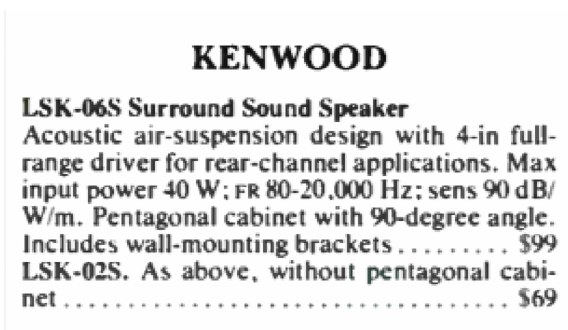
Process of Creating my Class A amplifier

So originally, I had wanted to create a Class A amplifier to practice the theoretical possible configurations in using the BJT as an amplifier (common collector, common emitter, and the common base). To do that, I felt that audio was the best choice, since I had a bunch of speakers in my basement that weren't being used. And so, this project was born. I wrote this process for people who may have wanted to start their own amplifiers but don't really understand how they should start building it.

The big thing that I learned from this project was understanding how to read datasheets of parts I was using in order to know how to use the part. This isn't something important in audio, but also other aspects in electrical engineering. I'll stress it again: **READ THE DATASHEET**. Sometimes, you may not be able to find a datasheet for the part you are working with. If you can, try and maybe use another part, or just be careful with the part (assuming you know how to use the part. I burned quite a few PNP Darlington transistors because I accidentally reversed polarity without realizing it). And don't be afraid to fail; it's a part of the learning process.

Going along with the bit of advice I written above, here were the specs for the Kenwood LSK-02S (speaker that I was talking about earlier).



KENWOOD

LSK-06S Surround Sound Speaker
Acoustic air-suspension design with 4-in full-range driver for rear-channel applications. Max input power 40 W; FR 80-20,000 Hz; sens 90 dB/W/m. Pentagonal cabinet with 90-degree angle. Includes wall-mounting brackets $99
LSK-02S. As above, without pentagonal cabinet $69

Specs for the Kenwood LSK-02S speaker

This was not an actual datasheet(obviously) for the speaker; I just pulled this out from an advertisement pdf file that I had found online (sometimes you have to be creative; any piece of information is helpful for the part you are using). I tried looking for something that resembled a datasheet for the speaker but was unable to (the speaker itself was old, but it was a good one). The specs of the speaker were, according to this document:

- Max input power 40W (not sure how believable this was, considering that these specs were pulled from an advertisement, as I said before, and this doesn't really tell me if they were specifying P_{RMS} or the P_{PEAK}. Sometimes advertisements like to give numbers to make something look better than it is in reality). Since I wasn't too sure about what type of power they were referring to, I wanted to use a signal that was smaller than the 40W they specified (less than 5W RMS most likely).
- Frequency response is 80Hz-20kHz
- Sensitivity is 90dB/(W/m) → this told me that this speaker seemed to be of good quality. In other words, try not to screw this up.

In order to give me ideas on how to build the amplifier, I looked up how to build a class A amplifier using the common emitter configuration. I initially built a circuit similar to the one that is shown below in ***Figure 1***.

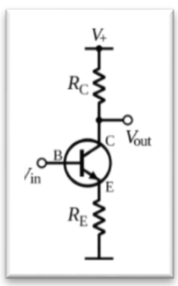


Figure 1: The basic common emitter configuration that I tried

	Definition	Expression (with emitter degeneration)	Expression (without emitter degeneration, i.e., $R_E = 0$)
Current gain	$A_i \triangleq \frac{i_{out}}{i_{in}}$	β	β
Voltage gain	$A_v \triangleq \frac{v_{out}}{v_{in}}$	$-\frac{\beta R_C}{r_\pi+(\beta+1)R_E}$	$-g_m R_C$
Input impedance	$r_{in} \triangleq \frac{v_{in}}{i_{in}}$	$r_\pi + (\beta+1)R_E$	r_π
Output impedance	$r_{out} \triangleq \frac{v_{out}}{i_{out}}$	R_C	R_C

Figure 2: The characteristics of the common emitter configuration (Wikipedia)

In ***Figure 1***, I was using a voltage divider to bias the Darlington transistor I was using at the time (the SK9455A) to around ½ the power rails (I was using +15V and GND, so it was biased to around 7.5V). I am going to go back and see why the circuit wasn't working again, but from what I saw, I wasn't able to get enough current flowing to my speakers. It is most likely due to the values of the resistors I was using (at the time, I was using resistors in the kΩ range). I'll try to prototype it again later. As you can see in ***Figure 2***, the ratio of R_C and R_E is what determines the gain of the voltage in this configuration. The next time I try to attempt this circuit, I should probably try and see if smaller resistor values would help.

