

## A New Take on a Classic Circuit

Most good circuits are classic circuits and electrical engineers are often quoted as saying “there is nothing new under the sun.” As soon as a new circuit is discovered someone points to a circuit invented several years ago that performs the same function in a similar style. So, with that we introduce this current booster driven by an opamp as a headphone amplifier. This style circuit has been used by many engineers in many fields. Here we have adapted it to our purposes; To amplify an audio signal and drive that signal into headphones with as little distortion as possible.

This circuit, pre-modification, can be found in several application notes authored by Jim Williams. Jim worked for several electronics parts manufacturers including Linear Tech, National Semiconductor and Texas Instruments. Examples of this circuit can be found in App Note 272 (National Semiconductor) and also App Note 272 (Texas Instruments). Jim Williams writes his papers in a way that nearly everyone can understand. He was a lover of very fast circuits and audio circuits. You will find many more examples of great audio circuits in his notes.

Jim had, at his disposal, components designed for RF (radio frequency) and near RF speeds. However, these components would be 20-30 years old today. What we have today can come close to matching those RF speeds at with the advantage of higher current capability, better linearity, lower noise and lower distortion. So, we have adapted a few of our currently and recently available parts to these ends. Jim’s circuit used 2N2219 and 2N2905 as output transistors. We will use 2SC5171 and 2SA1930. Jim used LF358 for the opamp. We will use LME49710. We will also add an additional LME49710 in front of his circuit to invert the input signal and add gain. You can change many of these components and in fact this kit will change over the years as parts are outdated or introduced.

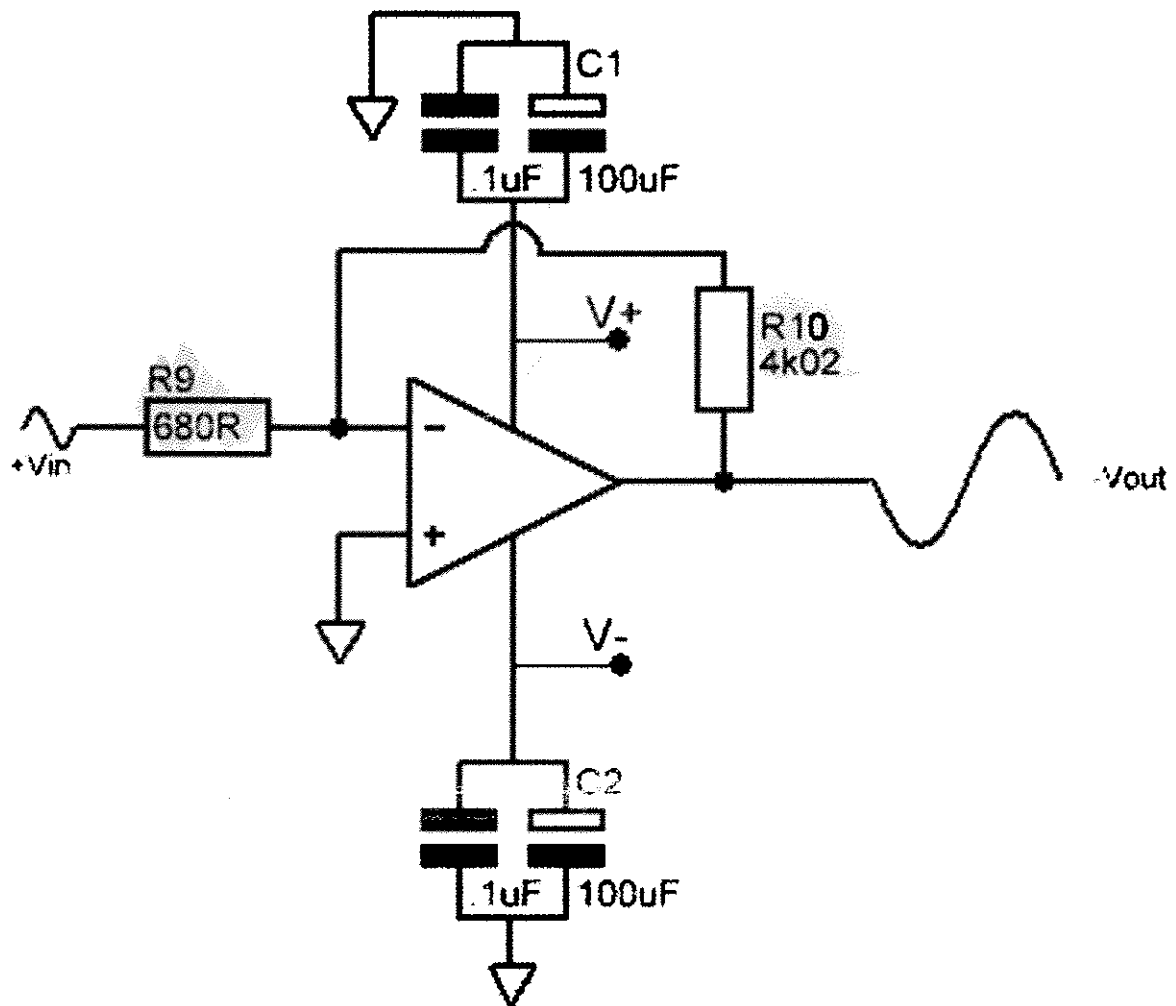
### A Quick Overview:

There are two opamps (we’ve added one to Jim’s circuit ) and a discrete buffer circuit. The first opamp inverts the signal and amplifies the signal. The second opamp inverts the signal (resulting in a non-inverted output) and sends it to the discrete BJT based buffer. This second opamp controls the buffer via a feedback loop where the opamp can monitor and correct any differences between the signal at the opamps input and the signal at the output of the buffer. The buffer does not amplify voltage at all but it does provide the output of the opamp with a boost of current so that the opamp can drive the same signal voltage easily into low resistance loads.

### Bits and Pieces:

We’re going to break the circuit into pieces and discuss each.

The first piece we will call Stage 1: Inverting amplifier



The above is a diagram of an INVERTING amplifier circuit. The gain of an inverting amplifier can be calculated by dividing the output signal by the input signal ( $V_{out}/V_{in}$ ) OR we can divide the feedback resistor value by the input resistor value ( $R_f/R_{in}$ ). So,

$$\text{Gain} = V_{out}/V_{in} = R_f/R_{in}$$

In this case we have a gain of almost 5.9 as  $4020/680 = 5.91$ .

To learn more about how this happens there are many many sources on the internet. A good example is

[http://www.electronics-tutorials.ws/opamp/opamp\\_2.html](http://www.electronics-tutorials.ws/opamp/opamp_2.html)

This circuit is what the first opamp circuit on your headphone amplifier board looks like. It inverts the signal and amplifies it by 5.9 times and sends it on to a nearly identical circuit (Stage 2). So our gain is actually a negative gain, -5.9 times. The signal is amplified 5.9 times and inverted 180 degrees out of phase with the original signal. In the next circuit we will amplify -1 times which will result in the same

output voltage as Stage 1 has, but will again invert by 180 degrees, coming full circle so that we have 0 degrees of signal inversion.

To learn how to transfer voltage gain to dB please see

<http://www.sengpielaudio.com/calculator-FactorRatioLevelDecibel.htm>

Before we leave Stage 1 let's ask a question. Why isn't this much of the circuit enough to drive our headphones? Why do we need more?

Really, it is enough to drive headphones but not adequately. If we want good hard hitting bass and we want our music presented to our ears without distortion no matter what the resistance of the headphones we are using we will need to have a large amount of current accompanying the output voltage.

If we look at the datasheet for the LME49710 we find that this opamp is capable of hifidelity signal output into loads of 600 ohms or more. For it to be capable of this it is better to have a power supply that comes close to the maximum voltage the opamp can handle. It can handle between +/-2.5V and +/-18V. The datasheet shows us via many many graphs that best distortion characteristics are available to us when we supply the opamp with a load of over 600 ohms, a supply of +/-12V to +/-17V and when we have an output voltage between 0 and 10V. There are not many headphones available with a resistance of 600 or more ohms. It is more likely that you have a pair of headphones between 32 and 300 Ohms. The lower resistance your headphones have then the more current is needed to get undistorted volume out of them. Since we know the opamp can provide the undistorted signal voltage when nearly zero current is demanded by the load then to drive current hungry headphones we will need a circuit that follows the output signal voltage of the opamp and adds current but does not request current from the opamp. A current buffer.

