EE 233 Circuit Theory
Lab 3: First-Order Filters

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1 Introduction

This lab is designed to teach students how to create and interpret Bode plots for various op-amp circuit topographies, through both mathematical analysis and SPICE simulation. Afterword, the lab will have students analyze and measure characteristics of simple analog amplifiers built with op-amps.

The circuits built in this lab are also part of the audio mixer system; more specifically, they are the preamplifier and the output summing amplifier in the equalizer. **You should keep them assembled on your breadboard**, and arrange them with the other audio mixer parts in mind. Read **Overview of Audio Mixer.pdf** for more information of the entire project.

This lab is split into a prelab exercise and hardware implementation. Submit one prelab report and one lab report per group, with the members' names are clearly written on the front page. There is no template for the prelab report, and the lab report template is available on Canvas. These reports must be in pdf format. There are multiple apps, including CamScanner, for Apple and Android phones that turn photos into pdf's.

2 Precautions

Op-amps (and all other IC chips) can be easily damaged by static electricity, so make sure that you always store them with their prongs attached to plastic foam, which you can acquire (for free) at the EE store. In addition, make sure to ground yourself by touching a metallic surface before handling an op-amp.

Over the course of the lab, your op-amp might burn out due to improper handling and use:

Static Discharge Damage: Your finger might carry a high static voltage (up to hundreds of volts) due to a combination of the clothing you wear (synthetic or wool is worse), the environmental humidity (dry is worse), or other factors. Picking up an IC package could burn out the circuit inside due to this static voltage. Remember to touch a grounded piece of metal (usually a wrist-strap attached to test benches) to discharge the static voltage before handling the IC.

Applying Out-of-Range Input Values: The input signals must be in the range set by the power supplies (see the specifications). If the input signal exceeds the power supplies, either more negative or more positive, the circuit might get burned out.

Burned-out chips look the same as good ones, and you can waste a lot of time trouble-shooting your circuit. Two signs of a burned-out op-amp are excessive current drawn from the power supply (greater than about 10mA with no load) and/or an op-amp hot to the touch. Of course, a blown-out op-amp may exhibit none of these symptoms. If you suspect that your op-amp is faulty, replace it.

You should also pay close attention to the circuit connections and the polarity of the power supplies, function generator, and oscilloscope inputs.

3 Prelab Exercises

Any linear, time-invariant system can be represented by its frequency response

$$H(j\omega) = \frac{V_{\text{out}}(j\omega)}{V_{\text{in}}(j\omega)}$$

The magnitude of the frequency response, $|H(j\omega)|$, is the gain of the system as a function of frequency, while the phase of the frequency response, $\angle H(j\omega)$, shows the difference between the input and output's phases as a function of frequency.

Example: Suppose the output voltage over a capacitor is $V_{\text{out}}(j\omega) = \frac{1}{1+j\omega RC} V_{\text{in}}(j\omega)$.

The transfer function is $H(j\omega) = \frac{V_{\text{out}}(j\omega)}{V_{\text{in}}(j\omega)} = \frac{1}{1+j\omega RC} = \frac{\text{N}}{\text{D}}$

The gain is $|H(j\omega)| = \frac{|\text{N}|}{|\text{D}|} = \frac{|1|}{|1+j\omega RC|} = \frac{1}{\sqrt{1+\omega^2 R^2 C^2}}$

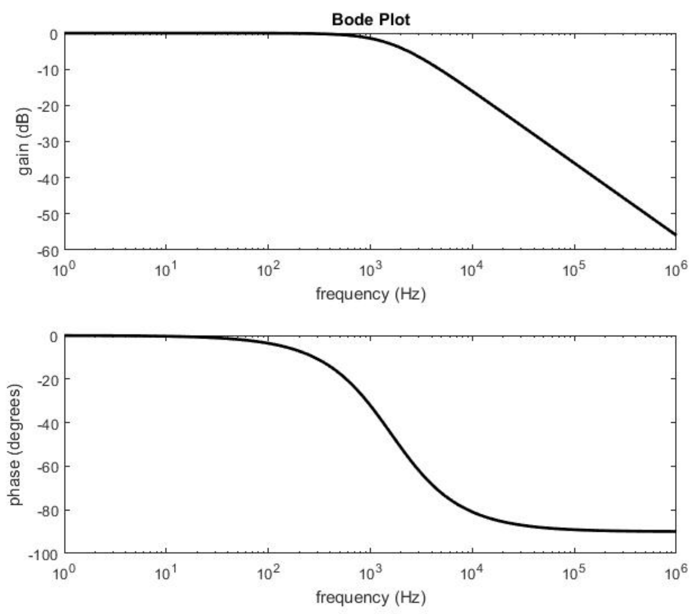
The phase is $\angle H(j\omega) = \angle \text{N} - \angle \text{D} = 0 - \tan^{-1}\left(\frac{\omega RC}{1}\right) = -\tan^{-1}(\omega RC)$

