University of North Carolina, Charlotte
Department of Electrical and Computer Engineering
ECGR 3157 EE Design II Fall 2013

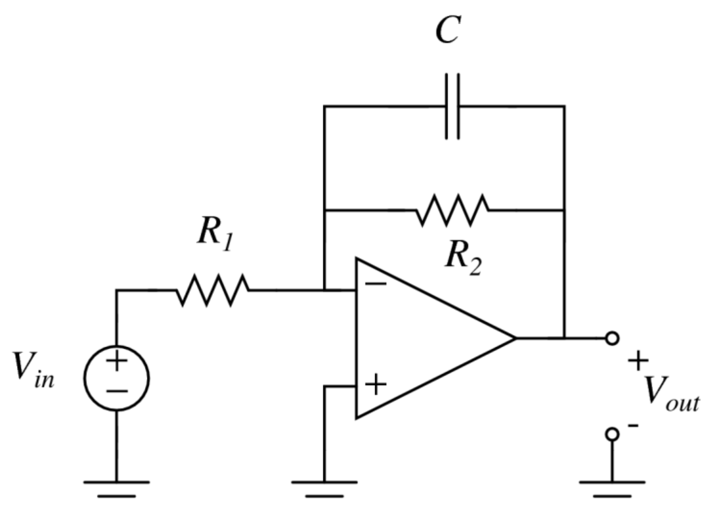
Lab 2
Stereo System Design

Issued: September 28, 2013 Due: October 14, 2013

In this assignment, you will build some basic amplifier circuits. Many of these amplifiers will make use of a common circuit building block known as the op-amp. We'll also use devices known as transistors. You'll learn a lot more about the physics of these devices in your other classes. In this course, you'll be learning how to use them to build a complete system.

**Exercise 1: Basic op-amp circuit design**

Now, let's look at a very basic amplifier.




This circuit is very similar to the inverting amplifier that we examined in class. The only difference is the insertion of the capacitor. Please answer or do all of the following:

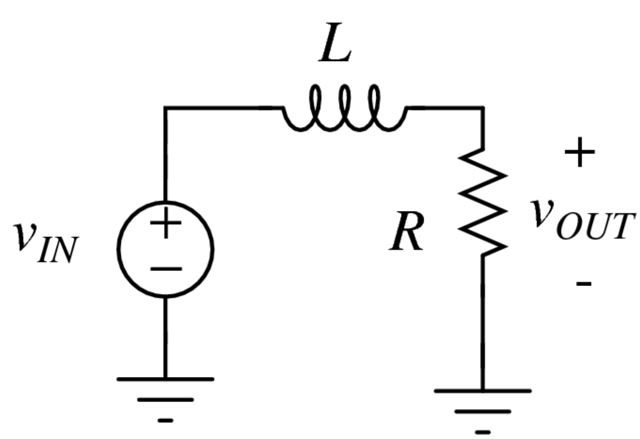
1. At low frequencies, does the capacitor act like a short-circuit or an open-circuit? Based on your answer, please draw an equivalent schematic that describes the circuit at low frequencies. In this schematic, the capacitor should be replaced with either an open-circuit or a short-circuit.
2. Determine an expression for the gain of the low-frequency equivalent circuit that you drew in Part 1. This expression is often referred to as the low-frequency gain of the circuit.
3. Chose components so that the magnitude of the low-frequency gain is approximately 10. When we construct this circuit, we will use the LF356. Use its datasheet and the comments that we made in class to help you to select resistor values.
4. At high frequencies, does the capacitor act like an open-circuit or a short-circuit? Based on your answer, please draw an equivalent schematic that describes the circuit at high frequencies. In this schematic, the capacitor should be replaced with either an open-circuit or a short-circuit.
5. Determine an expression for the gain of the high-frequency equivalent circuit that you drew in Part 4. This expression is often referred to as the low-frequency gain of the circuit.

6. Using the expression for capacitor impedance $1/(j\omega C)$, provide an expression for the overall gain $v_{OUT}/v_S$ of the circuit.
7. Your expression for the overall gain should look very similar to the transfer function of a low-pass filter. The cutoff frequency of this filter should be expressed in terms of *C* and a single resistance. Choose a value for *C* so that the cutoff frequency is approximately 1000Hz. Try to use standard capacitor values, i.e. 0.1µF, 0.33µF, etc.
8. Construct the circuit using the resistor and capacitor values that you determined in the previous parts of this exercise. Use the LF356 op-amp and power it using +12V at Pin 7 and -12V at Pin4. **Remember to use bypass capacitors.**
9. Apply a sine wave from the Tektronix function generator as the input $v_S$. This sine wave should have the following characteristics:
    - Amplitude: 100mV
    - Frequency: 10Hz
    - Type: Sine Wave
    - Offset: 0V

   Record the gain of circuit at this frequency and compare to the expected value. Make sure to measure the actual resistances so that you can very accurately determine the reason for any discrepancies.
10. Now, slowly increase the frequency of the sine wave input and try to find the cutoff frequency of the circuit. At the cut-off frequency, the amplitude of the output signal should be approximately 70% of its value at low frequency (i.e. 100Hz). Use this fact to find the cutoff frequency. At that frequency, sketch the input signal and the output signal.
11. Use your expression from part 6 to find the expected value of the overall gain at the frequency you measured in part 10. To do this accurately, you will need to use the true, measured component values. This means that you will need to measure the value of your capacitor using the LCR meter in the lab.