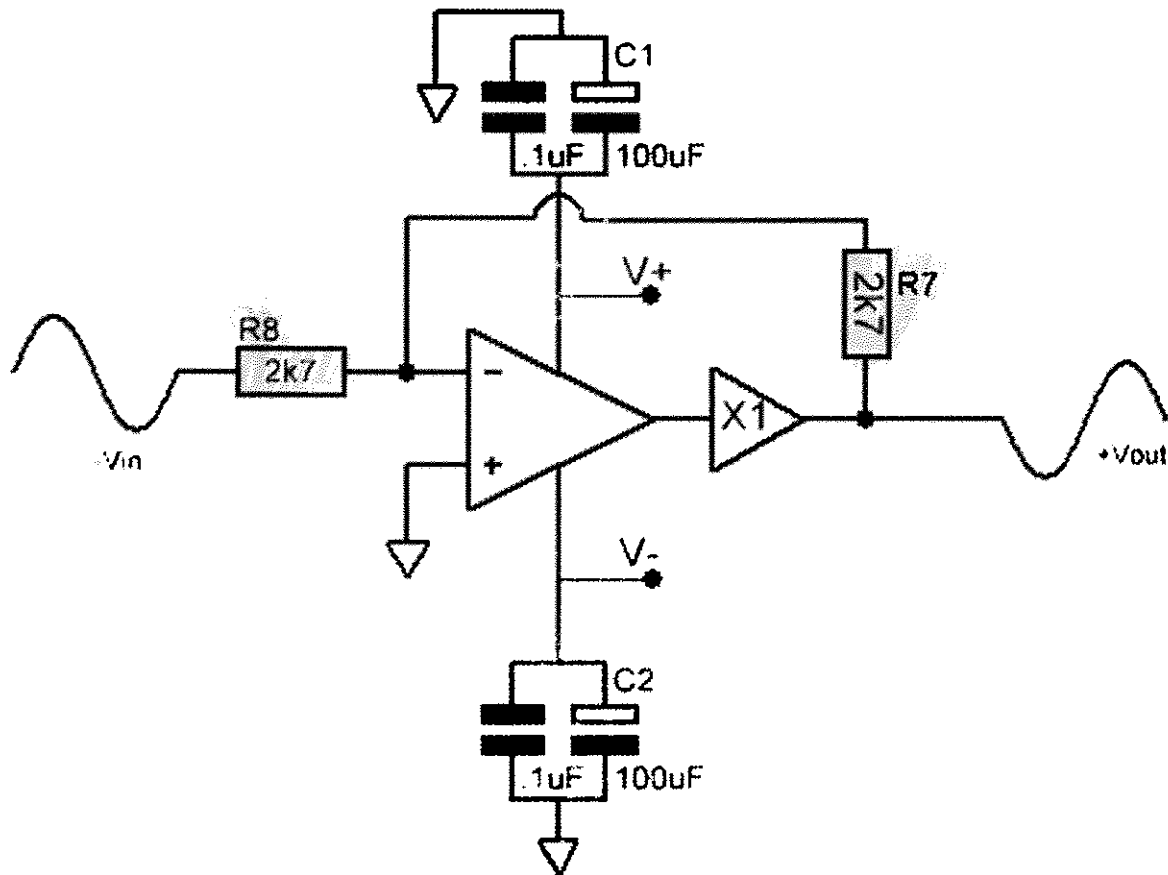
So, Stage 2 will invert Stage 1's signal voltage and will send the amplified and twice inverted signal into a current buffer. Stage 2 will monitor the output voltage of the current buffer and make adjustments to keep the distortion low.

Below is a schematic of Stage 2 which includes a simplified schematic of the current buffer. The current buffer is represented by the triangle with the "X1" inside it. We will look at the current buffer in more detail later as Stage 3.