The Bode plot is a graph of the frequency response, and it is composed of two plots: one each for the gain and phase. The gain plot has frequency on the x-axis, in a log scale, and the magnitude in decibels (dB) on the y-axis. The phase plot has the same x-axis properties as the gain's, and the y-axis is in degrees. Together these are referred as the frequency domain behavior of a system.

Example: Suppose $R = 10\text{k}\Omega$ and $C = 0.01\mu\text{F}$ for the system above.

The gain in dB is $|H(j\omega)|_{\text{dB}} = 20\log_{10}\left(\frac{1}{\sqrt{1+\omega^2(10^{-8})}}\right)$

The phase is $\angle H(j\omega) = -\tan^{-1}(\omega 10^{-4})$



Note: In this prelab procedure the default power supply voltage to the op-amp is $\pm 12\text{V}$.

3.1 Inverting Amplifier

Prelab #1:
Derive the frequency response for the circuit in Figure 3.1, in terms of R_s and R_f, and explain why this circuit is known as an inverting amplifier.

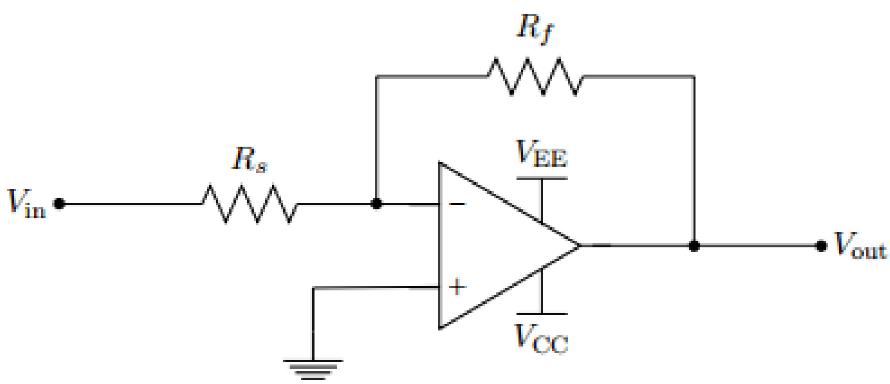


Figure 3.1: Inverting amplifier

Prelab #2:
Design an inverting amplifier that has a gain of -47 (this gain is negative). Pick resistor values that you have in your lab kit. Include a schematic of this circuit, with the component values labeled, with your completed prelab.

Prelab #3:

a) Use **Lab3_prelab.m** and **lab3plot.m** to plot the Bode plot for your inverting amplifier.

b) Simulate this inverting amplifier circuit with SPICE to make sure the circuit works as designed. Include the Bode plot generated by SPICE in your completed prelab. Comment on any differences from the results from part (a) and explain which result is closer to the actual behavior.

   Hint: Read the Bode plots in the op-amp's datasheet.

3.2 Non-Inverting Amplifier

Prelab #4:
Derive the frequency response for the circuit in Figure 3.2, in terms of R_s and R_f, and explain why this circuit is known as a non-inverting amplifier.

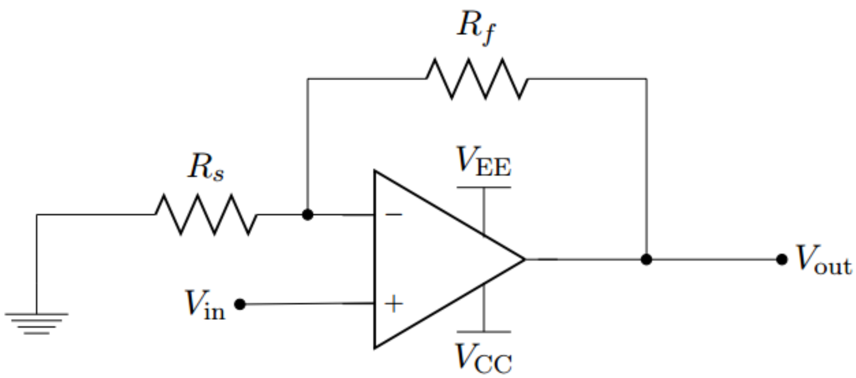


Figure 3.2: Non-inverting amplifier

Prelab #5:
Design a non-inverting amplifier that has a gain of +48 (this gain is positive). Pick resistor values that you have in your lab kit. Include a schematic of this circuit, with the component values labeled, with your completed prelab.