Figure 3 below shows what the first iteration of the class A amplifier that I built looked like. I know that instead of using the operational amplifier, I could have used another BJT as a first stage amplifier for voltage amplification. I would also learn a lot from that too, as this is my first personal project that I am deciding to undertake. However, I didn't want to make this project too difficult (still learning a bunch of things on the side too), and I felt like making the project fully discrete would just be annoying in the long run. Operational amplifiers nowadays are very cheap, and I had a bunch of extras at home that I could have used if I wanted to.

Also, the main reason why I used an operational amplifier was because I recently took an operational amplifier course where I learned about how operational amplifiers worked, as well as how to read datasheets to get information I wanted, amongst other things. I wanted to put that information to good use, so I decided, why not use operational amplifiers to start?

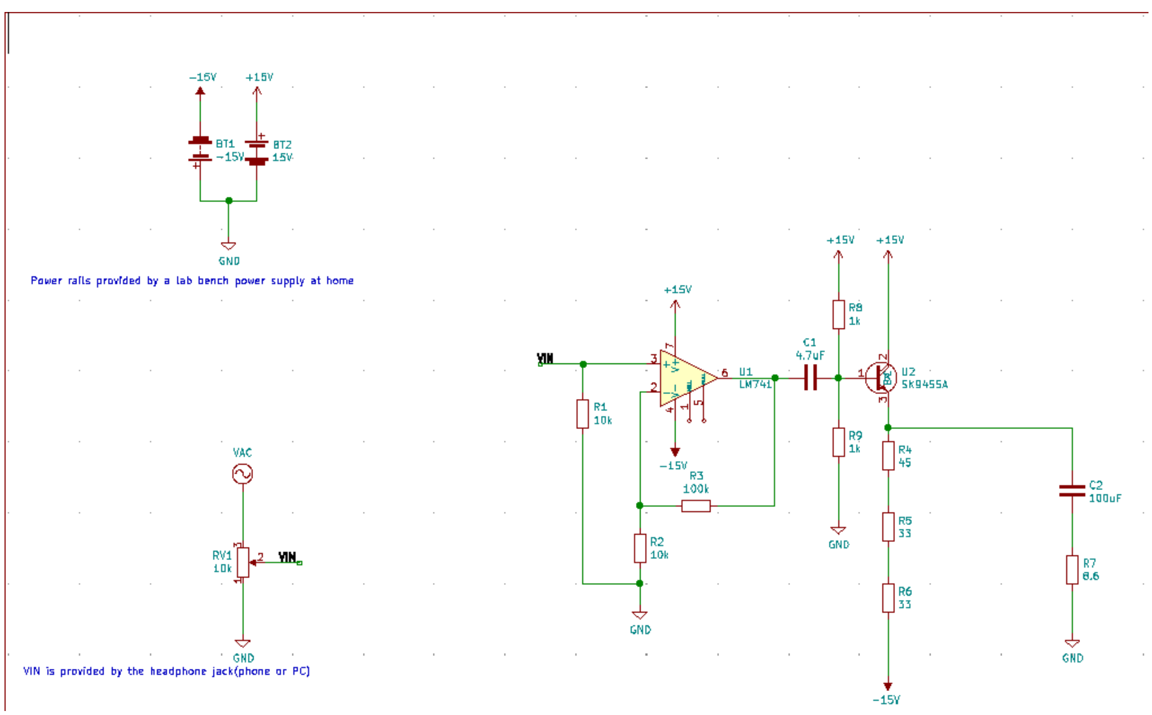
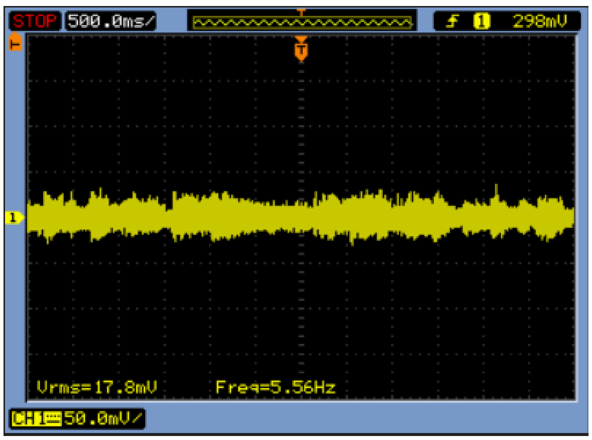
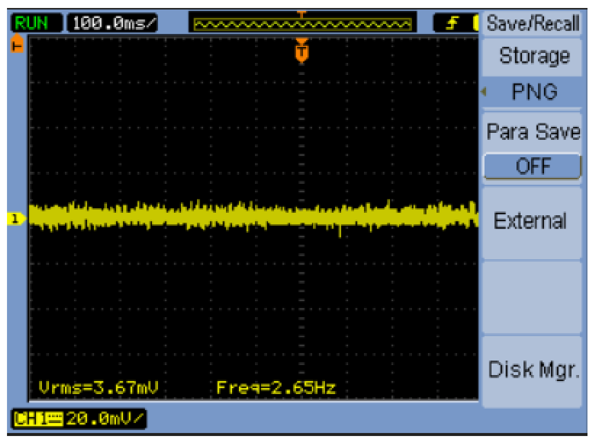