**Exercise 2: Analyzing a Filter Circuit (You don't have to build anything for this exercise)**

We have the following circuit:




Please answer the following questions. When working through this section, be sure to have your notes handy. They will help you through this section.

1) Using intuitive arguments (i.e. considering how the inductor behaves at different frequencies), describe what kind of filter this is (i.e. band pass, high pass, etc.). Explain your answer.
2) Determine the transfer function $V_{out}/V_{in}$ for the circuit shown here. Express your result in the following form:

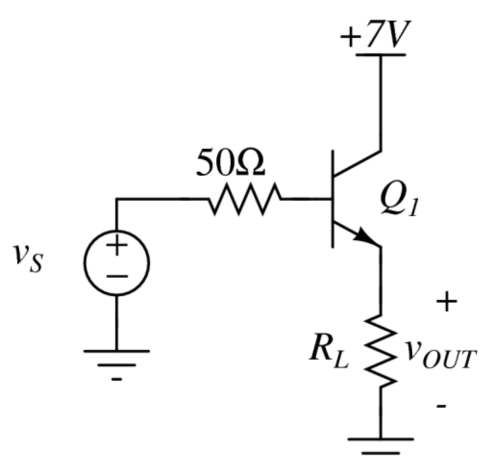
$$\frac{V_{out}}{V_{in}} = K\frac{\tau_Z s+1}{\tau_P s+1}$$

where K is known as the DC gain, $1/\tau_Z$ is a zero frequency (in radians per second), and $1/\tau_P$ is a pole frequency (in radians per second). In terms of the circuit components (i.e. R's and L's), what is the DC gain, zero frequency, and pole frequency for this circuit?
3) Assuming that R = 1kOhm and that L = 1mH, construct a plot that shows how the magnitude of the transfer function varies versus frequency. The magnitude should be plotted in dB, (i.e. $20\log_{10}|V_{out}/V_{in}|$). Plot the magnitude versus $\log_{10}(f)$. Note that I've specifically asked for the magnitude to be plotted versus the log of ***frequency in Hz*** and NOT the frequency in rad/sec.
4) Assuming that R = 1kOhm and that L = 1mH, construct a plot that shows how the phase of the transfer function varies versus frequency. Plot the magnitude versus $\log_{10}(f)$. Note that I've specifically asked for the magnitude to be plotted versus the log of ***frequency in Hz*** and NOT the frequency in rad/sec.

**Exercise 3: Basic Transistor Amplifier Design**

As we discussed in class, most op-amps provide a reasonable voltage gain, but they do not provide serious *power* gain for devices like antennas and speakers. In this exercise, we'll explore the transistor amplifiers that we'll need to combine with our op-amps in order to achieve serious power gain.

First, consider the following circuit, which is known as a Class A amplifier:

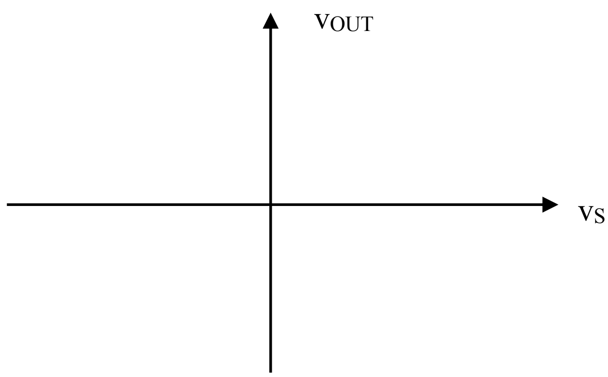



**Note that the power supply is 7V!**

Please answer or do the following:

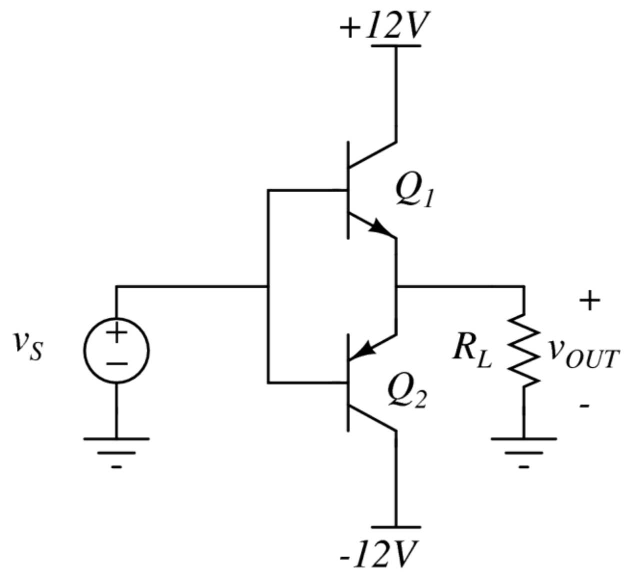
1. Construct a class A amplifier using a TIP29 or TIP31 NPN transistor. These transistors were given to you. **Place a heat sink on the transistor.** Use the transistor datasheet to determine which pin is the collector, which pin is the emitter, and which pin is the base. Choose the value of $R_L$ so that the output current is approximately 1mA when the output voltage is 2V.

2. You are going to use the function generator as the input source $v_S$. Before connecting the function generator to the circuit, place it into the DC mode and measure its output using an oscilloscope. You should notice that the measured voltage is approximately twice what the display says it is. Note that the value displayed on the screen assumes that the load on the oscilloscope is 50 Ohms. Knowing this, determine a Thevenin equivalent circuit for the function generator.
3. Connect the function generator as the source $v_S$ in your transistor circuit and then place the function generator into DC mode. Measure the circuit's output voltage and measure $v_S$. Increase $v_S$ in increments of 0.25V and record the output voltage at each setting. Increase the voltage to 10V. Sketch your results on a set of axes such as the following:




4. At a particular value of the input voltage $v_S$, the output voltage should stop increasing. Why?
5. At what approximate voltage $V_{BE,\,ON}$ does the transistor turn on?
6. The slope of the $v_{OUT} - v_S$ curve is known as the gain of this circuit. Please explain. What is the gain in this particular case?

Now, consider the following circuit, which is known as a Class B amplifier. This transistor amplifier stage is more efficient than the Class A design shown previously. It is commonly used in stereo amplifiers and small RF systems, such as cell phones.

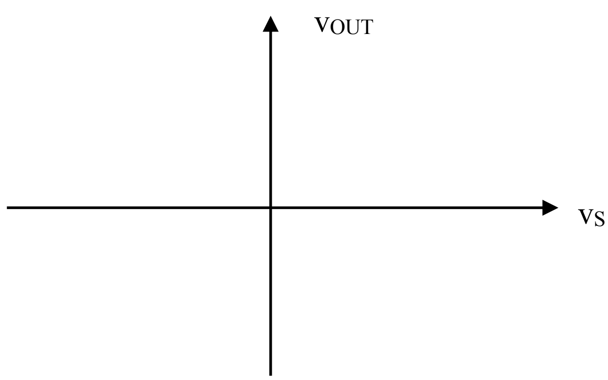



Please answer or do the following:

7. Construct a class B amplifier using the TIP29 and TIP30 transistors (or TIP31 and TIP32 transistors) available in the lab. Use the transistor datasheets to determine which pin is the collector, which pin is the emitter, and which pin is the base. For $R_L$, use the power resistor that you received for Lab 1.
8. Connect the function generator as the source $v_S$. Set the function generator as described below:

    - Type: DC
    - Offset: 0V

    Measure the output voltage. Increase the offset in increments of 0.25V and record the output voltage at each setting. Make sure to take into account the true value of $v_S$. Increase $v_S$ to 8V. Repeat for negative input voltages. Sketch your results on a set of axes such as the following:




9. Using your results from the previous part, determine the voltage gain of the Class B amplifier.
10. What is the base-emitter voltage $V_{BE, ON}$ at which the transistor $Q_1$ turns on? What is the base-emitter voltage $V_{BE, ON}$ at which the transistor $Q_2$ turns on?
11. Now, change the output of the function generator so that it provides a sine wave with the following characteristics:

- Type: Sine wave
- Offset: 0V
- Amplitude 5V
- Frequency: 1kHz

Sketch the output voltage and input voltage. Why does the output voltage appear as it does?