Prelab #6:

a) Use **Lab3_prelab.m** and **lab3plot.m** to plot the Bode plot for your non-inverting amplifier.

b) Simulate this non-inverting amplifier circuit with SPICE to make sure the circuit works as designed. Include the Bode plot generated by SPICE in your completed prelab.

3.3 Integrating Amplifier

The resistors in the inverting amplifiers can be substituted by any other type of impedance to achieve other functions rather than simple constant positive or negative gain. Change the resistor in the feedback loop to a capacitor, shown in Figure 3.3, and it becomes an integrating amplifier (integrator).

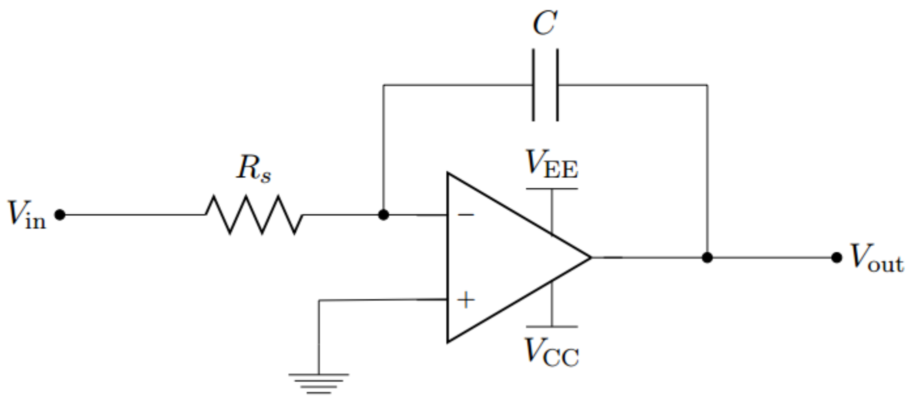


Figure 3.3: Integrating amplifier

Prelab #7:
Derive the frequency response for the circuit in Figure 3.3, in terms of R_s and C, then show that the circuit performs the function of an integrator.

Prelab #8:
Use SPICE transient analysis to simulate the circuit in the time domain using a sine wave input with an amplitude of 100mV and a frequency of 10kHz, with capacitor $C = 47\text{pF}$ and the resistor you chose in Prelab #2. From the SPICE output plot of the input and output waveforms, confirm that this circuit is an integrator.

Hint: The output signal takes time to reach steady state, so you might see unexpected waveforms in the beginning. To find the steady state output, you could use the oscilloscope in the software or set the time in transient analysis much later than zero. The integration of a sine wave should be a cosine wave.

Prelab #9:

a) Use **Lab3_prelab.m** and **lab3plot.m** to plot the Bode plot for your integrating amplifier.

b) Simulate this integrating amplifier circuit with SPICE, using the same resistor and capacitor, to make sure the circuit works as designed. Include the Bode plot generated by SPICE in your completed prelab.

Now consider what happens when another resistor is added in parallel to the feedback capacitor, as shown in Figure 3.4.

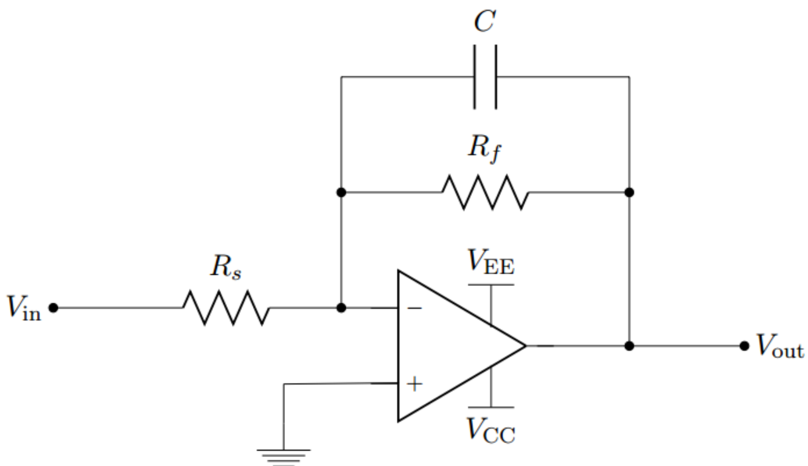


Figure 3.4: Integrating amplifier with shunt resistor

Prelab #10:

a) Derive the frequency response for the circuit in Figure 3.4, in terms of R_s, R_f, and C.

