ELECTRICAL ENGINEERING DEPARTMENT
COLORADO SCHOOL OF MINES

EENG 385 - Electronic Devices and Circuits
Audio Board: Amplifier Theory
Lab Handout

Objective

The objective of this lab is to analyze the operation and electrical characteristics of the audio amplifier stage of the Audio board and to prepare you to solder together the audio amplifier subsystem of the Audio board.

Audio Amplifier

The heart of the Audio Amplifier is shown in the schematic shown in Figure 1.

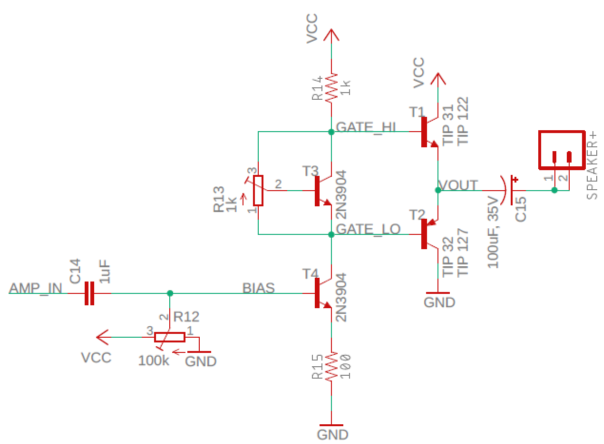


Figure 1: The core of the audio amplifier consists of a voltage gain stage followed by a current gain stage.

The output stage consists of a pair transistors T1 and T2 each in the common collector configuration. In the configuration shown in Figure 1:

- The base of T1 is 0.7V *above* the emitter.
- The base of T2 is 0.7V *below* the emitter

When an NPN and PNP transistor are arranged as shown in Figure 1, they are said to form a push/pull pair. The term alludes to the manner in which the pair pull the speaker towards VCC or push it towards GND. When we analyze the individual transistors in the push/pull pair, we will refer to them as emitter followers. The output of the push/pull pair should be centered at Vcc/2 = 4.5V so that the output voltage can swing as far as possible before hitting either rail.

Compute the emitter follower base voltages:

1) In order for the output of the push/pull pair be 4.5V, what should you set the base voltage of transistor T1 to?

2) In order for the output of the push/pull pair be 4.5V, what should you set the base voltage of transistor T2 to?
3) What is the voltage difference between the voltages found in Questions 1 and 2?

Common Emitter Theory

Transistor T4 in Figure 2 is configured as a common emitter. The base of T4 is the input and the collector is the output. Both the input and output voltages are measured with respect to the emitter terminal. Thus, the emitter is in common with both the base and the collector.

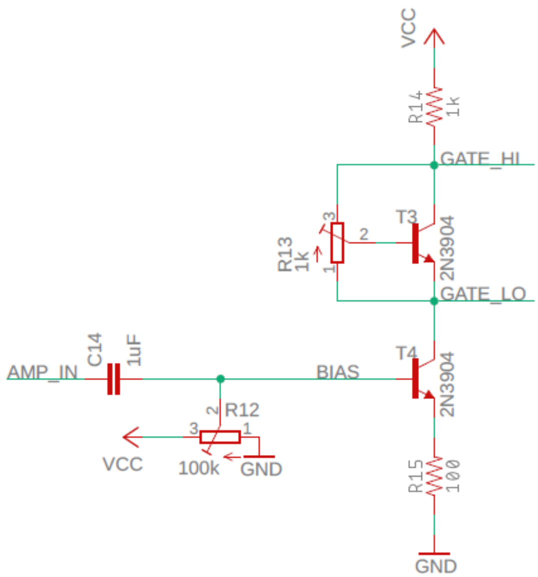


Figure 2: The common emitter stage of the audio amplifier.