Figure 3: First iteration of the LM741-based Class A amplifier built in KiCAD

The difference between this configuration and the previous class A amplifier that I created with the common emitter configuration was that I split this class A amplifier into two stages: the first stage was for voltage amplification (the stage with the UA741), and the second stage was for current amplification(the stage with the SK9455A Darlington transistor).

For the first stage, I decided to use a gain value of 11V/V, since I saw that the output of my headphone jack using my phone was around 100mV at full volume settings for one of the outputs (L/R). Here are pictures of the input signal taken using my oscilloscope. The left picture shows the louder input (Dance Monkey by Tones & I was playing for both pictures, albeit at different portions of the song).





In the second stage, I decided to only have the current amplified and have the voltage remain relatively unchanged, since the UA741 op amp already took care of the voltage amplification for me. Operational amplifiers, although they are nifty devices, have their own limitations, and one limitation that they have is in the current that they can output. Usually operational amplifiers can only output a few mA of current, although there are exceptions. Be sure to read the datasheet for the operational amplifier. I originally tried using the output of the UA741 for the input to my speaker, and although I did hear the music I was playing at the time, it wasn't audible a meter away. Because of this, I decided to amplify the current in the second stage too.

PARAMETER		TEST CONDITIONS(1)		MIN	TYP	MAX	UNIT
V_{IO}	Input offset voltage	$V_O = 0$	25°C		1	6	mV
			Full range			7.5	
$\Delta V_{IO(adj)}$	Offset voltage adjust range	$V_O = 0$	25°C		±15		mV
I_{IO}	Input offset current	$V_O = 0$	25°C		20	200	nA
			Full range			300	
I_{IB}	Input bias current	$V_O = 0$	25°C		80	500	nA
			Full range			800	
V_{ICR}	Common-mode input voltage range	25°C		±12	±13		V
		Full range		±12			
V_{OM}	Maximum peak output voltage swing	R_L = 10 kΩ	25°C	±12	±14		V
		R_L ≥ 10 kΩ	Full range	±12			
		R_L = 2 kΩ	25°C	±10			
		R_L ≥ 2 kΩ	Full range	±10			
A_{VD}	Large-signal differential voltage amplification	R_L ≥ 2 kΩ	25°C	20	200		V/mV
		V_O = ±10 V	Full range	15			
r_i	Input resistance	25°C		0.3	2		MΩ
r_o	Output resistance	V_O = 0; see(2)	25°C		75		Ω
C_i	Input capacitance	25°C			1.4		pF
CMRR	Common-mode rejection ratio	$V_{IC} = V_{ICRmin}$	25°C	70	90		dB
			Full range	70			
k_{SVS}	Supply voltage sensitivity ($\Delta V_{IO}/\Delta V_{CC}$)	V_{CC} = ±9 V to ±15 V	25°C		30	150	μV/V
			Full range			150	
I_{OS}	Short-circuit output current	25°C			±25	±40	mA
I_{CC}	Supply current	V_O = 0; no load	25°C		1.7	2.8	mA
			Full range			3.3	
P_D	Total power dissipation	V_O = 0; no load	25°C		50	85	mW
			Full range			100	

