does this amplifier load the circuit driving it? In other words, is the Thevenin input resistance an open circuit or does it present a finite R_{in} to the driving stage?

(b) Derive the voltage gain of the inverting amplifier using the Golden Rules. Explain the origin of the name of the amplifier. Does this amplifier load the circuit driving it? In other words, is the Thevenin input resistance an open circuit or does it present a finite R_{in} to the driving stage?

4. Cool For The Summer (optional)

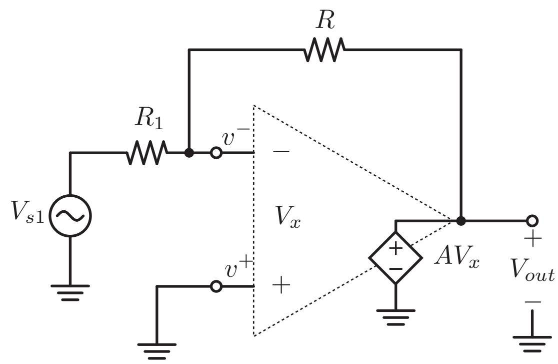
You and a friend want to make a box that helps control an air-conditioning unit. You both have dials that emit a voltage: 0 means you want to leave the temperature as it is. Negative voltages mean that you want to reduce the temperature. (It's hot so we will assume that you never want to increase the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

Your air-conditioning unit however responds to positive voltages. The higher the voltage, the more strongly it runs. At zero, it is off. (If it helps, think of this air-conditioning unit as a heat pump. If you run it with negative voltage, it pumps heat in the opposite direction — from outside to inside. If positive voltage, it pumps heat from inside to outside.)

So you need a box that is an inverting summer — it outputs a weighted sum of two voltages where the weights are both negative. (Weighted because each of you has your own subjective sense for how much to turn the dial down and you need to compensate for that.)

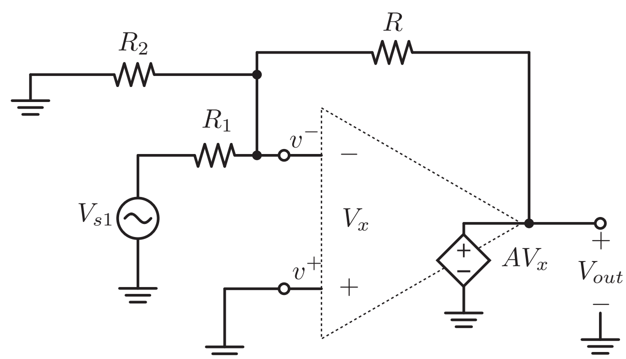
This problem walks you through this using an op-amp.

(a) Solve for V_{out} in terms of the other circuit quantities, i.e. R, R_1, A, and V_{s1}.

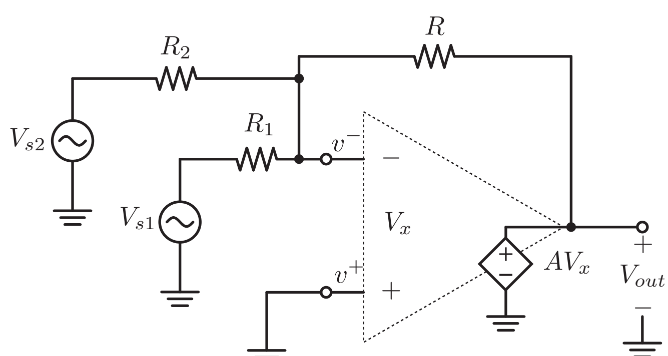


(b) What happens to V_{out} in the limit as A goes to ∞?

(c) Solve for V_{out} in terms of the other circuit quantities, i.e. R, R_1, R_2, A, and V_{s1}.



(d) What happens to V_{out} in the limit as A goes to ∞?



(e) Solve for V_{out} in terms of the other circuit quantities, i.e. R, R_1, R_2, A, V_{s1}, and V_{s2}. (Hint: use superposition)

(f) What happens to V_{out} in the limit as A goes to ∞?