12. The Class A and Class B circuits are very similar in that they are both power amplifiers, but they are very different in terms of their efficiency. Assume the following cases:

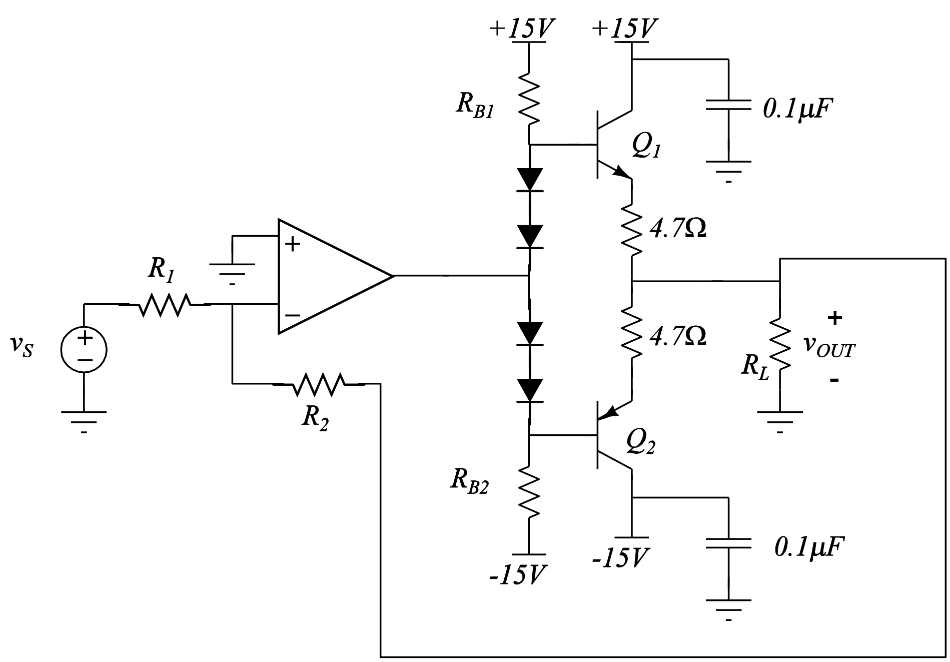
    a. The Class A circuit is provided with a sine wave and a DC voltage so that the output voltage is a sine wave added to a DC voltage.
    b. The Class B circuit is provided with a pure sine wave.

    In both cases, sketch the current in the NPN transistor and the corresponding voltage across it. Compare the power dissipation in the transistors. Which circuit is more efficient? Which one provides a higher quality output? Explain the trade-off.

**Exercise 4: Building the complete stereo power amplifier**

Now, we're going to combine the class B power amplifier from above with the op-amp stages studied previously. The op-amp will provide us with a voltage gain, and the transistor stage will provide us with a current gain. The combination of these elements will allow us to make a stereo amplifier that you will demonstrate at your check-off.

Now, let's modify our previous amplifier to the following:

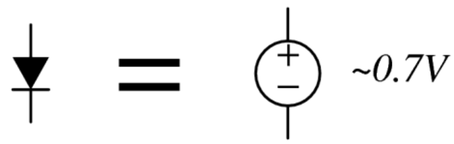



The diodes are the 1N4148 or 1N914 diodes that are available in the lab. These diodes are the small glass diodes.

Please answer or do the following:

1. The purpose of the diodes in this circuit is to ensure that the transistors are always turned on. In order to do that, you must make sure that the diodes are always turned on. This means that you need to choose values for the resistors labeled $R_{B1}$ and $R_{B2}$. Before designing, remember the following:

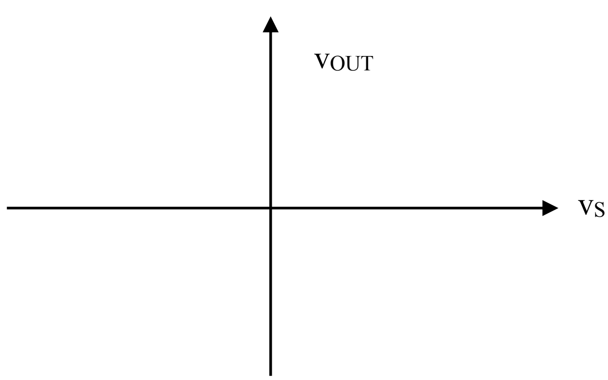
    - When a DC current is passed through a diode (as is the case here), the diode will turn ON. When the diode is ON, it can be modeled as a voltage source as shown below:

    - To choose values for $R_{B1}$ and $R_{B2}$ use the following steps. Assume that both the input voltage $v_s$ and the voltage at the output of the op-amp is 0V. Replace each diode with a 0.7V source. Assuming that a negligible amount of current flows into the base of $Q_1$ and the base of $Q_2$, select values for $R_{B1}$ and $R_{B2}$ so that the current through $R_{B1}$ and $R_{B2}$ is between 7mA and 10mA. **Be sure to show your design calculations.**
    - Design the complete circuit to have a gain of 20.
2. Construct the complete amplifier using the 1N4148 diodes and the transistors and op-amp that you used previously. Note that the cathode, or negative terminal, of the diode is marked with a black line on its package.
3. Use the function generator as the input source $v_S$. Setup the function generator to output a sine wave with the following characteristics:

    - Amplitude: 0.2V
    - Type: Sine
    - Frequency: 1kHz
    - Offset: 0V

    Using the oscilloscope, determine the overall gain of this circuit. An easy way to do this is to compare the peak value of the input signal to the peak value of the output signal.
4. What is the peak value of the output current?
5. Apply a pure DC input from the function generator and adjust the value from -0.1V to 0.1V by adjusting the Offset value. Record the output voltage at several different input voltages. Sketch your results on a set of axes such as the following:

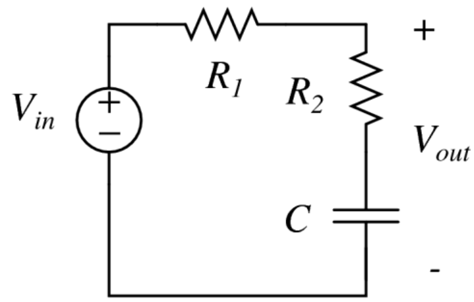


6. What was the primary effect of adding the diodes?

DO NOT DESTROY THIS CIRCUIT! YOU'LL NEED IT LATER IN THE LAB. This is the power amp for the audio stage.

**Exercise 5: Building Frequency-Dependent Circuits**

Now, you're actually going to start designing and building some filter circuits. Let's look at a pretty simple filter first. Consider the following circuit:




Please answer or do the following:

1) Determine the transfer function $V_{out}/V_{in}$ for the circuit shown here. Express your result in the following form:

$$\frac{V_{out}}{V_{in}} = K\frac{\tau_Z s+1}{\tau_P s+1}$$

where K is known as the DC gain, $1/\tau_Z$ is a zero frequency, and $1/\tau_P$ is a pole frequency. In terms of the circuit components (i.e. R's and C's), what is the DC gain, zero frequency, and pole frequency for this circuit?

2) Suppose that we want to use this circuit in a system that imposes the following requirements on the magnitude of $V_{out}/V_{in}$ :

- A magnitude of 1 for input frequencies below approximately 100Hz
- A magnitude that starts to fall at 20dB/decade at approximately 100Hz
- A constant magnitude for input frequencies above approximately 10kHz

Choose R and C values that will satisfy these requirements. Select components that are as close as possible to your design choices. When you select your components for this part, you should consider the following: you essentially have two design constraints – one for the zero and one for the pole. This will end up giving you two equations (one for the pole and one for the zero) that involve three unknowns ($R_1$, $R_2$, and C). When selecting values, this means that you have to choose one value arbitrarily and then solve for the other two. In this case, it makes the most sense to first go to the drawer and select an available capacitor. Once you've done that, solve for $R_1$ and $R_2$. Why does this process make sense?

3) Using your design values, construct a plot that shows how the magnitude of the transfer function varies versus frequency. The magnitude should be plotted in dB, (i.e. $20\log_{10}|V_{out}/V_{in}|$). Plot the

magnitude versus $\log_{10}(f)$. Note that I've specifically asked for the magnitude to be plotted versus the log of frequency in Hz and not the frequency in rad/sec.

4) Construct the circuit using your design values. Apply a sine wave from the Tektronix function generator as the input $V_{in}$. This sine wave should have the following characteristics:
   - Amplitude: 1V
   - Frequency: 1Hz
   - Type: Sine Wave
   - Offset: 0V

   Vary the frequency and create a table that shows how the magnitude of the output varies with frequency. Your table should include the following columns:

   | Frequency (Hz) | Input Amplitude (V) | Output Amplitude (V) | Output Amplitude (dB) |
   |---|---|---|---|
   | 1 | 1 | 1 | 0 |
   | | | | |

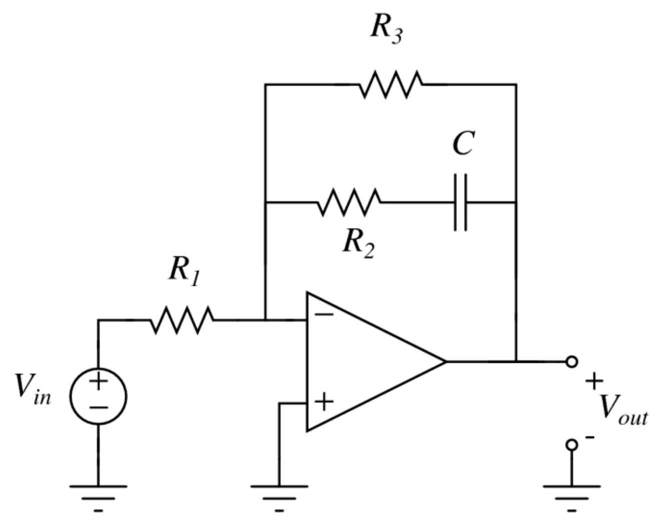
   Measure the output amplitude at the following frequencies: 1Hz, 10Hz, 20Hz, 50Hz, 100Hz, 200Hz, 500Hz, 1kHz, 2kHz, 5kHz, 10kHz, 20kHz, 50kHz, 100kHz, 200kHz. You do not need to measure the phase shift.

