

## 1a

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# Audio Amplifier Circuit

## Overview

In the first part of lab#1 you will construct a low-power audio amplifier/speaker driver based on the LM386 IC from National Semiconductor. The audio amplifier will be a self-contained, battery-operated component. In the second part of the lab you will construct a microphone circuit using a compact electret condenser microphone cartridge. These circuit modules are important building blocks of many audio communications systems, and will be used in our ultrasonic transceiver system.

By studying this document and experimenting with the components and circuits in the lab, pay attention to the following:

- Electrical characteristics of audio speakers
- Characteristics of condenser microphones
- Design of single-supply battery-operated op-amp circuits
- Use of diode limiters/clamps for input protection
- Use of active filters for tone control
- Choice of AC coupling capacitors

We will discuss the analytical aspects of active filter design in lecture we will see them in action again in our IR receiver system.

Remember, the objective here is not simply to create a working circuit, it is to learn about circuits! So, as you progress through the lab, try to understand the role of each component, and how the choice of component value may influence the operation of the circuit. Please tinker with component values, that is an especially valuable way to learn. Ask yourself questions such as: Why is this resistor here? Why does it have this resistance value? Why is this blocking capacitor  $1\mu\text{F}$  instead of  $0.1\mu\text{F}$  or  $10\mu\text{F}$  or  $100\mu\text{F}$ ? Why was this particular op-amp chosen? It is only when you can answer such questions that you will truly understand the labs and progress towards designing your own circuits. In the process you may even find a better solution; in fact, many of the laboratory experiments in this course now include several slight modifications from the original that were inspired by student feedback.

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## Pre-lab Preparation

### ***Before Coming to the Lab***

- Read through the lab experiment to familiarize yourself with the components and assembly sequence. Before coming to the lab, each group should obtain a parts kit from the ECE Shop.
- With reference to the full schematic in Figure 1-1 calculate the lower cutoff frequency imposed by capacitors C1-3 and R1-3 in the summing network:

$$f_{low} = \underline{\hspace{2cm}} \text{ Hz}$$

### ***Schedule for Lab #1***

To stay on schedule, you must do the following:

- Week #1: Audio amplifier
- Week #2: Microphone circuit

The audio amplifier project is more difficult and time-consuming than the microphone pre-amp, so part of week #2 may be used to finish the audio amp. All breadboarding and testing can and should be done in lab. Soldering and hardwiring can and should be done outside lab.

**Parts List**

	Qty	Description	Circuit
<b>Audio Amplifier</b>	1	Audio Speaker, 8-Ohm, 2 Watt, 0.3-9KHz	
	1	LM386N-3 Low-Voltage Audio Power Amplifier	U2
	1	LM358 Low-Power Dual Op-Amp	U1
	2	8-pin low-profile IC socket	
	1	10 Ohm 1/2W resistor	R10
	2	2.2k 1/4W resistor	R13,R14
	8	10k 1/4W resistor	R1-5,R9,R12,R15
	2	100k 1/4W resistor	R6-7
	1	10k trimpot	R8
	1	20k trimpot	R11
	1	470 uF 16V electrolytic capacitor (PC lead)	C9
	1	100uF 16V electrolytic capacitor (PC lead)	C10
	2	10uF 16V electrolytic capacitor (PC lead)	C4,C6
	4	1uF capacitor	C1,C2,C3,C5
	1	0.033uF capacitor (CK05 low-voltage ceramic )	C7
	2	0.022uF capacitor (CK05 low-voltage ceramic )	C11,C12
	1	0.1uF capacitor (CK05 low-voltage ceramic )	C8
	2	1N4148 small-signal Silicon diode	
	1	4.5" x 5.67" vectorboard	
	4	Rubber feet	
	1	Stereo Audio jack	
	1	3.5mm male-to-male stereo patch cord	
	1	9V battery leads	
	1	9V battery holder (adhesive backed)	
	1	9V battery	
	1	Doubled-sided adhesive tape for mounting speaker	
	2	flea clips	
	6"	#22 stranded wire (black)	
	6"	#22 stranded wire (red)	