Figure 4: The datasheet for the UA741

In ***Figure 4***, we see that the short circuit output current (or the max current that the operational amplifier can supply at the output when the output is connected to GND) is around 25mA typical and maxed out at 40mA. In this scenario, best case power supplied to the output would be $(40mA)^2*(8.6\Omega)$ = 12.8mW of power supplied to the speaker, which isn't a lot of power supplied at all and would explain the almost inaudible sound that I heard from the speaker.

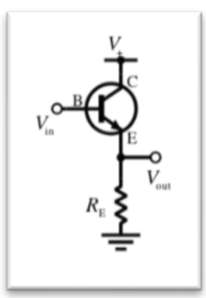


Figure 5: Common Collector configuration

	Definition	Expression	Approximate expression	Conditions
Current gain	$A_\mathrm{i} = \frac{i_\mathrm{out}}{i_\mathrm{in}}$	$\beta_0 + 1$	$\approx \beta_0$	$\beta_0 \gg 1$
Voltage gain	$A_\mathrm{v} = \frac{v_\mathrm{out}}{v_\mathrm{in}}$	$\frac{g_m R_\mathrm{E}}{g_m R_\mathrm{E} + 1}$	≈ 1	$g_m R_\mathrm{E} \gg 1$
Input resistance	$r_\mathrm{in} = \frac{v_\mathrm{in}}{i_\mathrm{in}}$	$r_\pi + (\beta_0 + 1) R_\mathrm{E}$	$\approx \beta_0 R_\mathrm{E}$	$(g_m R_\mathrm{E} \gg 1) \wedge (\beta_0 \gg 1)$
Output resistance	$r_\mathrm{out} = \frac{v_\mathrm{out}}{i_\mathrm{out}}$	$R_\mathrm{E} \parallel \left(\frac{r_\pi + R_\mathrm{source}}{\beta_0 + 1}\right)$	$\approx \frac{1}{g_m} + \frac{R_\mathrm{source}}{\beta_0}$	$(\beta_0 \gg 1) \wedge (r_\mathrm{in} \gg R_\mathrm{source})$

Figure 6: The characteristics of the common collector configuration (Wikipedia)

Figure 5 shows a simple example of the common collector configuration, which was the circuit that I had used for the class A amplifier. I found that because I only needed current amplification and keep the voltage around the same, the common collector configuration was perfect for me to use in this case. Now I will try to explain the two stages in a bit more detail.