   When you make your measurements, make sure that your scope is DC coupled.

   Create a plot that shows how the output amplitude (in dB) changes versus the $\log_{10}(f)$. Look specifically at your measured magnitude at 1kHz and 2kHz. At what rate is the magnitude dropping between those frequencies? Why did you expect this?
5) Provide an intuitive explanation for the behavior of the measured magnitude. To answer, think about the behavior of the capacitor as frequency varies.
6) Now AC-couple the scope channel that measures the output voltage. Reset the input frequency to 1Hz. What is the magnitude of the output voltage now? Why is it different than what you measured previously? Hint: Think about what it means to AC-couple the oscilloscope, and then think about how the oscilloscope must be accomplishing this function.

**Exercise 6: An Audio Tone Control**

Now we want to build a circuit that is useful in audio systems. In particular, we want to build a circuit that can provide "Bass Boost." This circuit will provide gain at low frequencies and it will attenuate higher frequencies. The circuit is shown below.




Please answer or do the following:

1) Determine the transfer function $V_{out}/V_{in}$ for the circuit shown here. Express your result in the following form:

$$\frac{V_{out}}{V_{in}} = K\frac{\tau_Z s+1}{\tau_P s+1}$$

In terms of the circuit components (i.e. R's and C's), what is the DC gain, zero frequency, and pole frequency for this circuit?

2) Which is lower in frequency, your pole or your zero? You should be able to answer based on your pole and zero equations. Why is this desirable for a bass-boost circuit? To answer, you'll need to remember how a pole and zero affect the magnitude of the gain.
3) We want to design our bass-boost circuit so that we meet the following specifications:
   a. A constant gain of approximately 35dB for input frequencies below about 100Hz
   b. A gain that falls at -20dB/decade between 100Hz and 10kHz
   c. A gain that is constant for input frequencies above 10kHz

   Based on these constraints, at what frequency should you place the pole? At what frequency should you place the zero? Provide values for each of the R's and C's.
4) Using your design values, construct a plot that shows how the magnitude of the transfer function varies versus frequency. The magnitude should be plotted in dB, (i.e. $20\log_{10}|V_{out}/V_{in}|$). Plot the magnitude versus $\log_{10}(f)$. Note that I've specifically asked for the magnitude to be plotted versus the log of frequency in Hz and not the frequency in rad/sec.
5) How do zeros affect the phase of a transfer function? How do poles affect the phase of a transfer function?
6) Using your design values, construct a phase plot for the transfer function. You should plot the phase of $V_{out}/V_{in}$ versus $\log_{10}(f)$. The Lecture Notes should help.
7) Construct the circuit using your design values. Use your LF356 from the last lab. Power your op-amp from +15V and -15V. Remember to place bypass capacitors close to the chip. Apply a sine wave from the Tektronix function generator as the input $V_{in}$. This sine wave should have the following characteristics:
   - Amplitude: 0.05V
   - Frequency: 1Hz

- Type: Sine Wave
- Offset: 0V

Vary the frequency and create a table that shows how the magnitude of the output varies with frequency. Your table should include the following columns:

| Frequency (Hz) | Input Amplitude (mV) | Output Amplitude (V) | Gain (dB) |
|---|---|---|---|
| 1 | 50 | | |
| | | | |

Measure the output amplitude at the following frequencies: 1Hz, 2Hz, 5Hz, 10Hz, 20Hz, 50Hz, 100Hz, 200Hz, 500Hz, 1kHz, 2kHz, 5kHz, 10kHz, 20kHz, 50kHz. At each frequency, you should also record the phase shift between output and input. .

When you make your measurements, make sure that your scope is DC coupled.