### Full Schematics for Lab #1

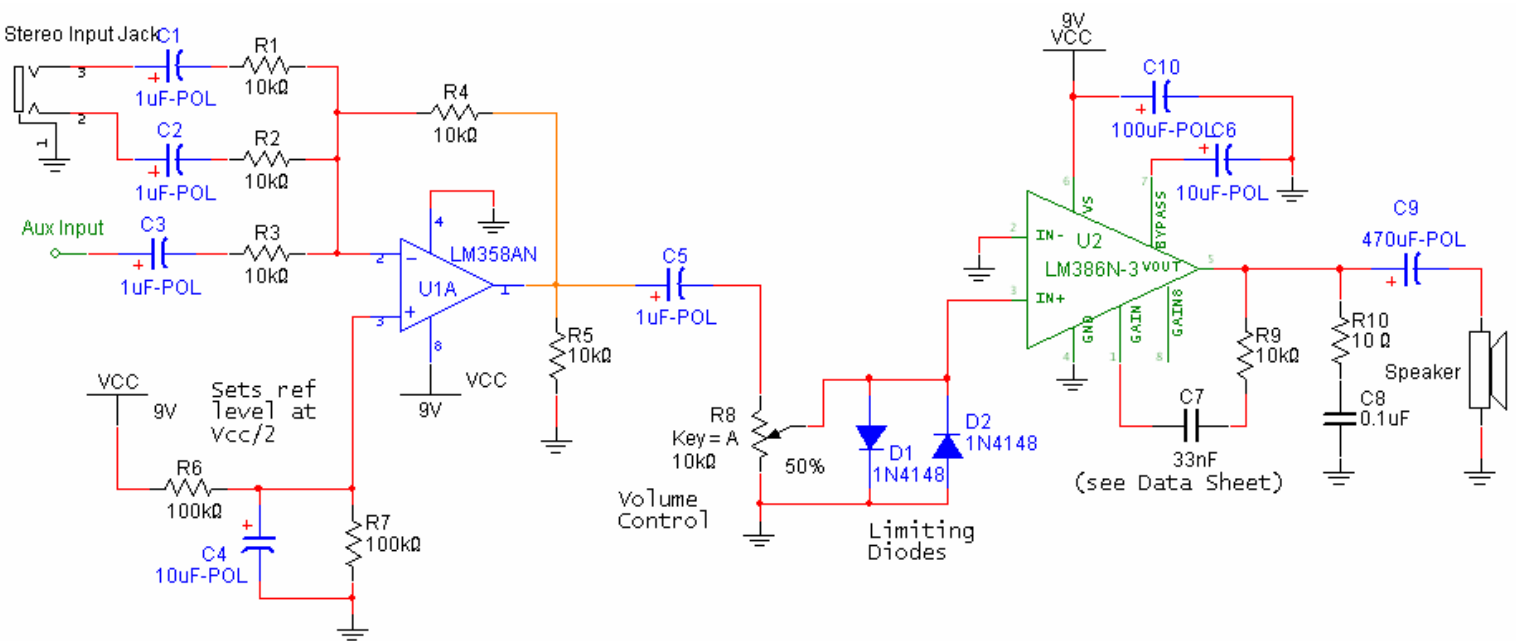


Figure 1-1 – Schematic for the basic audio amplifier.

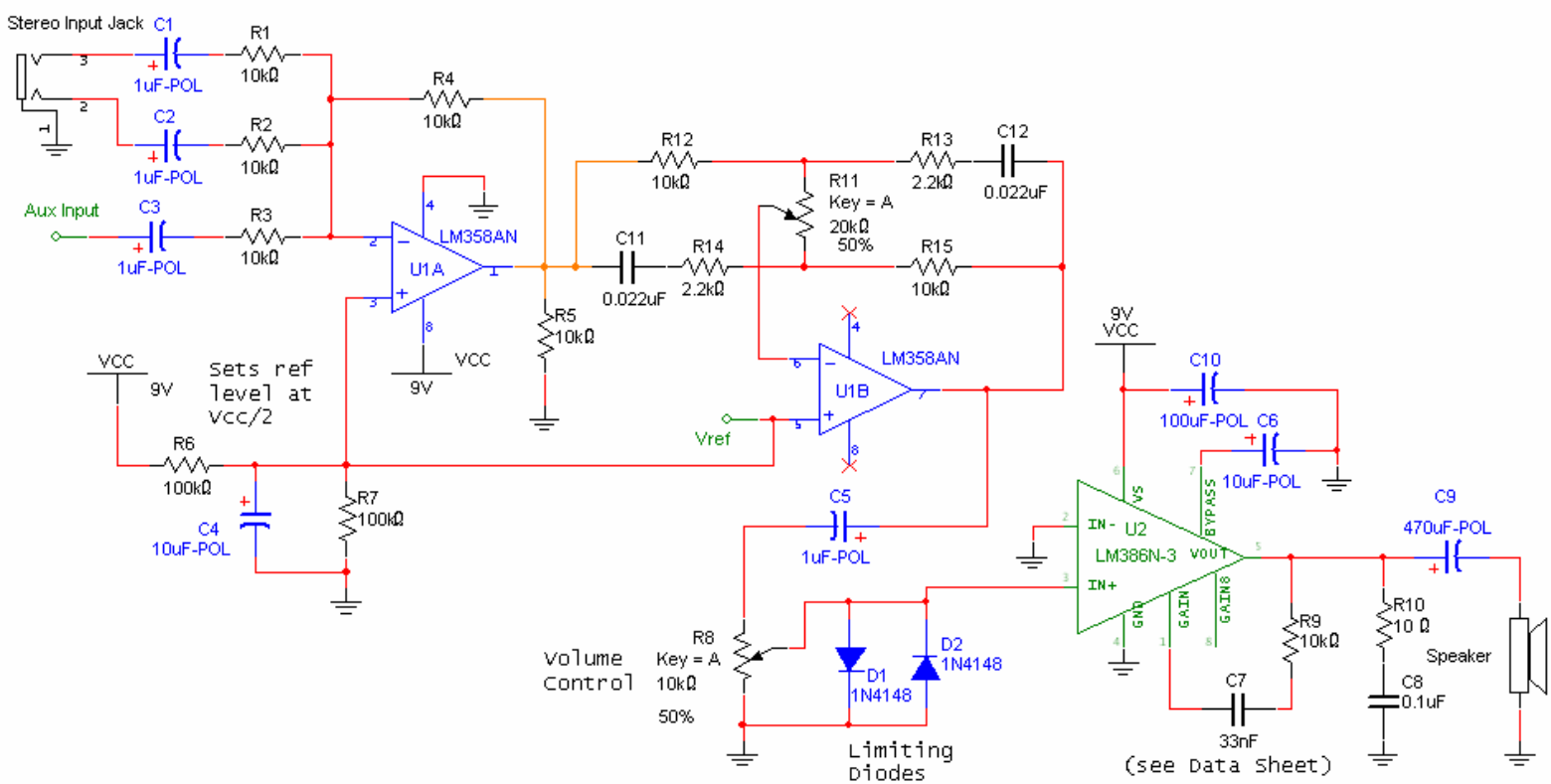


Figure 1-2 – Schematic for the audio amplifier with optional tone-control circuit.