The AMP_IN signal in Figure 2 comes from our audio source (that is, your phone or computer). Capacitor C14 removes the DC component from the audio signal and passes along an AC signal centered at 0V. The audio signal output of the capacitor is added (via superposition) to the bias voltage supplied by the potentiometer. You need to adjust the bias voltage so that the bases of the push/pull pair are set to the voltages you calculated in Questions 1 and 2 above. In other words, in the absence of an AC signal source, you need to:

- Set GATE_LO to 3.8V.
- Set GATE_HI to 5.2V.

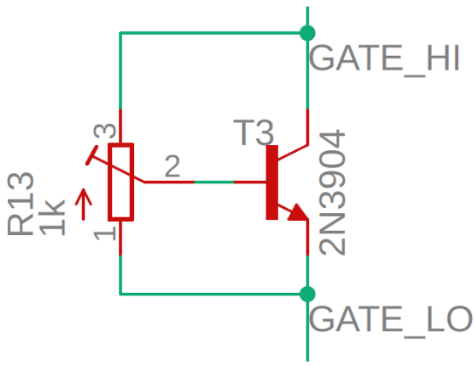
Now you will use this information to adjust the bias voltage of the common emitter stage.

Compute the common emitter bias voltage:

1) Find I_C (the current through R14) so that GATE_HI is 5.2V where VCC = 9V
2) Find V_E assuming that I_E is equal to I_C
3) Find V_B (your value should be close 1V).

The Vbe Multiplier

The preceding section should have made it clear that the base of the two output transistors T1 and T2 in **Figure 1** need to be 1.4V apart. The function is performed by the transistor T3 and the potentiometer R1called out in left-side of **Figure 3**. This circuit is called a Vbe multiplier for reasons that we will now explore.



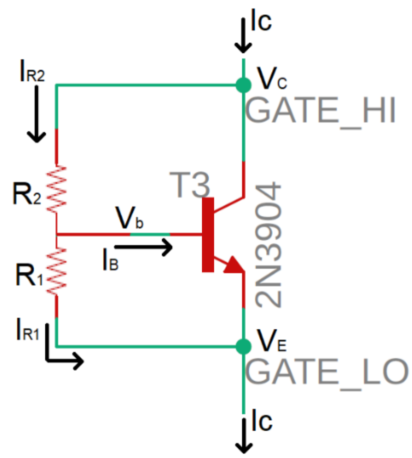


Figure 3: (left) The Vbe multiplier circuit used in our Audio amplifier. (right) The circuit used in the analysis.

Look at the left circuit Figure 3; adjusting the potentiometer R13 moves the center tap of the potentiometer along a 1kΩ track of resistive carbon film connecting terminals 1,3. If the center tap is moved closer to terminal 1 then the resistance between terminals 1,2 decreases and the resistance between terminals 2,3 increases. Thus, the sum of the resistance between terminals 1,2 plus the resistance between terminals 2,3 adds to 1kΩ.

You will use the circuit shown in the right side of Figure 3 to analyze the Vbe multiplier. Note that the potentiometer is replaced with a pair of resistors so that $R_1 + R_2 = 1k\Omega$.

1. From the previous section, what is the current I_C?

Assume that the BJT in Figure 3 is in the active region and that ß = 100,

2. What is I_B for this value of I_C?
3. Write an equation for the current I_{R1} in terms of V_{BE} and R1.
4. Assume that the center tap of the potentiometer is halfway so that $R_1 = R_2$ and $V_{BE} = 0.7V$. What is the current I_{R1} equal to?
5. In this case, how much larger is I_{R1} than I_B? Compute this as the ratio I_{R1}/I_B.
6. Write a KCL equation for the V_B node.
7. Since I_{R1} is a lot larger than I_B, rewrite this KCL assuming that $I_B = 0$.
8. Write an equation for V_{CB} in terms of I_{R2} and R2.
9. Replace the I_{R2} term in the previous step with the equation in step 3
10. Write an equation for V_{CE} in terms of V_{CB} and V_{BE}.
11. Replace the V_{CB} term in the previous step using the equation in part 9
12. Factor out the V_{BE} term in the previous step.

This final equation shows that V_{CE} is V_{BE} times some factor. In other words, V_{BE} is multiplied by a factor to get V_{CE}. Hence the name, Vbe multiplier.