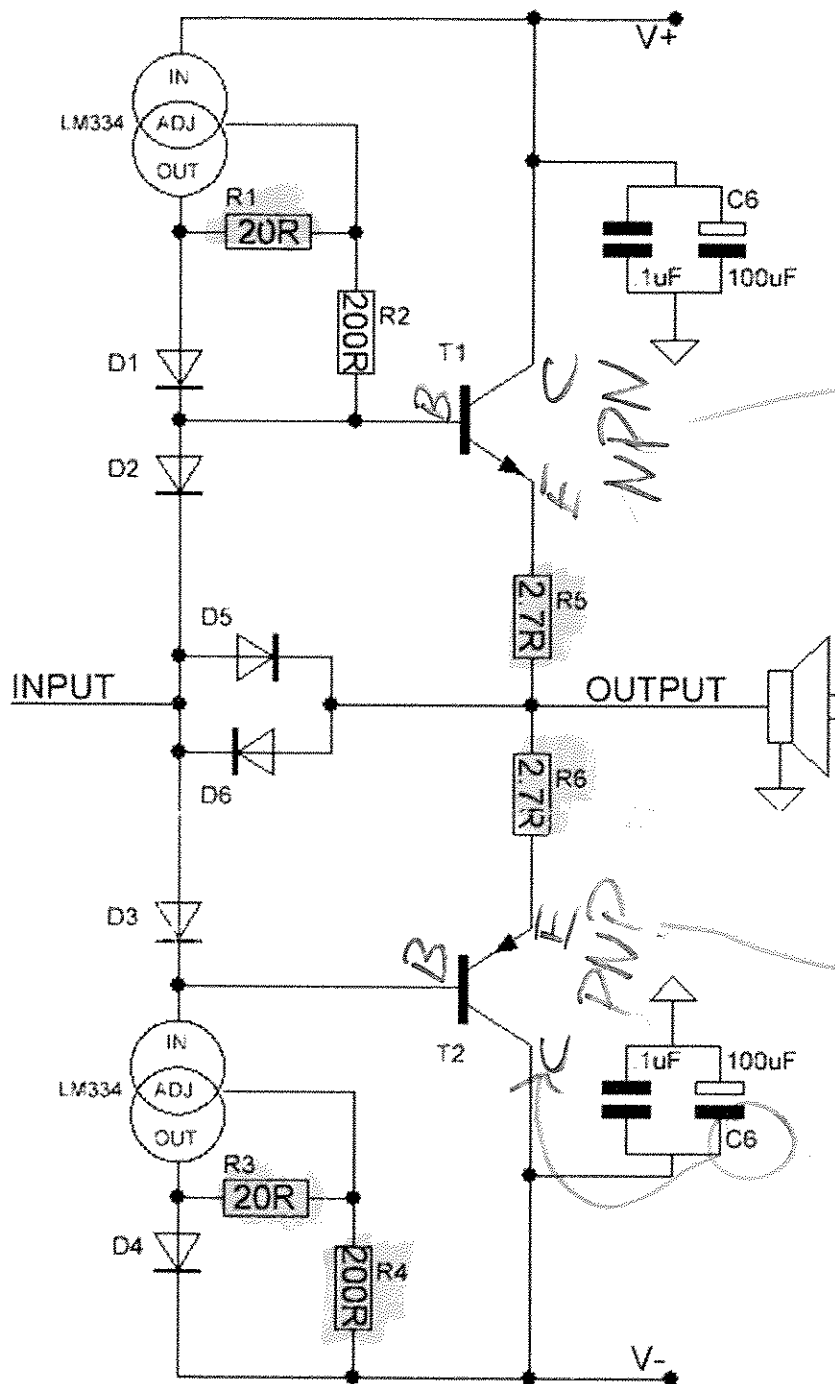
In Stage 2, if we ignore the current buffer, we basically see the same thing as Stage 1 with some different resistor values. 2k7 for both resistors. This presents a 2k7 ohm load to the opamp in Stage 1 and offers no gain at all since 2k7 divided by 2k7 equals a gain of 1. A gain of 1 simply multiplies the input voltage to Stage 2 by 1 resulting in no difference in voltage. The one caveat is that it is really a gain of negative 1 because the opamp is set up in an inverting configuration. So when Stage 1 outputs a -5.9 gain and then we multiply that by Stage 2's -1 gain we get  $-5.9 \times -1 = 5.9$ . This simply means that while both stages invert the resulting output of the whole circuit is non-inverting. There is no change of phase.