## Background information

### Audio Speakers

Audio speakers convert electrical signals into mechanical motion. The most common speakers for high-quality audio are constructed as shown in Figure 1-3\*. The electric signal is passed through a coil of wire (the “voice” coil), which is suspended in a strong magnetic field provided by a permanent magnet. A time-varying current in the coil leads to a mechanical deflection relative to the magnet. The coil is attached to a lightweight conical membrane (usually made from a heavy-grade paper) that couples the mechanical motion of the coil to the surrounding air molecules.

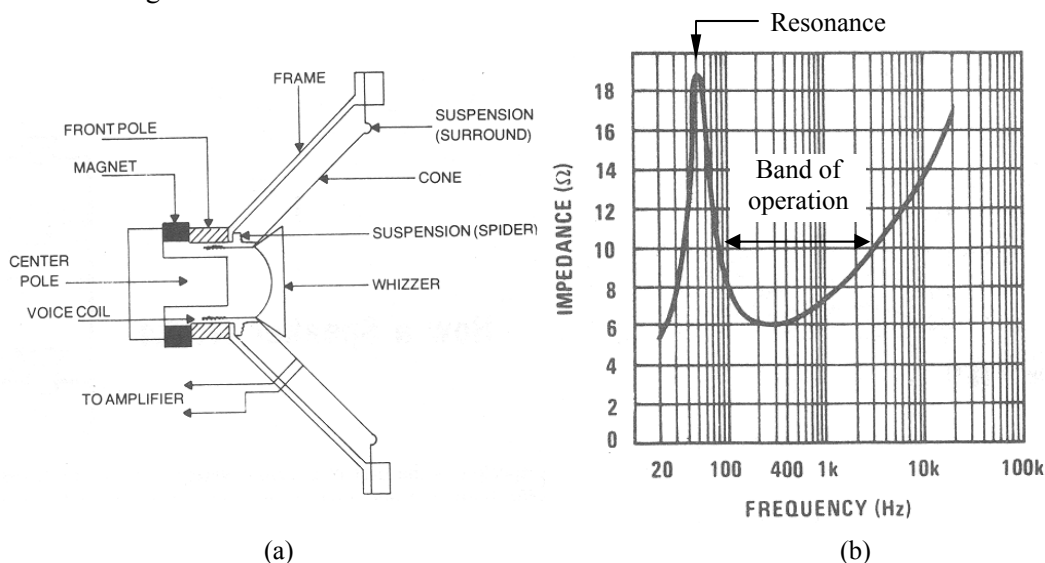


Figure 1-3 – (a) Cross section and (b) Impedance curve for a typical 8Ω dynamic speaker.

If you look through catalogs of audio-speakers, you will find many different sizes and price ranges. For example, check out <http://www.tb-speaker.com/tbp.htm>. High-quality audio speakers can be quite expensive, and are designed for a flat, omni-directional frequency response in the specified operating range. Small inexpensive speakers, such as the ones used in this lab, have poor low-frequency response and limited power-handling capacity.

Speakers are commonly specified by their frequency response, impedance level, and power-handling capacity. Typical speaker impedances are “8Ω” or “4Ω” or “16Ω”. This is often a source of confusion because it suggests the speaker is modeled by a constant resistance of this value. In reality there is a significant reactive component of impedance and hence a strong variation of impedance with frequency, as shown in the figure above. The impedance can also depend strongly on the surroundings. For example, a speaker measured in isolation (the “free-air” response) will have a different impedance than one mounted in a wooden enclosure.

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\* D. B. Weems, *Designing, Building & Testing your Own Speaker System*, Tab Books: Blue Ridge Summit, PA, 1984

The AC impedance often displays at least one resonance, relating to the size and stiffness (“compliance”) of the cone. Electrically this mechanical resonance can be modeled by a parallel RLC circuit. The operating frequency range for the speaker begins at or above this resonance, and in this range the speaker impedance is well modeled by just a resistance in series with an inductance. The inductance comes from the voice coil itself. The resistance term is largely the DC resistance of the voice coil, with a small additional contribution which represents energy conversion to mechanical motion. The combination of the two resistances is usually close to the specified impedance of the speaker (*e.g.*  $8\Omega$ ) in the middle of the operating range.

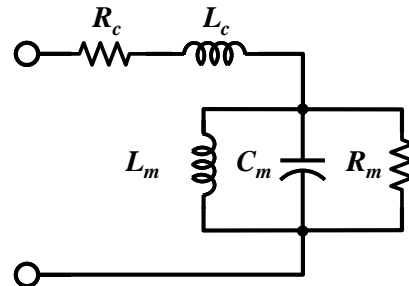


Figure 1-4 – Equivalent circuit for an audio speaker

A pretty good equivalent circuit model for any speaker is shown in Figure 1-4 and can be created by measuring or finding the following parameters:

- DC Resistance of the voice coil,  $R_c$
- Free-air resonant frequency,  $f_s$
- Input resistance  $R_t$  at  $f=f_s$  (the impedance is purely resistive at resonance)
- Bandwidth  $\Delta f$  of the resonance (between the points where  $|Z_t| = R_t / \sqrt{2}$ ). The Q-factor is then  $Q_{ms} = f_s / \Delta f$
- Inductance  $L_c$  of the voice coil (measure at a high frequency,  $f \gg f_s$ )

The free-air mechanical resonance is modeled by a parallel RLC circuit. Since the Q-factor of a parallel resonator is  $Q_{ms} = \omega RC$ , and the resonant frequency is  $f_s = 1 / 2\pi\sqrt{LC}$ , the equivalent circuit parameters can be found as

$$R_m = R_t - R_c \quad C_m = \frac{Q_{ms}}{2\pi f_s R_m} \quad L_m = \frac{1}{(2\pi f_s)^2 C_m}$$

One last point about speakers: for a single-speaker application the polarity of the speaker is irrelevant. However, if multiple speakers are used, it is important to connect them together with the correct polarity so that the voice coils and cones will move in phase with each other. For this reason, speaker terminals are often designated with a “+” or “-” symbol.