STAGE 1: VOLTAGE AMPLIFICATION USING THE UA741

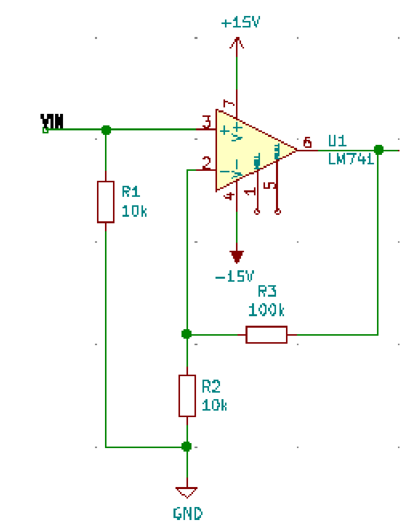


Figure 7: Stage 1 Voltage Amplification

As said briefly, ***Figure 7's*** stage is a 11V/V gain stage $((R_3/R_2) + 1 = (100/10) + 1 = 11V/V)$. The extra 10k resistor was used as a way for the signal to travel to GND, since an ideal op amp should have no current going into the inputs when configured for negative feedback. However, the UA741 op amp is far from an ideal op amp, and we see that there is some current that actually goes into the inputs (refer to ***Figure 4*** for the input bias currents = 800 nA and the input offset current = 300 nA). If I wanted to make the design better, I'd probably use a less noisy operational amplifier for the voltage amplification. I noticed that there is some noise being played along with the music I'm listening to right now. It's only noticeable if you pay really close attention and have really good hearing, but it is still probably worth it to swap the UA741 for a less noisy operational amplifier like the NE5532 op amp, which has an equivalent noise input voltage of 5nV/ (Hz), which is pretty good. If you wanted to, you could probably look into operational amplifiers that were more geared for audio applications like the LM833N, which has an equivalent noise input voltage of 4.5nV/ √(Hz), which is slightly better and both of which are in my possession. In this case, I'm probably going to edit the schematic to substitute the UA741 for the LM833N, since that op amp is more geared for audio applications.

STAGE 2: CURRENT AMPLIFICATION USING THE SK9455A DARLINGTON TRANSISTOR

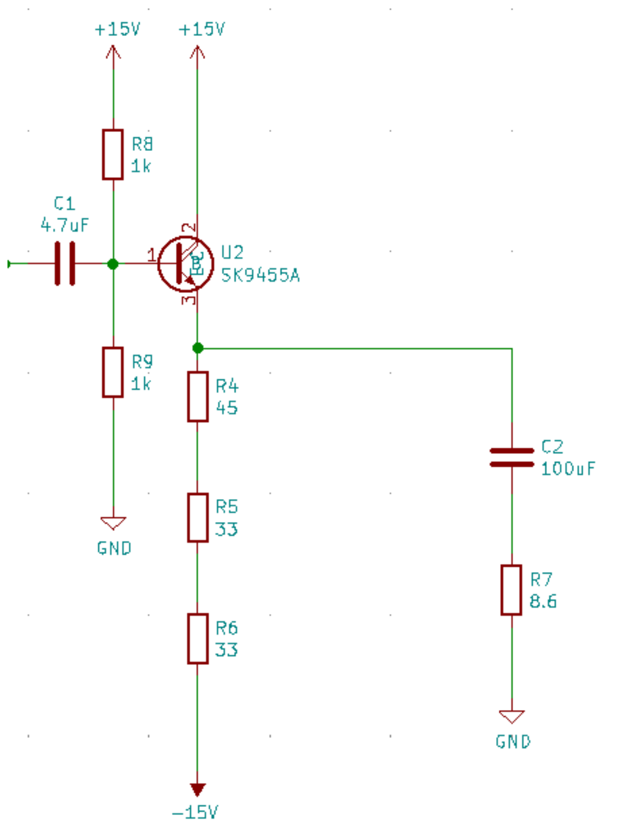


Figure 8: Stage 2 current amplification

As I briefly said before, all of this was made with spare parts that I had lying around in my basement at the time. The Darlington transistor that I had used was probably in my basement before I been born, not going to lie.

This was the closest thing that I could find that could be called a datasheet for this part.

TCE Type (*complementary device type)	Device Polarity & Material	Application	Maximum Ratings					
			Device Power Dissipatn. P_T W	Collector Current Continuous I_C A	Base Current I_B A	Breakdown Voltages: Collector-to-Base BV_{CBO} V	Collector-to-Emitter BV_{CEO} V	Emitter-to-Base BV_{EBO} V
SK9443 *SK9442	PNP/Si	Preamp Input Circuits	0.625	-0.5	.....	-60	V_{CES} = -60	-10
SK9444	NPN/Si	Microwave Low-Noise Amp for CATV, Antennas, Etc.	0.25	0.07	.....	25	12	3
SK9445	NPN/Si	High-Voltage, High-Current Switching	40	5	.....	250	80	6
SK9446 *SK9447	NPN/Si	High-Power Linear Amp	150	15	5	200	200	6
SK9447 *SK9446	PNP/Si	High-Power Linear Amp	150	-15	-5	-200	-200	-6
SK9448 *SK9449	NPN/Si	High-Power Linear Amp	200	17	5	200	200	6
SK9449 *SK9448	PNP/Si	High-Power Linear Amp	200	-17	-5	-200	-200	-6
SK9450 *SK9451	NPN/Si	AF Power/Switching Circuits	75	15	5	90	80	5
SK9451 *SK9450	PNP/Si	AF Power/Switching Circuits	75	-15	-5	-90	-80	-5
SK9452	NPN/Si	High-Speed Switching	75	4	2	.....	400	9
SK9453 *SK9454	NPN/Si	High-Current Switching/Power Amp	0.9	2	.....	50	50	5
SK9454 *SK9453	PNP/Si	High-Current Switching/Power Amp	0.9	-2	.....	-50	-50	-5
SK9455A *SK9456A	NPN/Si	Darlington AF Amp	0.75	1	.....	60	50	10