In Stage 2 the opamp does not have to worry about the output current. It only has to provide a very small amount of current along with its signal voltage to drive the current buffer. The current buffer then drives the headphones. In this way the opamp is isolated from the current demanding load of the headphones. However, the opamp monitors the voltage output of the current buffer via the feedback resistor which is

the resistor labeled R7. R7 envelopes the current buffer and as far as the opamp is concerned the current buffer is a part of the opamp. It knows no different as it thinks the current buffers output is it's own output.



Stage 3 is the current buffer. This is the discrete output section that is represented by the triangle with the "X1" inside it. Jim Williams gives an excellent explanation of how this current buffer works. Its quite similar to many circuits that are meant to be line drivers. I will essentially paraphrase what Jim says about how this section works. I think it would be much too involved for me to explain how each part works. Maybe in a simple kit that is purely discrete components we can get more involved. Lets get a look at the discrete section of our headphone amplifier. Remember, this section does not increase or decrease the voltage to the load but it does increase the current to the load.



Both current sources (LM334 and 20R resistor) do the same job for different transistors. They provide bias current for the BJT emitter followers. The 200ohm resistor sets the LM334's output current. Download and review the LM334 datasheet for equations and explanation. Diode D1 and R2 help to keep LM334 from changing its output current due to temperature variations. D4 and R4 provide the same corrective adjustment for their LM334. This effect is also discussed in the LM334 datasheet but in brief the diode and the LM334 change in opposition to each other as they are heated or cooled and therefore

the current output stays equal whereas without the diode the LM334 would change output with temperature variations.

T1 allows current to flow from the positive power supply rail to ground (it sources current) through R5 and the speaker/headphone when the opamp outputs a positive signal. T2 allows current to flow from the ground to the negative supply rail (sinks current) through the speaker/headphone and R6 when the opamp outputs a negative signal.

This is an extremely low distortion design. Without D2 and D3 the distortion would be much higher in the form of crossover distortion. Crossover distortion happens when BJTs working in this or similar arrangement are switched on and off. There is a diode drop inside the BJT. This is also referred to as  $V_{be}$ . Voltage between base and emitter= $V_{be}$  and is a .65V drop. The BJT needs a voltage on its base that greater than the  $V_{be}$  or it will not turn on. So when we are at a, for example .7V signal coming from the opamp the BJT is conducting current but as the voltage drops toward .65V the BJT STARTS TO TURN OFF rather than just turning directly off which puts a bit of a wiggle into the output signal as it is in a nonlinear operating area before turning off. Then the darn thing turns off and for the remaining .65V of signal input we get no output. D2 and D3 with a small amount of current flowing through them will hold the base of each BJT at about .7V, .05V higher than the  $V_{be}$  of the BJT so it is held on all the time. This is what makes this a class AB amp rather than class B, the fact that the BJTs are always on and therefore can not enter that nonlinear region that adds distortion. A great description of crossover distortion is here:

[http://www.electronics-tutorials.ws/amplifier/amp\\_7.html](http://www.electronics-tutorials.ws/amplifier/amp_7.html)

D5 and D6 protect the transistors from short circuiting by shunting current away from them when the output exceeds around 250 milliamps. This value can be changed by following the formula  $V_t/R_5$ , or  $.7V/2R_7=.259A$ .

In all stages of this circuit the 100uf capacitors are there to decouple AC frequencies from entering the opamp at the power supply pins. While the opamp rejects power supply ripple at 125dB (basically noise from power supply ripple is attenuated by 125dB) we would still like to help it out by creating a high pass filter. You might be wondering where is the resistor in this high pass filter? Well its inherent to the capacitors. The caps have what is called ESR, or equivalent series resistance. So, while the capacitor will try to allow all frequencies to pass through it, some will make it through easier than others because of both the value of the capacitance and the value of the ESR. We have 2 capacitors in parallel on each power supply leg of the opamp. Each capacitor works independently and cooperatively from and with the other capacitor. This small amount of capacitance will do a good job decoupling most frequencies from entering the opamp but they will not do much energy storage to help with extended bass notes.

If you would like to increase the impact of the bass from your amp you will need a robust power supply with a large amount of capacitance available for the amplifier to draw instantaneous current from. My suggestion would be in the realm of 2200uf to 4700uf. There are diminishing returns to additional capacitance, however it couldn't hurt.