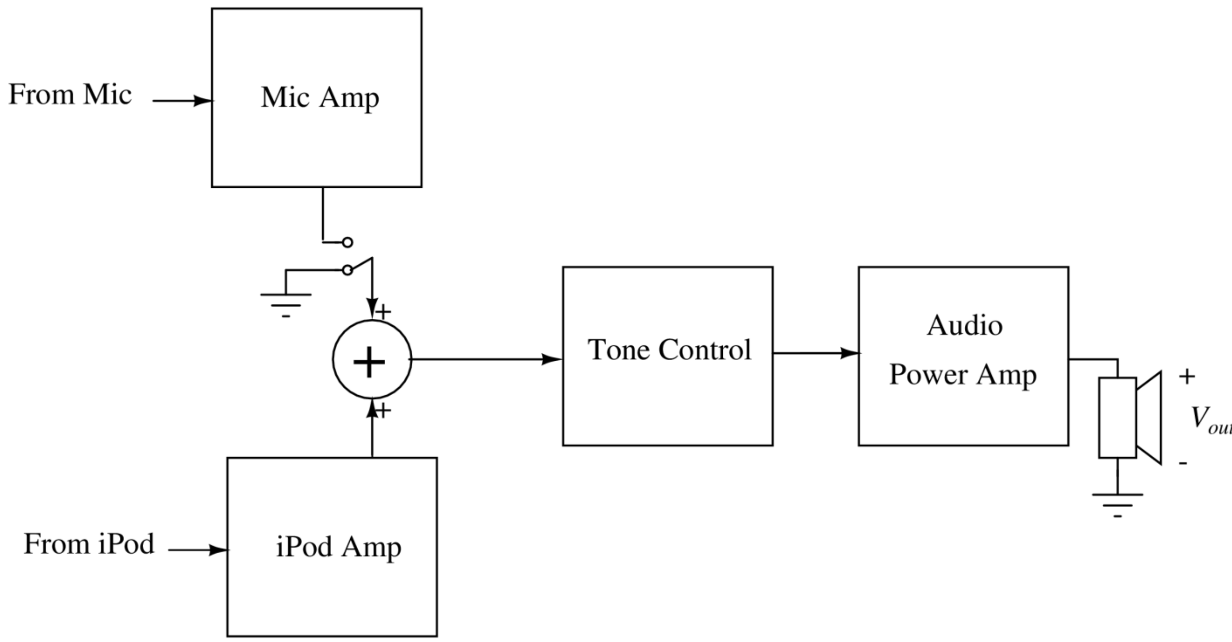
Create a plot that shows how the gain (in dB) changes versus $\log_{10}(f)$. Also, create a plot that shows how the phase changes versus $\log_{10}(f)$. How do these compare to what was expected?

8) Provide an intuitive explanation for your measured gain at 20kHz. In other words, you should be able to predict this gain based on what you know about how the impedance of a capacitor varies with frequency.

9) We apply a sine wave $V_{in} = V\cos(2\pi ft)$ into this circuit, Use your magnitude and phase plots to give an approximate expression for the output at the following frequencies: 10Hz, 500Hz, 20kHz. To answer this, remember what the Bode plot tells you. Use your notes on Bode Plots to help you.

**Exercise 7: Design a Simple Stereo with Karaoke**

You are now going to design a small stereo system as shown in the block diagram below. You must complete your design and present it at your team's design-review session.




This system has the following components:

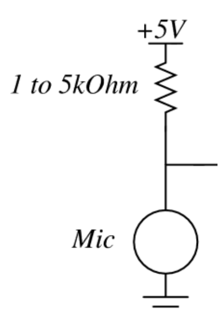
- A microphone and amplifier
- An input amplifier for an iPod or other audio source
- A summer
- Tone control circuit

**In this exercise, you will design each of the individual components. The audio power amplifier is the same amplifier that you constructed in the previous exercise.**

The individual components should meet the following specifications:

Circuit 1: Microphone and Amp

Microphones provide a very tiny output voltage, so they require an additional amplification. Here is the basic microphone circuit. You need this in order to turn the microphone on. The voltage across the mic is the signal that is to be amplified.



Design an amplifier circuit that has the following characteristics:

- The amplifier should have a gain with a magnitude of approximately 10
- Prior to amplification, remove the DC component of the microphone voltage using a high-pass filter with a cut-off frequency below the audio band, which starts at about 20Hz
- **Make sure that there is a DC path to ground at both inputs to any op-amps that you use**

Circuit 2: iPod Amplifier

Design an amplifier circuit that has the following characteristics:

- The amplifier should have a gain whose magnitude that *can vary* from 0 to 1. This variability provides volume control
- The iPod should see an input impedance that is at least 10kOhms no matter the volume control setting.