Now let's dig into the amplifier using the framework shown in Figure 4. This figure is an abstract version of Figure 1 for small AC signals. It describes how the signal is mathematically manipulated. The Source is the audio input that you are providing.

The blue area labeled Common Emitter in Figure 4 is the circuit shown in Figure 2. Let's look at this stage in the overall circuit shown in Figure 1. The input to this stage, Vce is the voltage at the base of transistor T4 in Figure 1, the BIAS test point on the PCB. The output of the Common Emitter stage is the collector of transistor T4 in Figure 1, the GATE_LO test point.

The blue area labeled Emitter Follower in Figure 4 is the circuit shown in Figure 6. Let's look at this stage in the overall circuit shown in Figure 1. The input to this stage, Vef is the voltage at the base of transistor T2 in Figure 1, the GATE_LO test point. The output from this stage is the emitter of transistor T2 in Figure 1, the VOUT test point.

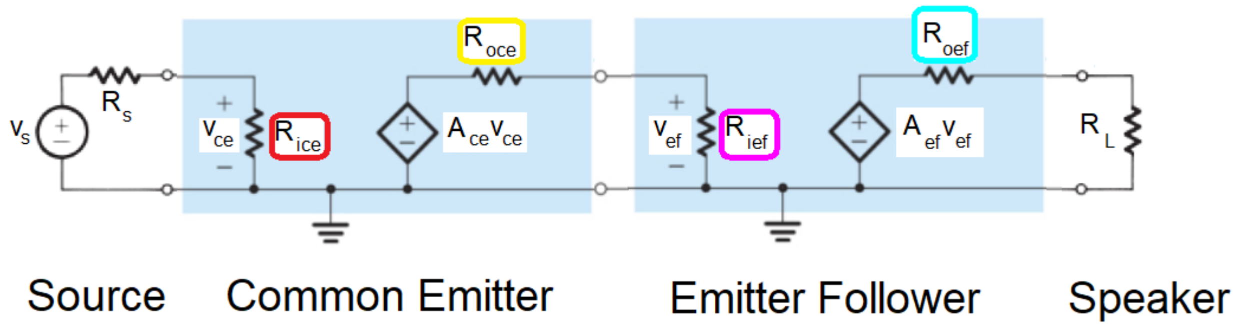


Figure 4: The small signal model of the Audio board. The input signal goes through a common emitter to amplify the voltage and then into an emitter follower to amplify the current before being sent out to the speakers.

Your task is to assign equations and values to the variables in Figure 4 and put them into Table 1. This information is critical in understanding how to improve the quality of the audio output.

Table 1: Model parameters for the cascade amplifier shown in Figure 4.

	R_{in}	R_{out}	**Voltage Gain**
Source	N/A	$R_s = 10\Omega$	N/A
Common Emitter	R_{ice} =	R_{oce} =	A_{ce} =
Emitter Follower	R_{ief} =	R_{oef} =	A_{ef} =
Speaker	$R_L = 8\Omega$		

Let's start by analyzing the common emitter amplifier from Figure 2, but in the more reduced form shown in Figure 5. Note the Vbe multiplier has been remove from Figure 2 and replaced by a wire. This is an acceptable substitution because we are interested in the behavior of the common emitter BJT, not the Vbe multiplier.

In this analysis you are frequently going to be asked to find the change in voltage of a node. A change in a voltage is not the same thing as the value of the voltage. For example, if I asked you to describe the relationship between the change in the emitter voltage (ΔV_E) in Figure 5 and the change in emitter current (ΔI_E), you could use Ohm's law to write:

$\Delta V_E = R\,\Delta I_E$

If you were then asked to solve this equation for ΔI_E, you would write:

$\Delta I_E = \Delta V_E/R$

The steps in the derivations are numbers. Occasionally you will need to use an equation derived in a previous step to move the derivation forwards. When doing this, look for equivalent variables in the two steps, you will probably either substitute one equation into another or set two equations equal.