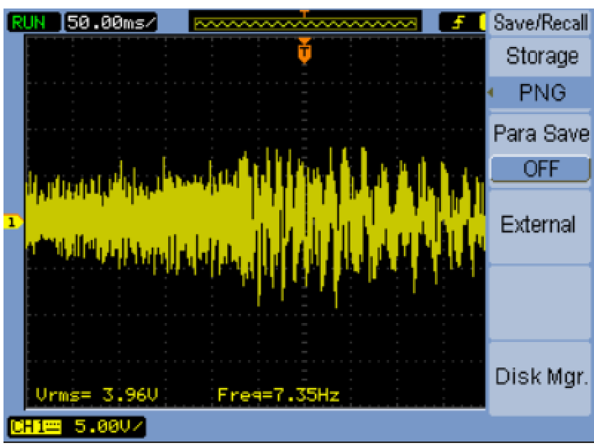
Figure 9: "Datasheet" for the SK9455A Darlington transistor consisting of a line among lines of parts

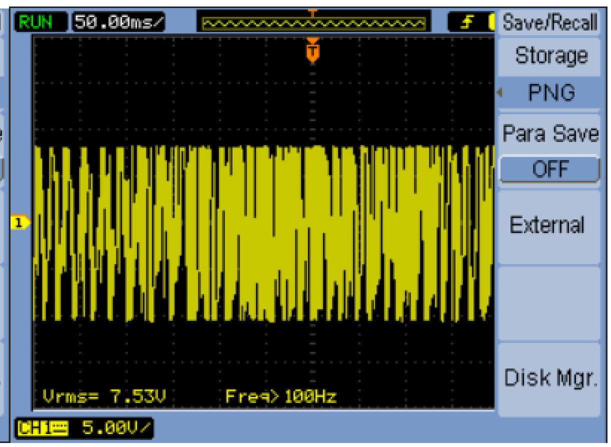
The pins names were on the packaging of the transistor. I found out a couple of minutes after searching on Google and looking up the pin configuration for this transistor and getting nada. At the very least, I still had the packaging.

According to the datasheet, I saw that the transistor was capable of dissipating 0.75W of power, but most importantly had a maximum collector current of around 1 A, which is probably more than I needed. Playing around with the transistor also allowed me to figure out that the V_{BE} voltage drop was around 1.1-1.2V, which made sense since a Darlington transistor was basically two transistors connected together to have the beta parameter be the product of the two transistor beta parameters.

In this case, I decided to just bias the base of the Darlington transistor to ½ of the positive power rail (so +15V in this case) for convenience. I could have removed the bias transistors in order to save on the bias resistors and have the emitter terminal be at ~-1.2V, but less current would be flowing through the circuit ((6.5V-(-15V)/ 111) = ~ 0.2A compared to (-1.2V-(-15V))/111 = ~ 0.12A, which is a pretty significant drop in power). If worst comes to worst, however, you could remove 1 of the resistors to increase the current flowing through the emitter terminal. The three resistors that I used were basically the highest value rated resistors that I had (rated for around 0.5W as far as I could tell). All the other resistors that I had were rated for ¼ W. I had used a 4.7uF capacitor in order to separate any DC bias that may have come from the previous stage (there isn't going to be any in this scenario, but I originally was going to do a single power supply circuit before switching to a dual supply to allow for more headroom, since I didn't really have a small value resistor in my possession). I had chosen a 100uF capacitor in order to remove any DC bias within the circuit (there was around 6.5V at the emitter terminal), and the capacitor and loudspeaker act as a high pass filter of sorts. I measure the loudspeaker's impedance to be around 8.6 Ω, so the 8.6 Ω resistor along with the 100uF capacitor would provide a 3dB cutoff of around 1/ (2* π *100uF*8.6 Ω) = 185Hz. In other words, signals below this frequency wouldn't be passing to the loudspeaker properly (attenuation), while frequencies above this cutoff will be able to go through just fine.