## In-Lab Procedure

### 1.1 Some comments on our choice of ICs

#### **Why the LM386?**

At first glance this project looks simple; all we need is an amplifier to drive an audio speaker, right? Why not just use a simple op-amp gain stage? Well, one immediate challenge is that speakers have a low impedance, typically 8-Ohm. Even for a low-power 0.5W audio amplifier,  $P = I^2 R / 2$  requires that the amplifier must be able to source a peak AC current of around 350 mA with an 8-Ohm load. This is a lot more than a typical op-amp is designed to provide. For example, the LM358 and LF353 (two op-amps used in this lab) can source around 20-40mA at most. So we need a device that can handle higher currents. We also want a device that can be operated from a single supply voltage (a battery in this case). It is possible to make a suitable amplifier using an op-amp and a couple of external power transistors, but we went with a simpler solution, and chose a chip that was specifically designed as an audio driver, the LM386, shown in Figure 1-5.

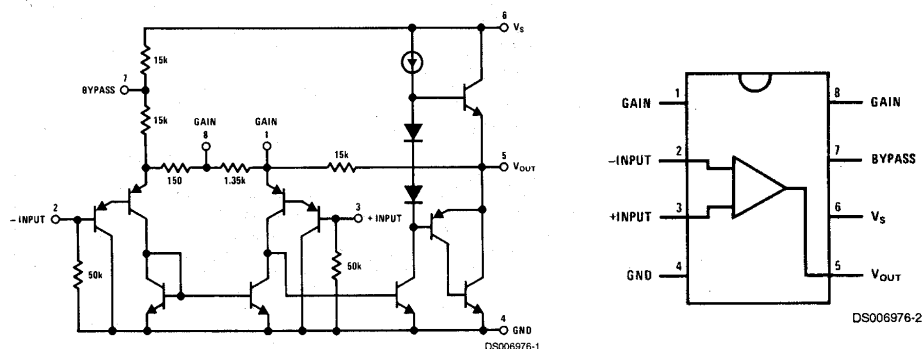


Figure 1-5 – LM386 internal circuit and 8-pin DIP pin assignments.

This is an old chip that has been a popular choice for low-power audio applications for many years. There are many other audio amp ICs on the market (LM380 and LM383 are similar but higher-power amps from National), but the LM386 is sufficient for our purposes. It comes in three-flavors, the LM386-1, LM386-2, and LM386-3, which can provide 0.3W, 0.5W, and 0.7W respectively, more than adequate for this lab. Another nice thing about the LM386 is that the gain-frequency curve can be shaped with some external feedback components, so it is a very flexible device. If you do a web search on “LM386”, you will find many examples of clever circuits that people have come up with over the years. The one in this lab is a minor modification of a circuit described in the data sheet.

#### **Why the LM358?**

For the remainder of the circuit (a simple unit-gain summing network) we have chosen an LM358 op-amp, which is a low-power device that can be operated from a single voltage supply, therefore appropriate for battery-operated circuits. Low-power op-amps draw very little quiescent current and hence help prolong the life of the battery. The LM358 is a garden-variety op-amp and there are many other possibilities that could be used, but this one is very cheap! We also chose a dual device in case you choose to do the optional tone-control



circuit. It doesn't matter which of the two internal op-amps you use for the summing network or the tone-control circuit, they are identical.

## 1.2 Speaker Equivalent Circuit

We'll start by measuring the characteristics of the audio speaker in your kit. This is a small, general-purpose speaker used for intercoms and other inexpensive audio systems.

*For these measurements, it is important to keep the speaker **face-up**.*

- Using the  $R$ - $L$ - $C$  meter in the lab, measure the coil resistance and coil inductance (the meter uses a frequency that is well above the speaker's mechanical resonance).
- Now we'll use the function-generator at your workstation to drive the speaker. Since the speaker has a small impedance, we must be careful to keep the amplitude of the function generator low so that it doesn't have to source a lot of current. Adjust your function generator to produce a sinusoidal wave with an AC amplitude of  $V_g = 200$  mV and zero DC offset.
- Electrically connect your speaker to the function generator as shown in Figure 1-6, using a small resistor  $R$  in series with the speaker (something around  $50\ \Omega$ , or two  $100\ \Omega$  resistors in parallel, seems to work well). This creates a voltage divider, so that the voltage across the speaker is proportional to the magnitude of its impedance. Thus by measuring  $V_g$  and  $V_L$  we can map out the variation of impedance with frequency using the formula in Figure 1-6.
- Find the resonant frequency (somewhere in the range of 100-200 Hz), and record the impedance at resonance and the bandwidth. Then compute the equivalent circuit parameters as discussed in the background information.

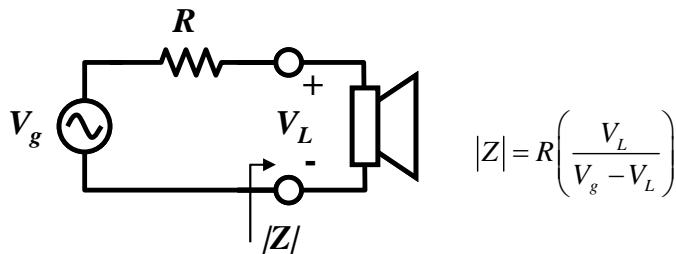


Figure 1-6 – Speaker test circuit

## 1.3 Assemble Amplifier on Breadboard

The schematic for an LM386-based amplifier is shown in Figure 1-7. We will first construct this amplifier using your plastic solderless breadboard and bench power supply. Once you debug the circuit and demonstrate that it works properly, you will “hard-wire” it onto a vectorboard and power it from a 9V battery. The idea of breadboarding the circuit first is not to create more work! It is good practice in general, since it allows you to debug your design more easily, allows you to experiment with component values, and most importantly will help preserve your battery in the event of a wiring error! The battery is in fact one of the most expensive components in this lab.