### Assembly

Assembly is pretty simple. There is no tweaking to do afterward and nothing to match beforehand. Just make sure you get the right parts in the right holes. The holes for the resistors are pretty tight so a bent

up resistor lead is going to be really frustrating. Keep them pretty straight and bent from the resistor at a 90 degree angle.

First flip the board over and solder in the ceramic surface mount capacitors. Don't freak out. Its not that bad to solder any of this kit's surface mount devices. My advice would be to put a drop of solder on one pad where the capacitor goes and then, with tweezers, grab the cap and bring it close to the blob of solder that you are keeping hot with the iron. As soon as the cap touches the solder it will get sucked in by the solder. Just make sure its positioned to where the other side of it is also sitting on a surface mount pad. Remove heat and it will be welded in place. Now hit the other side of it with the iron and a bit of solder. The solder must adhere to the pad so you must get the pad hot. It is absolutely going to solder to the cap but this pad might be tough so you need to be sure that a connection did happen between the pad and the cap via the solder. If you decide to throw in the towel on these caps its not a big deal as these caps are not absolutely necessary for proper operation.

Solder in all resistors and diodes next. Follow that up with the opamps and then terminal blocks.

Now the large surface mount caps get soldered to the topside. The four near the opamps should be easy. You want to be sure that the little metal tabs on their bottom side actually bond with the solder. A little flux doesn't hurt to help this along. These tabs need to get hot and need to be forced down into the solder with finger pressure, then touch the solder right to the tab with the iron. If the cap is getting hot to your finger maybe give it a while to cool down. Test if the cap is soldered in place by trying to wiggle it back and forth. The two caps near the transistors you need to be careful to not fill the transistor's through holes with solder.

Now solder in the transistors. The back of the transistors face the bold solid line of their silkscreen outline.

You need a way to control the volume. You can use an attenuator before the board with the output of the attenuator/potentiometer going to the terminal block. I'll give you my opinion and then you can go do whatever you want. I like the sound of lower value potentiometers versus the higher value pots. A 10k pot, to me, is way better than a 100k pot. Any pot will do the trick though so probably you'll want to find a stereo 10k potentiometer at EPO and wire it up to feed signal to these boards.

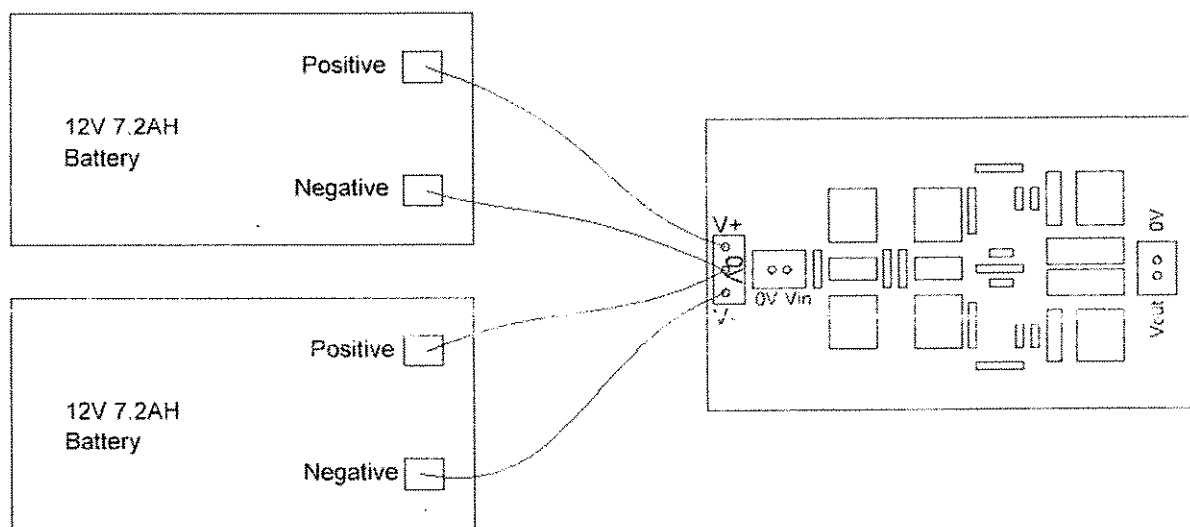
Why do I not include a potentiometer in this kit? You need to pick a pot that is right for your project. You should try to select a pot with a total resistance of 10 times or more than the output impedance of whatever signal source you are using. So if your CD play has a 250 ohms output impedance then you need at least a 2500 ohm stereo potentiometer. If its got 1500 ohms output impedance then you need at least a 15000 ohm stereo potentiometer. If you just want to be safe and cover all bases get a 20k ohm stereo pot and you will probably be fine. I prefer to go as low as I can and this way I get a super transparent and crisp sound. Going with that 100k pot gives you a very smooth but veiled sound. I just don't appreciate that sound as much as the more crisp sound.