(g) Given that R=10 kΩ, choose R_1 and R_2 such that $V_{out} = -(\frac{1}{4}V_{S1} + 2V_{S2})$ in the limit as A goes to ∞.

5. 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 EE16 lab kit with op-amps, wires, and 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 "left" or "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. For simplicity, we assume that the audio signals V_{Left} and V_{Right} are both DC and that the 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 4Ω.

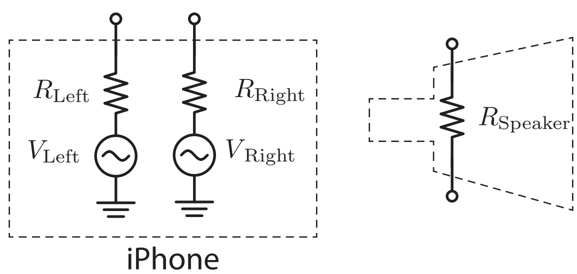
For this problem, we'll assume that

$$V_{\text{Left}} = V_{\text{vocals}}$$
$$V_{\text{Right}} = V_{\text{vocals}} + V_{\text{instrument}}$$

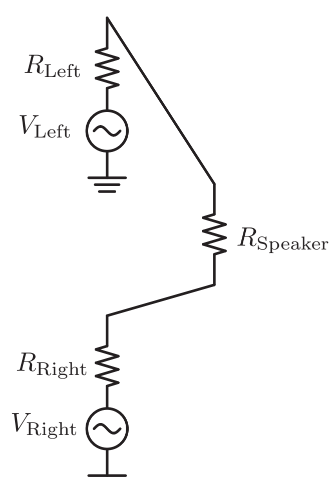
where $V_{\text{vocals}} = 120.524mV$ and $V_{\text{instrument}} = 50mV$.

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 takes its difference. Let's see what happens.



(a) One of your island survivors suggests the following circuit to do this. Calculate the voltage across the speaker. 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) How much power is delivered to the speaker?

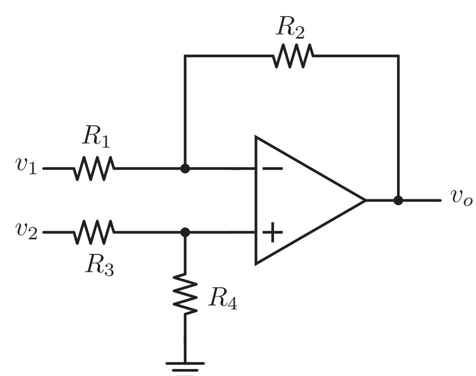
(c) Clearly, we need to boost the sound level to get the party going. We can do this by *amplifying* both V_{Left} and V_{Right}. Keep in mind that we could use the inverting or non-inverting amplifiers from Problem 3 for this – an inverting amplifier has negative gain, and a non-inverting amplifier has positive gain.

Let's assume, just for this part, that all the amplifiers we have produce a gain of 100 (if they are non-inverting), and -100 (if they are inverting). How would you take the difference of the two amplified outputs across the speaker?

(d) 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 should be able to deliver $1W$ into the speaker load. You can use up to three op-amps, and each of them can be inverting or non-inverting.

(Hint: Use the circuits from problem 3 as building blocks.)

(e) The trouble with the previous part is the number of op-amps required. Let's say you only have one opamp 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 $v_2 = 0V$, what is the gain from v_1 to the output v_o? (this is the inverting path)

(f) If we set $v_1 = 0V$, what is the gain from v_2 to the output v_o? (this is the non-inverting path)

(g) Now, determine v_o in terms of v_1 and v_2. (Hint: use superposition!) Set R_1, R_2, R_3 and R_4 such that, as before, $1W$ is delivered to the speaker load and we don't hear the vocals.

6. Your Own Problem Write your own problem related to this week's material and solve it. You may still work in groups to brainstorm problems, but each student should submit a unique problem. What is the problem? How to formulate it? How to solve it? What is the solution?