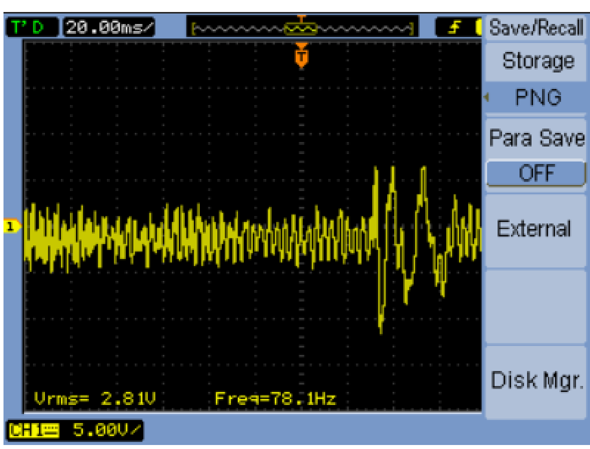
Here are sample pictures of the output signal fed into the speaker at maximum volume(L/R):





The output signal from the louder input seems to show a distorting output.

Here are some more sample pictures of the output signal zoomed in:



The distortion in the output signal becomes much more obvious here zoomed in.

THINGS I WOULD PROBABLY CHANGE

A lot of designs have flaws, and this project is no exception. If I wanted to change some stuff, I would probably do these things to improve the design of this amplifier:

- **I would probably swap in the UA741 for the NE5532 or the LM833N op amp.**
  - Both operational amplifiers seem to have a better resistance to noise than the UA741.
  - The NE5532 operational amplifier has a much smaller output impedance (0.3 Ω for a stated load resistance of 600 Ω compared to a constant 75 Ω. I'm not too sure how much the output impedance would change for a load resistance of 8.6 Ω, but I will try it out and see).
  - The LM833N is an operational amplifier that has audio applications in mind, so I might try that out and save the NE5532 for a later project.
- **I would try to add in a resistor bias network for the stage 1 part of the amplifier.**
  - In case I wanted to try and power the circuit with a single power supply later on, it would most likely be helpful to add in a voltage divider at the input in order to bias the output to the middle of the power supply rails.
- **Change stage 1 part of the amplifier to incorporate filters (wide band pass filter).**
  - This part would help with shunting unwanted high frequency or low frequency signals to GND. I was prototyping this circuit using a breadboard, and I noticed that every wire that I had sticking out of the breadboard incorporated noise to the circuit.
  - It was cool to see why something like a filter may have been needed instead of just learning about it in theory and not really applying it.
  - Either increase the power supply voltage or decrease the gain slightly in order to reduce the distortion at the output (if you keep the UA741). The NE5532 and the LM833N may not behave the same way as the UA741 in terms of the amount of distortion that we see at the output for a powering supply voltage of +/-15V.
- **Add in bypass capacitors to help with noise within the power supply lines.**
  - This would be another way of getting any unwanted signal/noise to go to GND without any extra hassle.
- **Switch in the 100uF for a bigger capacitor (maybe a 1mF capacitor)**
  - This is a little nitpicky, but I would also try to switch the capacitor to have the 3dB point at 20Hz instead of around 200Hz (sweet spot for the speaker was 20Hz to around 20kHz).
- Increase the ratings of the resistors in the collector and emitter
  - Probably could have made an omelet with the amount of heat being dissipated.

Class A amplifiers seem to provide good sound quality. The only problem that I could see is the amount of power dissipated is quite high, and the amplifier is quite inefficient. Even when I had no input signal, the amplifier was consuming a lot of power for no reason.