b) What is the magnitude of the gain of this circuit? Use **Lab3_prelab.m** and **lab3plot.m** to plot the Bode plot, with capacitor $C = 47\text{pF}$ and the resistors chosen in Prelab #2.

Prelab #11:

a) Explain why the low-frequency ($\omega \to 0\text{Hz}$) gain of this circuit is the same as the gain of an inverting amplifier. Compare this Bode plot with the plot for the inverting amplifier and explain any differences between them.

b) Explain why the high-frequency ($\omega \gg 1/(R_f C)$) gain of this circuit is the same as the gain of a simple integrator at high frequencies.

c) Explain the function of the resistor R_f in the circuit, compared to the circuit in Figure 3.3.

Hint: Compare the difference of gain with and without the shunt resistor R_f, especially at low frequencies.

Prelab #12:

a) Use SPICE to simulate the frequency response of Figure 3.4. If the input signal has a low frequency what is the expected gain? If the input signal has a high frequency what is the expected gain?

b) Comment on whether this circuit is a low-pass, high-pass, or band-pass filter. Explain why this circuit is a better choice for an audio preamplifier, over a simple inverting or non-inverting amplifier.

Hint: Consider noise from the input signal. Read Reference **Error! Reference source not found.** for more details about noise.

3.4 Differentiating Amplifier

Replacing the source resistor with a capacitor turns an inverting amplifier into a differentiating amplifier (differentiator).

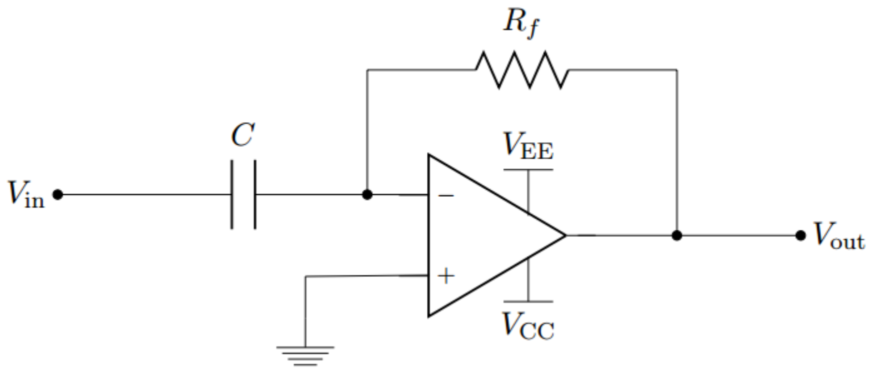


Figure 3.5: Differentiating amplifier

Prelab #13:
Derive the frequency response for the circuit in Figure 3.5, in terms of R_f and C, then show that the circuit performs the function of a differentiator.

Prelab #14:
Use SPICE transient analysis to simulate this circuit in the time domain using a sine wave input with an amplitude of 100mV and a frequency of 1kHz, with capacitor $C = 0.1\mu\text{F}$ and $R_f = 50\text{k}\Omega$. From the SPICE output plot of the input and output waveforms, confirm that this circuit is an integrator.

Hint: The output signal takes time to reach steady state, so you might see unexpected waveforms in the beginning. To find the steady state output, you could use the oscilloscope in the software or set the time in transient analysis much later than zero.

Prelab #15:

a) Use **Lab3_prelab.m** and **lab3plot.m** to plot the Bode plot for your differentiating amplifier.

b) Simulate this differentiating amplifier circuit with SPICE, using the same resistor and capacitor, to make sure the circuit works as designed. Include the Bode plot generated by SPICE in your completed prelab.

4 Experimental Procedure and Data Analysis

Make sure to keep what is built on the breadboard in this lab for later experiments. Also, have your TA check your circuit before you leave to make sure that it is working well.