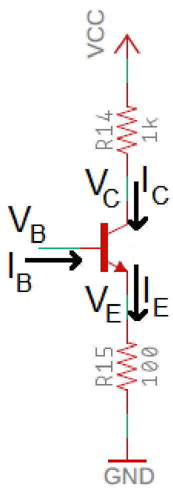


Figure 5: A simplified version of the common emitter shown in Figure 2.

Compute the input impedance of the common emitter stage - R_{ice}. You will need to reference Figure 2 during this analysis.

1) What is the relationship between ΔV_B and ΔV_E?
2) Use Ohm's law to describe the relationship between ΔV_E and ΔI_E.
3) Solve the previous equation for ΔI_E and replace ΔV_E with ΔV_B from Equation 1.
4) Write down the relationship between ΔI_E and ΔI_B? *(Hint, it is a bad parameter.)*
5) Equate the equations from step 3 and 4 using ΔI_E.
6) Solve equation from step 5 for $\Delta V_B / \Delta I_B$, this is the input impedance of the common emitter. Insert this value into the R_{ice} cell of Table 1.

Compute the output impedance of the common emitter stage - R_{oce}. You will need to reference Figure 5 during this analysis.

1) Use Ohm's law to describe the relationship between ΔV_C and ΔI_C.
2) Solve Equation 1 for $\Delta V_C/\Delta I_C$. This value is the output impedance of the common emitter. Insert this value into the R_{oce} cell of Table 1.

Compute the gain of the common emitter stage - A_{ce}. You will need to reference Figure 2 during this analysis.

1) What is the relationship between ΔV_B and ΔV_E?
2) Use Ohm's law to describe the relationship between ΔV_E and ΔI_E.
3) Solve the previous equation for ΔI_E.
4) Replace ΔV_E in the equation from step 3 with the relationship found in the equation from step 1.
5) Use Ohm's law to describe the relationship between ΔV_C and ΔI_C. Note the sign!
6) Since $\Delta I_E = \Delta I_C$, replace ΔI_C in the previous step with ΔI_E.
7) Substitute ΔI_E from the equation in step 4 into the equation from step 6.
8) Let $\Delta V_C/\Delta V_B$, be the gain. What is the gain of our amplifier? Insert this value into the A_{ce} cell of Table 1.

Emitter Follower Theory

We now return our attention to the cascade amplifier of Figure 4 and fill in the Table 1. We will focus on the push/pull output stage formed by a pair of emitter followers. I've made some changes to the push/pull circuit shown in Figure 1 to produce the circuit shown in Figure 6.

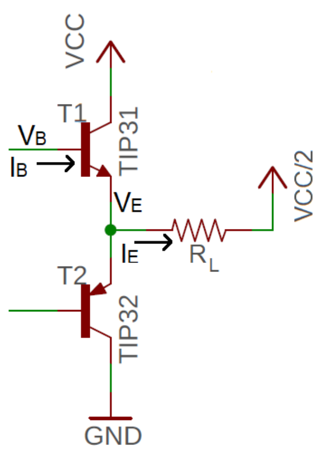


Figure 6: The output stage of the audio amplifier consists of a pair of emitter followers.

I made the changes going from Figure 1 to Figure 6. These changes are valid and made to simplify the analysis. For example, since this is a small signal analysis (we are looking at changes in values e.g. ΔV_B) we will ignore the 100uF capacitor C13 in Figure 6 because the capacitor appears as a short at audio-frequencies. The speaker is rated as an 8Ω load, represented by R_L – please use R_L in the subsequent analysis. Finally, focus on the labeled NPN transistor, T1, in Figure 6 when answering the following questions.

Compute the input impedance of the emitter follower - R_{ief}. You will need to reference Figure 6 during this analysis.

1) What is the relationship between ΔV_B and ΔV_E?
2) Use Ohm's law to describe the relationship between ΔV_E and ΔI_E. Call the resistance of the speaker R_L.