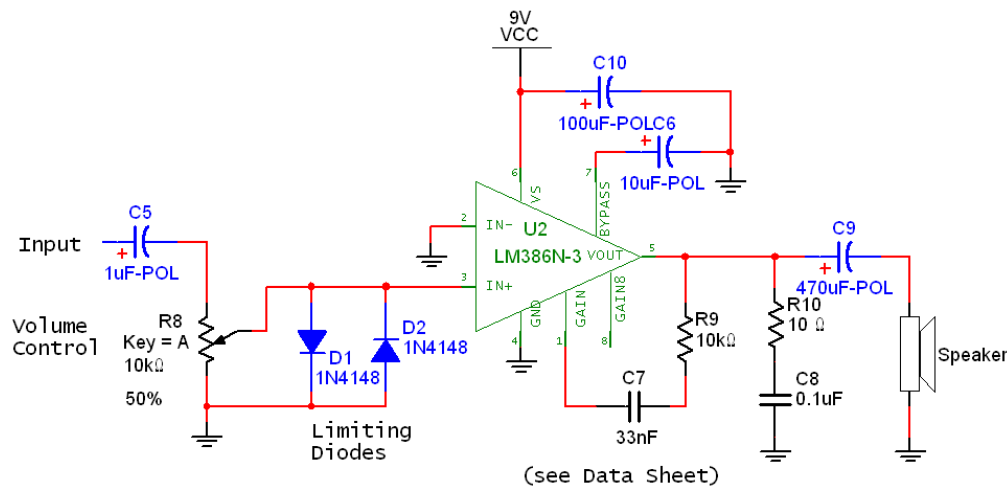


Figure 1-7 – Schematic of LM386 Amplifier.

- First study the schematic carefully, and locate all the necessary parts in your kit. Find the LM386 chip and compare it with Figure 1-5 and the schematic in Figure 1-7 to correlate pin numbers with the circuit connections.
- Configure your breadboard with connections to the power supply and appropriate wiring to the power busses, then add the LM386 IC and make the power (pin 6) and ground (pin 4) connections as shown in the schematic. Add the 100μF and 10μF bias/bypass capacitors.
- With reference to the schematic, add in the resistor and capacitor elements as shown. Note the role of each component:
  1. 1μF capacitor: DC blocking, AC couples the input signal
  2. 10k trimpot: voltage-divider for volume control
  3. 10μF capacitor: Internal AC bypass (see data sheet).
  4. 10kΩ resistor and 33nF capacitor between pins 1-5: bass-boost feedback circuit (see data sheet), helps compensate for the poor low-frequency response of our speaker
  5. 470μF capacitor: DC blocking (why is this so large compared with other blocking/bypass capacitors?)
  6. 10Ω resistor and 0.1μF capacitor: a “snubber” circuit for high-frequency stabilization, prevents potential oscillation due to inductive loading.
- Add in the back-to-back diodes at the input terminal of the device. These diodes clamp the input voltage on pin 3 at +/- 0.7 V, to insure that excessive voltage is never applied to this pin, which could damage the circuit.
- Add the speaker. You will need to first solder wire jumper leads to the speaker terminals.

You are now ready to test the circuit as shown in Figure 1-8.

- First connect your bench function generator to the oscilloscope and adjust for a 1kHz sine wave with a 0.2 V amplitude, and verify on the oscilloscope. Then apply this signal to your amplifier along with the +9V bias. If all goes well, you should hear a tone. Adjust the volume control as necessary.

- With the volume adjusted to a reasonable level, sweep the frequency to determine the lowest and highest audible tones and record your data.
- Observe the output waveform at pin 5 on the oscilloscope for a 0.5V amplitude input at 1 kHz. Note that the output is level shifted to approximately half the power supply voltage. Can you see distortion as the volume is increased? Why is this happening?
- Remove the LM386 temporarily and apply a  $\pm 1\text{V}$  sinusoid at 1 kHz to the amplifier input and observe the waveform at pin 3 under full-volume conditions. You should observe the clamping or limiting action of the input diodes. Record this waveform.
- Reconnect the IC and speaker and insert the bench multimeter in series with the power supply as shown above to measure the DC current flow into the amplifier. Record the current under the operating conditions.

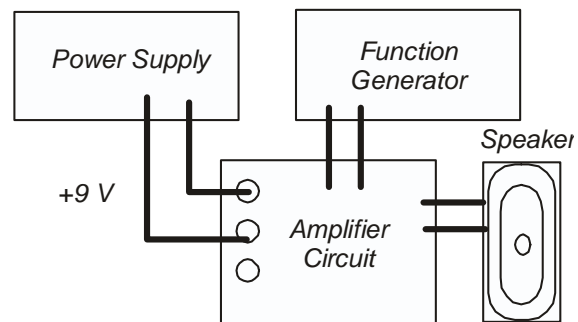


Figure 1-8 – Testing the amplifier circuit

## 1.4 Summing network

The next step is to add the summing network, which is used to combine several audio inputs into a common output signal. For example, if we want to hook our “mono” amplifier to a “stereo” signal, such as produced by an MP3 player or CD player, then we need to add the left and right stereo channels together so that the amplifier can amplify both simultaneously and deliver them to the speaker.