4.1 Equalizer

4.1.1 Preamplifier

Build the circuit in Figure 4.1, with power supplies $V_{CC} = 12\text{V}, V_{EE} = -12\text{V}$. Set $R_s = 1\text{k}\Omega, R_f = 47\text{k}\Omega$, and $C = 47\text{pF}$; then let R_v be a $50\text{k}\Omega$ potentiometer set to zero in the circuit.

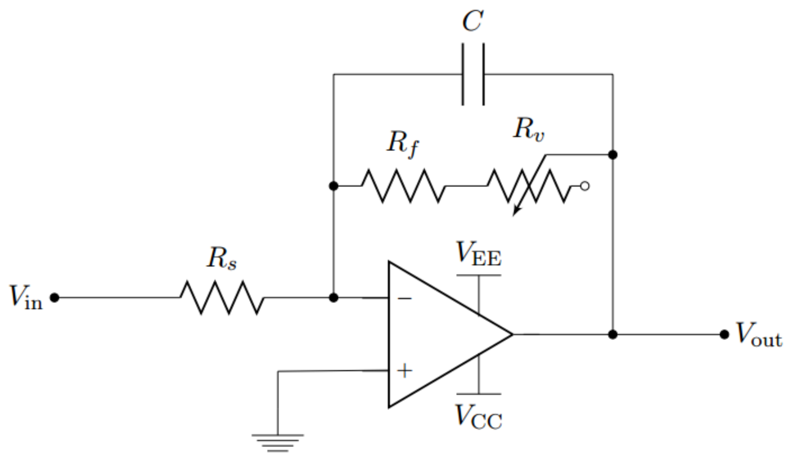


Figure 4.1: Preamplifier circuit

Use the function generator to produce an input sine wave with an amplitude of 100mV and frequency of 10Hz, then vary the frequency using the 1-2-5 sequence up to 5kHz, keeping the amplitude 100mV. **Record the amplitude and phase change of the output signal at every frequency.**

> **Analysis #1:**
> Using Microsoft Excel, draw the Bode plot from 10Hz to 5kHz and compare it to the results in Prelab #10b.

Apply a sine wave input signal with an amplitude of 300mV and a frequency of 300Hz. Display the input signal on Channel 1 of the oscilloscope and the output signal on Channel 2. Adjust the time base to display 2-3 complete cycles of the signals. Capture both the waveforms in the scope display to confirm that the circuit is an integrator. **Turn this oscilloscope waveform in as part of your lab report.**

Now set the potentiometer to 50kΩ and repeat the same frequency sweep from Analysis #1 (the input amplitude should be 100mV). **Record the amplitude and phase change of the output signal at every frequency.**

> **Analysis #2:**
> Using Microsoft Excel, draw the Bode plot from 10Hz to 5kHz. Compare the plot with that Analysis #1 and comment on the difference caused by changing the potentiometer.

4.1.2 Summing Amplifier

Build the circuit in Figure 4.2, with power supplies $V_{CC} = 12V, V_{EE} = -12V$. Set the capacitor to 0.1μF and make all the resistors 100kΩ potentiometers.

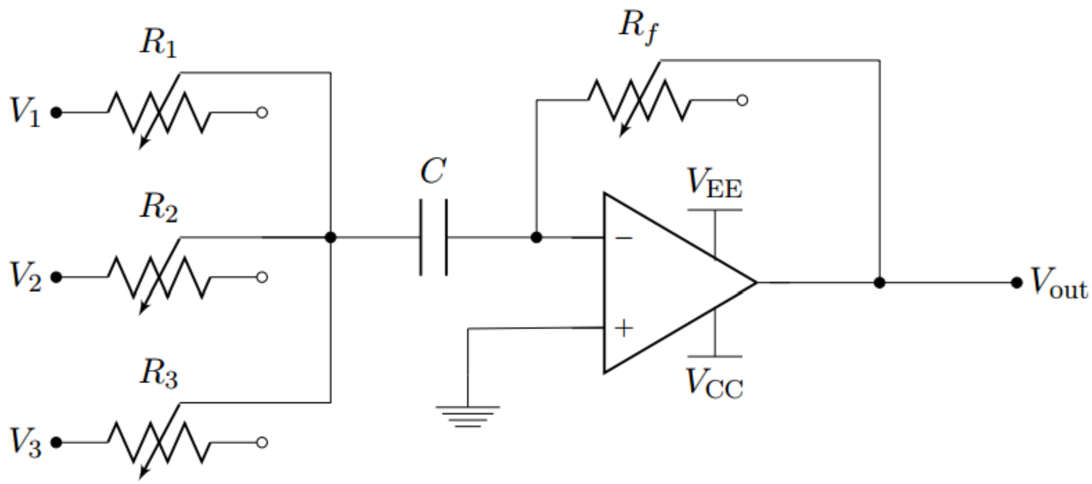


Figure 4.2: Summing amplifier circuit

Apply the function generator to V_1 with an amplitude of 500mV, and leave the other two inputs empty. Sweep the frequency of V_1 starting at 10Hz, then vary it using the 1-2-5 sequence up to 5kHz, while keeping the amplitude the same. **Record the amplitude and phase change of the output signal at every frequency.**