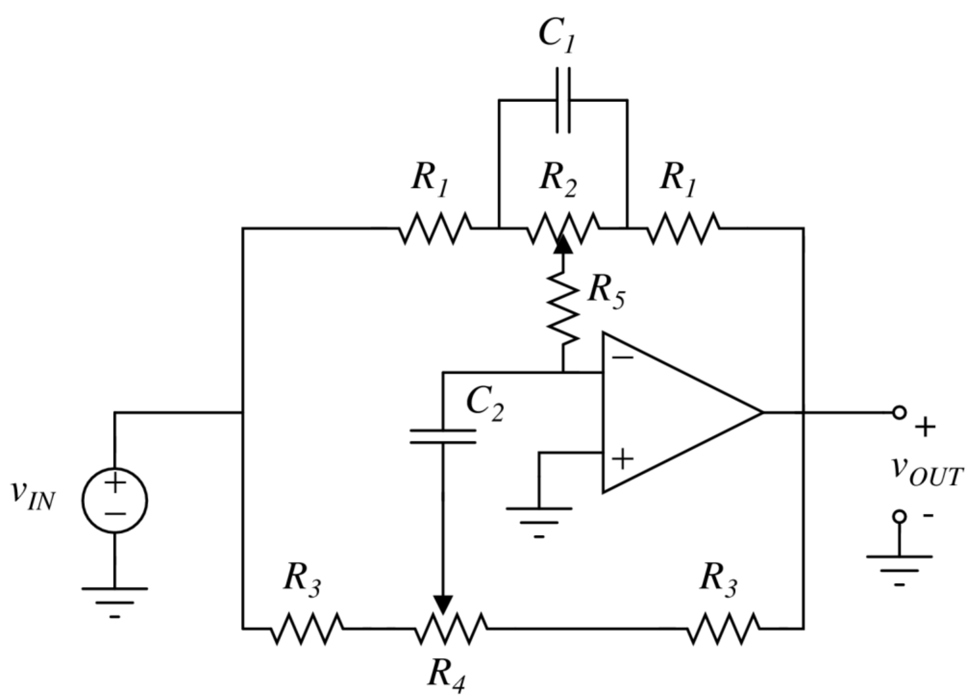
Circuit 3: Summer

Design the summing amplifier to meet the following specifications:

- The amplifier should have a unity gain for both input signals
- The output of the iPod amplifier should always be connected to the summer
- The output of the microphone amplifier should be able to be connected to the amplifier via a switch as shown in the block diagram.

Circuit 4: Tone-Control Circuit

The summer circuit should be followed by a tone-control circuit. This is a very common circuit:



Here is what we have:

- Resistor $R_2$ is the bass knob
- Resistor $R_4$ is the treble knob

You are given the following specifications:

- The bass cut-off frequency $f_{bass}$ should be ~30Hz. In other words, bass signals are considered to be those below 30Hz.
- The treble cut-off frequency $f_{treble}$ should be ~10kHz. In other words, treble signals are considered to be those above 10kHz.
- The gain for the bass signals should be adjustable by approximately $\pm 20dB$
- The gain for the treble signals should be adjustable by approximately $\pm 20dB$

Design of this circuit appears to be complicated, but this is where approximations can really help. Here are some hints that should help your analysis and selection of the resistances:

- Select $R_2$ to control the gain for the bass signals
- Select $R_4$ to control the gain for the treble signals
- When analyzing the behavior for the bass signals:
  - Make a reasonable assumption about the impedance of the capacitors
- When analyzing the behavior for treble signals:
  - Make a reasonable assumption about the impedance of the capacitors
- Throughout your analysis assume that the resistance of $R_4$ is so much larger than all of the other resistances that the current through it is negligible.

Selection of the capacitance can be a bit tough. To do so, you must determine the time constants associated with $C_1$ and $C_2$. Here is one way to determine those time constants:

- Bass Signals: Determine the resistance "seen" by $C_1$ while $C_2$ is an open circuit. To find the resistance "seen" by $C_1$, replace this capacitor with a current source $i$ and solve for the voltage $v$ across it. $R = v/i$. This resistance and the capacitance $C_1$ form the time constant that determines $f_{bass}$
- Treble Signals: Determine the resistance "seen" by $C_2$ while $C_1$ is a short circuit. To find the resistance "seen" by $C_2$, replace this capacitor with a current source $i$ and solve for the voltage $v$ across it. $R = v/i$. This resistance and the capacitance $C_2$ form the time constant that determines $f_{treble}$ Again assume that $R_4$ is so large that the current through it is negligible.

Circuit 5: Audio Power Amplifier

You will use the same audio power amplifier that you have already built. You may need to reduce the gain, however, in the laboratory due to potentially high distortion levels.

**Design Package:**

At your design review, you must present the following:

- A schematic of each individual circuit
- An analysis for each individual circuit. **Be prepared to defend individual calculations, although I do not necessarily want to see each individual calculation.**
- A table of values for each individual circuit

- **A proposal for the complete circuit layout**

Your report should also include schematics for each individual circuit, as well as your complete design calculations.

**Exercise 8: Build the stereo**

You must build the complete stereo circuit and demonstrate it. I recommend that you build and test each individual circuit separately before putting everything together. **Also, make sure that the speaker is placed far from the microphone.**

**PLEASE NOTE THAT YOU WILL LOSE POINTS AT YOUR CHECK-OFF IF YOU DO NOT HAVE AN APPROPRIATE LAYOUT!!!**

In your report, you must include the following:

1) Provide plots in your report that clearly demonstrate that you meet the gain *and* frequency specifications for the microphone amplifier. To do so, replace the microphone with the function generator.
2) Provide plots in your report that clearly demonstrate that you meet the gain specifications for the iPod amplifier. To do so, replace the iPod with the function generator.
3) Provide plots in your report that clearly demonstrate that you meet the gain and frequency specifications for the tone control circuit. Again, this circuit can be tested in isolation using a function generator.

Speakers will be available in the lab, and microphones and switches will be placed in the bottom drawer of the resistor cabinet in Room 2148.