- Add the summing circuit as shown in Figure 1-9. Just put in the AUX channel for now (C3-R3), don’t worry about the stereo jack and associated RC elements, those can be added in the hardwired version

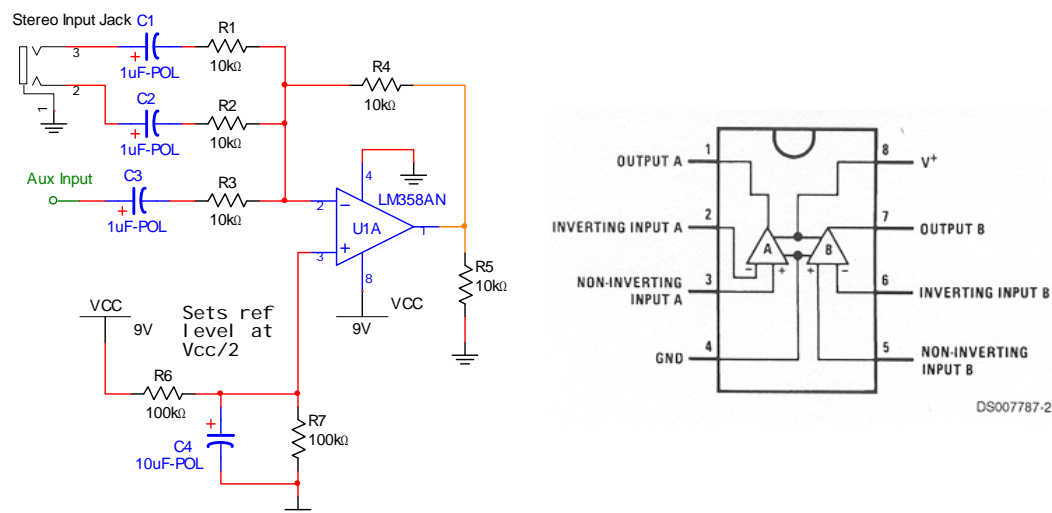


Figure 1-9 – Single-ended unity-gain summing network and LM358 pinout

There are two important points to understand here, both of which are related to the use of a single (battery) supply. First, in the textbook dual-supply op-amp summing circuit, the positive (non-inverting) input is usually grounded. The voltage at this pin defines the “reference” voltage for the input signals, which is the desired average or DC output level in an audio system. We usually choose this level to maximize the possible AC voltage swing, hence it should be midway between the two supply voltages. For a dual (bipolar) supply, this would be ground (0 V), but for our 9V battery supply, it is half the supply voltage, or 4.5 Volts. This is accomplished using the two 100k resistors in a voltage divider (we choose 100k resistors here to minimize the current draw from the battery). The 10 $\mu$ F bypass capacitor helps prevent this voltage level from fluctuating during operation, maintaining a constant potential and hence a good AC ground.

Secondly, since the input and outputs of this summing network will be capacitively coupled, the data sheet recommends adding an external resistive DC current path to ground at the output of the op-amp, to increase the bias current through the transistors in the op-amp’s output stage during operation. This is what R5 is for. You’ll have to wait until ECE 137AB to fully appreciate the details. Again, we’re choosing a large value resistor here to minimize the DC current draw from the battery.

- Once everything is put together, test your circuit as in the previous section, applying the signal from the function generator to the input ports.
- The capacitive coupling at the input introduces a low-frequency pole, giving the summing network a high-pass response. Sweep the frequency to determine the cutoff and compare this with your prelab calculation.

## 1.5 Optional -- Tone-Control Circuit

The LM358 is a dual op-amp so we have an extra op-amp to play with. Why not use it? This is not a required element of your project, but is a common feature in simple audio systems to improve/adjust the sound quality.

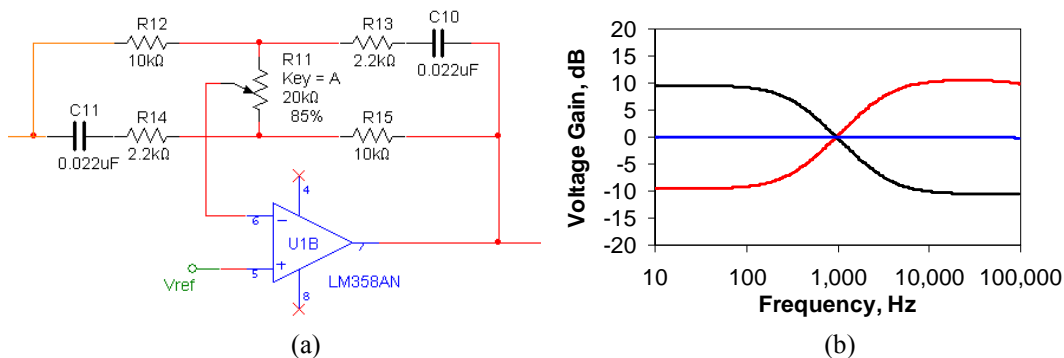


Figure 1-10 –(a) Single-knob tone control circuit. This makes use of the second op-amp in the LM358. You can use the same Vref as for the summing circuit. (b) Bode plots for the tone-control circuit at opposite extremes of the potentiometer setting.

There are many possibilities for tone-control circuits. The basic idea is to selectively boost or “cut” (attenuate) signals depending on their frequency. This is usually done using an op-amp gain stage with frequency-selective feedback. The circuit in Figure 1-10a is a simple example that basically starts with a unity-gain inverting amplifier configuration, and adds

series RC networks in parallel with feedback resistors. A potentiometer controls the tapping point for the feedback. When the wiper is at its midpoint, both sides of the feedback network are identical, and the system has unity gain for all frequencies (assuming identical component values). When the wiper is at the top, there is a low-frequency gain of around 3 (10 dB), and high-frequency attenuation of about 1/3 (-10dB). When the wiper is at the bottom, the action reverses so that the low-frequencies are cut and the high-frequencies are boosted. Figure 1-10b shows the Bode plots for the midpoint and two extremes of the potentiometer setting.