Analysis #3:
Using Microsoft Excel, draw the Bode plot from 10Hz to 5kHz and comment on whether the circuit is a low-pass, high-pass or band-pass filter.

Set $R_1 = 0\Omega$ and $R_f = 50k\Omega$. Apply a sine wave input signal to V_1 with an amplitude of 300mV and a frequency of 300Hz. Display the input signal on Channel 1 of the oscilloscope and the output signal on Channel 2. Adjust the time base to display 2-3 complete cycles of the signals. Capture both the waveforms in the scope display to confirm that the circuit is a differentiator. **Turn this oscilloscope waveform in as part of your lab report.**

Apply a sine wave input signal to V_1 with an amplitude of 100mV and a frequency of 1kHz and display the output signal in the oscilloscope. Set $R_1 = 1k\Omega$ and increase R_f until the output waveform becomes distorted.

Analysis #4:
Explain the reason why the output becomes distorted, and comment on how to avoid such distortion.
Hint: The distorted sine waveform should become flat on top and bottom. Record the maximum and minimum value of the distorted waveform and compare them with V_{CC} and V_{EE}.

Apply a low frequency sine wave to V_1 and connect V_{out} to the speaker. Listen to the sound in the speaker, then remove the capacitor and listen to the sound again.

Analysis #5:
Explain the function of the capacitor in the output summing amplifier.

4.2 Microphone

The microphone in your lab kit has two pins: pin 1 is the positive end, and pin 2 the negative end. To use the microphone, you need to ground pin 2 and use a resistor to connect pin 1 to a positive voltage supply (this is known as a "pull-up resistor", since it pulls the pin up to power). A capacitor is then connected between the output of the microphone and the input of the preamplifier, to help reduce noise.

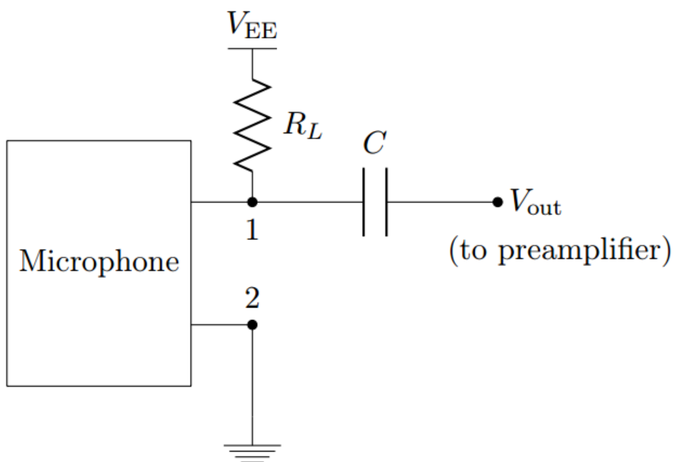


Figure 4.3: Microphone circuit

Build the circuit in Figure 4.3, using the power source $V_{EE} = 12\text{V}$, $R_L = 10\text{k}\Omega$, and $C = 1\mu\text{F}$. Connect the microphone to your preamplifier, and then connect the output of the preamplifier to the speaker. Play a sound from a cell phone, harmonica, guitar or any other instrument into your microphone, or you can sing into or tap on the microphone and listen to the sound from the speaker.

4.3 Mixer

Now that you have a microphone and some filters, you are ready to mix signals with the audio mixer. Connect the speaker to the output terminal of the output summing amplifier and use headphone jacks to provide three channels of signals from your laptops or cell phones. You can also use your microphone for one of the channels. Listen to the sound of the speaker and tell whether the three signals are mixed.

Now use the potentiometers in the output summing amplifier to change the whole volume and the ratio of volumes between three channels. This is exactly the same thing as what happens in audio studios. Let your TA check your sounds to make sure your mixer works well.