3) Solve the previous equation for ΔI_E and replace ΔV_E with ΔV_B (using the relationship in equation 1)
4) What is the relationship between ΔI_E and ΔI_B? Hint, it involves a bad parameter.
5) Equate the equations from steps 3 and 4 using ΔI_E.
6) Solve equation in step 5 for $\Delta V_B/\Delta I_B$, this is the input impedance of the emitter follower. Insert this value into the R_{ief} cell of Table 1.

Compute the output impedance of the emitter follower – R_{oef}. You will need to reference Figure 6 during this analysis.

1) Use Ohm's law to describe the relationship between ΔV_E and ΔI_E. Call the resistance of the speaker R_L.
2) Solve the equation from step 1 for $\Delta V_E/\Delta I_E$, this is the output impedance of the emitter follower. Insert this value into the R_{oef} cell of Table 1.

Compute the voltage gain of the emitter follower - A_{ef}. You will need to reference Figure 6 during this analysis.

1) What is the relationship between ΔV_B and ΔV_E?
2) Solve the equation from step 1 for $\Delta V_E/\Delta V_B$, this is the voltage gain of the emitter follower. Insert this value into the A_{ef} cell of Table 1.

Compute the overall gain of amplifier with no load:

Since our analysis will break down if we do not have a load resistance, we will model an open circuit output as a 1MΩ resistor as shown in Figure 7. In this analysis assume a value of β =100.

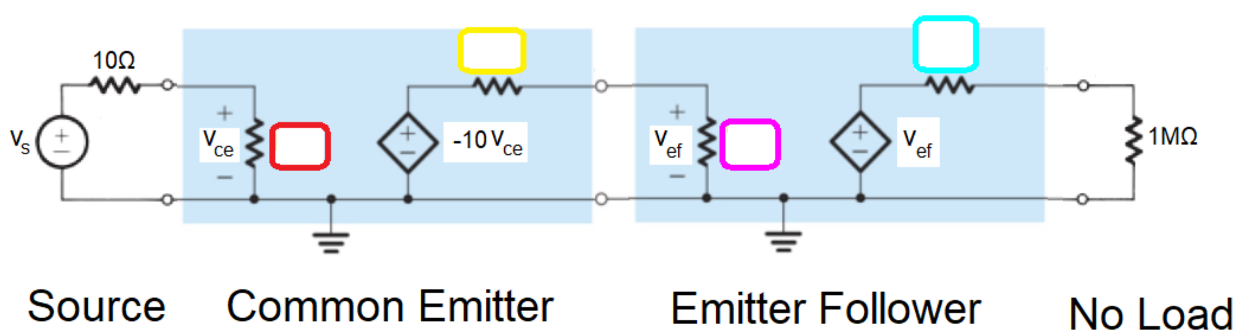


Figure 7: The Audio amplifier with a very high load resistance that models no load.

1. Fill in the values of the resistors shown in Figure 7.
2. Compute Vce in terms of Vs. Use this to determine the gain Vce/Vs. Assume 20,000 + 10 = 20,0000.
3. Compute Vef in terms of Vs. Use this to determine the gain Vef/Vs. Assume 200,000,000 +1,000 = 200,000,000
4. Calculate the current delivered to the 1MΩ load. Assume that 1/1,000,000 = 0.

Analysis of amplifier with 8Ω load

We will model the speaker as an 8Ω resistor as shown in Figure 7. In this analysis assume a value of β =100.