## 1.6 Hardwire the Amplifier

Now we are ready to put everything together, and add the stereo jacks and battery supply. Before we go further, let's consider the standard 3.5mm audio connectors. They look like the picture in Figure 1-11, and are probably familiar to everyone.



Figure 1-11 – Standard 3.5mm stereo audio plug

The stereo “plug” (sometimes called “male” instead of “plug”) has three separate cylindrical connectors, each separated by a thin plastic insulator. The largest of these is the ground connection. The other two carry the left and right channels of the stereo signal. The 3.5mm designation refers to the diameter of the cylindrical conductors. There are other diameters on the market, but 3.5mm is the standard for audio.

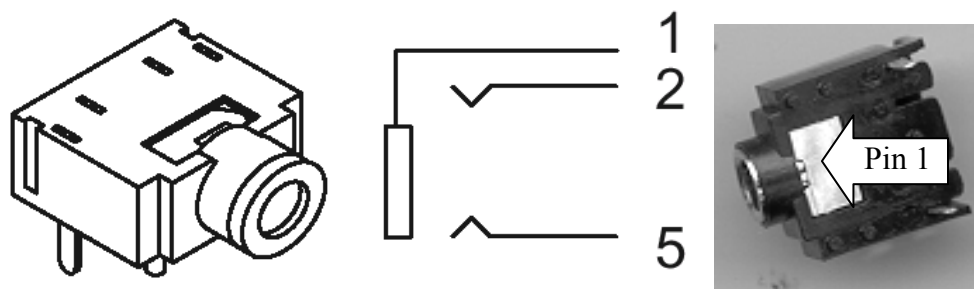


Figure 1-12 – 3.5mm stereo audio jack used in this lab.

In your kit you should have been provided a stereo “jack” (or “female”) similar to that shown in Figure 1-12. There are a large variety of different jack configurations, depending mostly on how they will be mounted (*i.e.* surface mount, PC board, panel mounted, etc.). Some jacks also have more than three pins which are connected in a way that gives an open

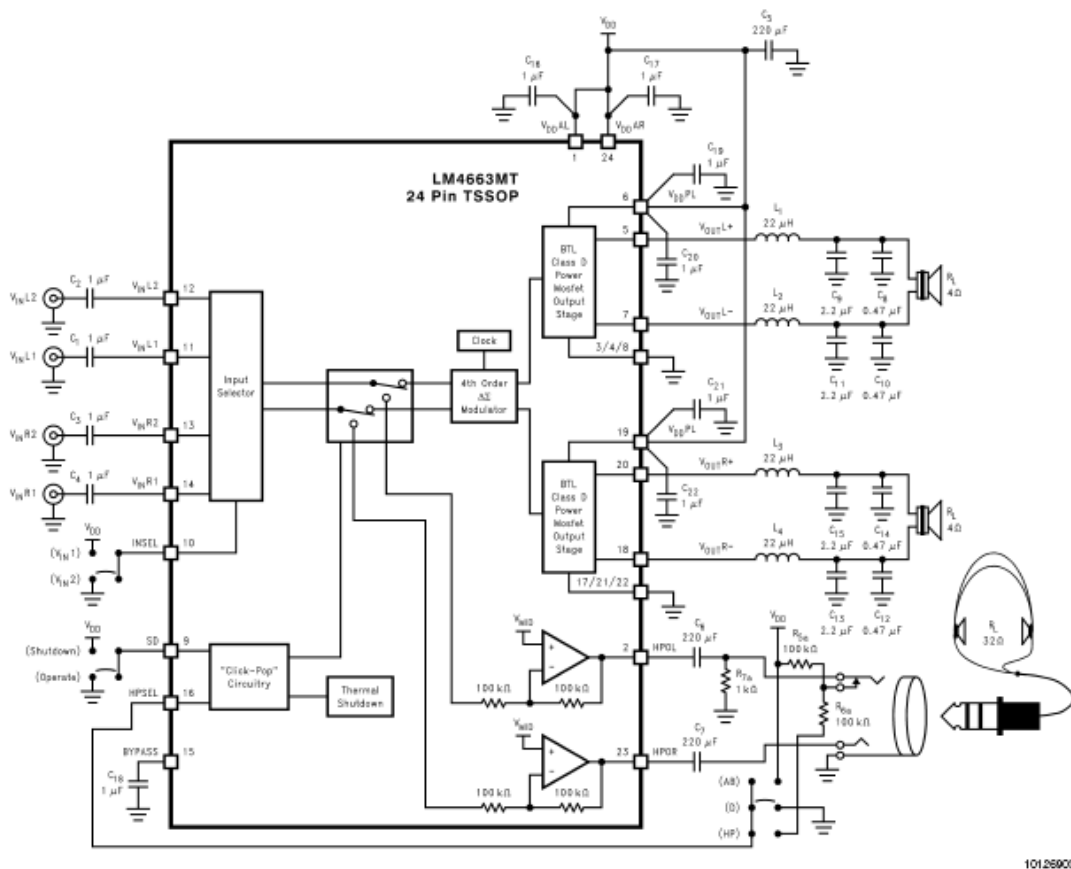
or short connection when a plug has been inserted or removed from the jack. The one we will use is just a simple 3-terminal PCB stereo jack. On the backside you will see each pin marked by a number, corresponding to the diagram above.

- Transfer the amplifier design to the vectorboard and “hardwire” everything into place. Use the IC socket provided in the parts kit so that if anything goes wrong with the LM386 or LM358, you can replace it without having to resolder the circuit.
- Add the 9V battery leads supplied in your kits. If you were given a battery holder, install that as well.
- Attach the stereo jack to the edge of the vector board. Connect pins 2 and 5 to the summing network, and connect pin 1 to ground.
- Attach the remaining “aux” input on the summing network to a flea clip.
- Lastly, attach the speaker to the vectorboard. If the speakers have a mounting bracket, you will be given some screws/nuts to attach the speaker to pre-drilled mounting holes, otherwise you will be given some double-sided tape to secure the speaker.
- Test your circuit using the bench power supply. When it is working, add the battery and test again under battery operation. Answer all the remaining questions in the lab record.
- Using the patch-cord in your kits, you can now test your amplifier by hooking it up to the headphone jack on a portable CD player, MP3 player, or computer.

***Congratulations: you now have a portable audio amplifier!***

## 1.7 Possible Improvements

The circuit you’ve just built is a nice building block for many projects where it is desirable to have a simple, inexpensive and versatile audio output. The obvious deficiencies with this system are: 1) it is monophonic (not stereo); 2) it has relatively low output power; 3) it is not very efficient in terms of battery life; and 4) the small speaker size limits the low-frequency response. These are all areas that can be easily improved upon if you are interested. For a true stereo output we would need separate amplifiers for the left and right channels, not to mention separate left/right speakers. Nowadays you can often pick up a cheap set of speakers designed for use with computer systems that often have surprisingly good performance, much better than the little paper-cone speaker we chose for this lab. In terms of power and efficiency, there are now several single-chip Class-D audio power-amps on the market that can generate much high powers with very little power consumption. As one of many such examples, the National Instruments LM4663 chip is a self-contained 2W stereo amplifier chip that can directly drive two external speakers and a set of headphones, powered off a single 5V supply, with >83% efficiency, and it costs around \$1.50! Clearly if you really needed to build an audio power amp for a critical engineering application, a single-chip solution like the LM4663 is probably going to be much more attractive in terms of size and cost than piecing together a system from several discrete parts, as we did in this lab. On the other hand, you most certainly learned more about the circuit building it from scratch than you would have by simply hooking up the LM4663 circuit below!



Another possibility for future work is to create a more sophisticated tone control, like a multi-band graphic equalizer. Most work on similar principles as the single-knob tone control circuit we used here. A web search will turn up many possibilities, and you can also come up with your own ideas.

Lastly, you may wish to put your circuit in some kind of enclosure to protect it, with shaft & knob potentiometers for the volume and tone controls, and perhaps a jack for headphones (note that there are headphone jacks available that have an extra set of contacts for disabling the speaker connection when a headphone plug is inserted). Another nice addition would be a power switch with an LED power indicator. We didn't put an LED in the project to reduce the quiescent current draw and thus keep the battery alive longer.

Congratulations!  
You have now completed Lab 1a

## Lab 1 Record

Section \_\_\_\_\_ Names: \_\_\_\_\_  
\_\_\_\_\_

### ***Equivalent Circuit modeling for the Speaker***

Record the input resistance at 1kHz: \_\_\_\_\_ Ohm

Record the coil inductance at 1kHz: \_\_\_\_\_ H

Record the resonant frequency: \_\_\_\_\_ Hz

Record the  $|Z|/\sqrt{2}$  bandwidth: \_\_\_\_\_ Hz

Calculate the Q-factor of the resonance Q: \_\_\_\_\_

Calculate the equivalent circuit parameters for the parallel resonance:

Rm: \_\_\_\_\_ F      Cm: \_\_\_\_\_ F      Lm: \_\_\_\_\_ F

### ***Audio Amplifier on Breadboard***

What is the low-frequency cutoff of the amplifier: \_\_\_\_\_ Hz

Record lowest frequency audible tone: \_\_\_\_\_ Hz

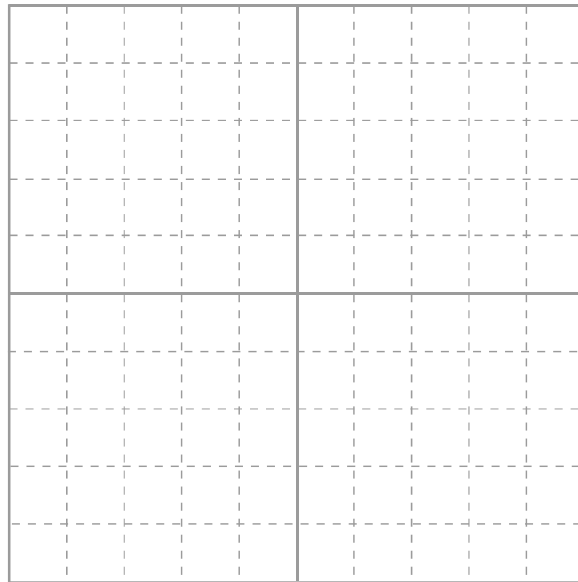
Record Highest frequency audible tone: \_\_\_\_\_ kHz



Are the limits above related to limits on your hearing or are they due to the limited frequency response of the speaker itself?

Why is the output waveform clipped for large input signals?

Record input waveform at pin 3 with a  $\pm 1\text{V}$  sinewave at 1kHz and the speaker disconnected:



Average current drawn by audio amplifier under full-volume conditions with a  $\pm 0.025\text{ V}$  1kHz sinewave input: \_\_\_\_\_ mA

Average current drawn by audio amplifier under full-volume conditions with a  $\pm 0.25\text{ V}$  1kHz sinewave input: \_\_\_\_\_ mA

Average current drawn by audio amplifier when playing music audio under normal listening conditions : \_\_\_\_\_ mA

From your answer above, estimate the battery life for this circuit assuming a 500 mA-hr battery rating: \_\_\_\_\_ hrs