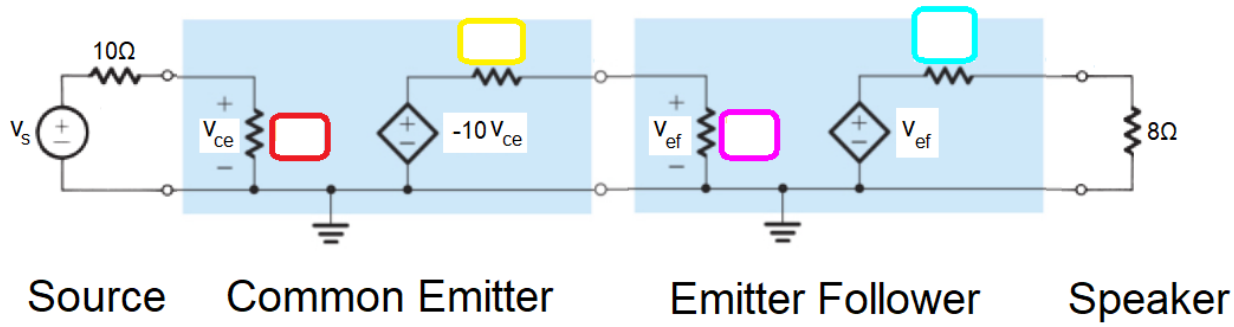


Figure 8: The Audio amplifier with an 8Ω load that represents a speaker.

1. Fill in the values of the resistors shown in Figure 8. Assume β =100.
2. Compute Vce in terms of Vs. Use this to determine the gain Vce/Vs. Assume 20,000 + 10 = 20,0000.
3. Compute Vef in terms of Vs. Use this to determine the gain Vef/Vs.
4. Calculate the current delivered to the 8Ω load in terms of Vs.

Soldering Together the Amplifier Subsystem

You will be soldering the amplifier subsystem for the Audio board this week. The schematic is shown in Figure 9.

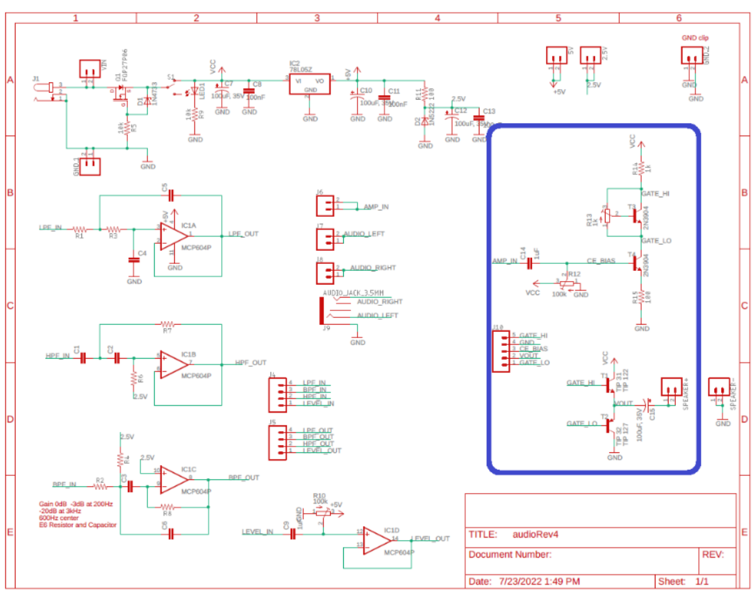


Figure 9: The schematic for the Audio board with the power subsystem circled in blue.

Like, your previous experiences, the parts in this schematic have a designator and a value. These designators are used to relate a part in the schematic with the layout. I converted the schematic in Figure 9 to the layout shown in Figure 10. As before, the physical position of the parts in the schematic and layout are unrelated, the schematic is an abstraction of the finished layout. The layout contains all the data used in the fabrication of the PCBs – the layout and the fabricated PCB are identical.

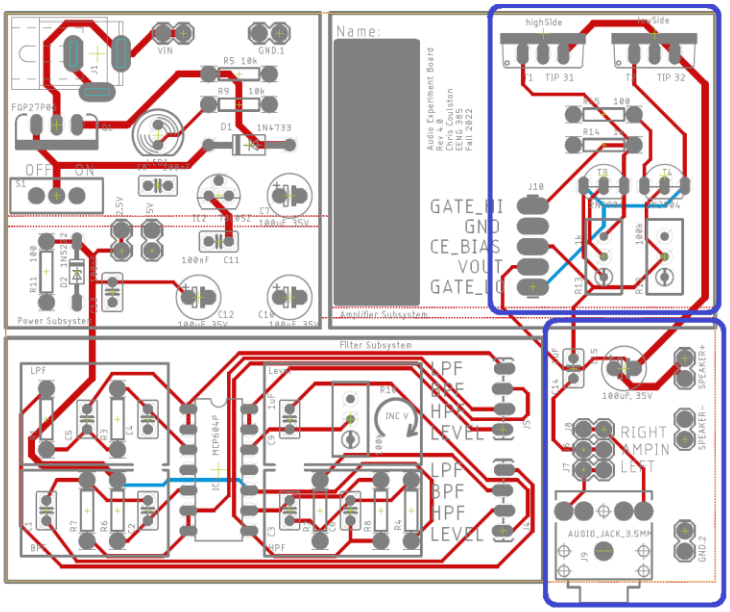


Figure 10: The layout of the Audio board with the power subsystem outlined in blue.

You should notice parts logically related in the schematic are physically proximal in the layout.

Polarized Parts

Most of the parts to be soldered into the PCB can be installed in more than one way. Parts which must be installed in a correct orientation are called polarized. Polarized parts have some physical indication of their orientation, and the silk screen will have some markings to show you where this physical indicator should be aligned. Let's walk through all the polarized parts that you will solder this week and how you will install them in the PCB.

- Red 100 µF capacitors
  The 100 µF capacitors have a white stripe which indicates the negative terminal. The negative terminal should align with the white bar (opposite the "+" bar) on the PCB silk screen.
- TIP31 and TIP32 transistors
  The TIP31 and TIP32 transistors are in TO-220 packages with metal tabs on the back. These metal tabs should face the edge of the board.
- 2N3904 transistor
  The 2N3904 transistor is in a small TO-92 package - the package is marked "2N3904". Make sure that its flat side matches the silk screen.
- Potentiometers
  While potentiometers are not strictly polarized, you can install them either way and they will work properly, if you install them backwards, the silkscreen will not align to their function indicated on the silk screen. So, make sure to align the metal screw on the pot over the circle on the silk screen.

General Guidance

- Reference the class soldering guide.
- You should take care with your soldering and align the resistors so their gold tolerance bands all face the bottom or right side of the board. This alignment will make it easier to compare your resistor locations with the pictures of the assembled board posted on the Canvas page.
- Solder in wire loops to the following pairs of terminals. Note I used trimmed resistor leads for this and they work great.
    - GND.2
- Solder in 2-pin headers into the following pairs of terminals
    - SPEAKER+
    - SPEAKER-
- Solder in a 2x3 header into the RIGHT, AMP_IN, LEFT headers
- Do NOT solder anything into the GATE_HI, GND, BIAS, VOUT GATE_LO headers
- Do not solder in components for the filter subsystems.

Testing the Amplifier Subsystem

Until the pair of potentiometers are adjusted, your amplifier subsystem will not work properly. It would be best to have someone else check your component placement and orientations and check theirs. Then come to lab next week ready to learn how to adjust the potentiometers and get some sound from your amplifier.

Turn In

Make a record of your response to numbered items below and turn them in a single copy as your team's solution on Canvas using the instructions posted there. Include the names of both team members at the top of your solutions. Use complete English sentences to introduce what each of the following listed items (below) is and how it was derived.

Audio Amplifier
Steps 1 – 3
Common Emitter Theory
Steps 1 – 3
The Vbe Multiplier
Steps 1 – 12
Compute the input impedance of the common emitter stage - R_{ice}.
Steps 1 – 6
Compute the output impedance of the common emitter stage - R_{oce}.
Steps 1 – 2
Compute the gain of the common emitter stage - A_{ce}.
Steps 1 – 8

Compute the input impedance of the emitter follower - R_{ief}.

Steps 1 – 6

Compute the output impedance of the emitter follower – R_{oef}.

Steps 1 – 2

Compute the voltage gain of the emitter follower - A_{ef}.

Steps 1 – 2

Compute the overall gain of amplifier with no load

Steps 1 – 4

Compute the overall gain of amplifier with 8Ω load

Steps 1 – 4

Complete Table 1