On the bottom of the board is a bit of silkscreen that looks like . Above this symbol are two solder pads. Solder a small piece of wire from one pad to the other. You might even get a solder blob to cover both of them and not need the wire. I had intended to put a potentiometer between the two opamps at this point but I think we should just stick with a potentiometer being off board.

## Power Supply

Your power supply must supply the amplifier board with dual polarity DC. You can use very low voltages if you need to but I suggest, for best sound quality, to stay between  $\pm 12\text{V}$  and  $\pm 15\text{V}$ .  $\pm 17\text{V}$  is the max but I don't recommend this extreme. When we say  $\pm 12\text{V}$ , etc., what we mean is you will need a supply that gives a positive  $12\text{VDC}$  and a negative  $12\text{VDC}$ . This must have a  $0\text{V}$  point on the supply also. Maybe a more precise and detailed way to say it would be  $+12\text{V}/0\text{V}/-12\text{V}$ . You can power this from  $12\text{V}$  batteries found here at EPO if you like. It will play quite some time and loudly from a pair of their  $12\text{V } 7.2\text{AH}$  lead acid rechargeable batteries. If you go this route make sure to have a way to recharge them. Below is an example of how you might use batteries.



The terminal blocks are not well marked on this board. Please see the board outline above for indications of where power supply connections need to be made as well as input and output signals.

If you choose to use a different power supply EPO does sell a kit for a dual polarity linear supply that would be great for this headphone amp when coupled with a  $12\text{VAC}$  dual secondary transformer.

## Testing

Its going to be pretty hard to do this incorrectly so I don't see you having any trouble. However, in the interest of safety, my safety, I will first absolve myself of any responsibility for your safety. Anything you do here is on your own and best judgement. I am simply giving my opinion and its up to you to either already know, or research, whether my description of the build, testing, and use of this device should be followed or if you even have the capability to proceed without hurting or killing yourself. You sure could kill yourself with the  $120\text{VAC}$  that the input of your power supply will require unless you use batteries and if you put any part of your body somehow in electrical contact with the positive and negative rail it will



hurt quite a bit and I suppose its possible this could also kill you. Consider yourself warned and proceed if you agree to NOT hold me responsible for your inept or perfect build and any damages to yourself or anything that you connect to this device.

Really you should wait a day after your build and then come back and review your assembly. Any mistakes I make I can usually find if I leave it alone for a while and come back with a fresh mind and eyes. Backwards capacitors really will explode and really could take an eye out. So, review after a rest.

If all parts are inserted and soldered correctly this circuit will JUST WORK. Once you connect power you will want to feel the tops of the opamps and the output transistors with your finger. If they are warm, that's fine. If they are hot you should be looking for mistakes. There is no trouble shooting here. There is really only finding which part is in the wrong place or which part did not get soldered or got a cold solder joint. You should short the input  $V_{in}$  to  $V_0$  and measure for DC voltage on the output. I have never had more than 12mV of DC offset on the output and its almost always in the 3 to 4 mV range. Outside of this range is not alarming but numbers over 50mV would really have me wondering whats wrong here?

This is a very low distortion design and it is very fast. I have measured it as low as .0003% total harmonic distortion and at speeds up to 1.6MHz for sine waves but it operates best under 600kHz for square waves. It will drive 16 Ohms speakers at these specs and will drive headphones of any impedance. For headphones of 600 ohms it definitely needs the gain provided by the first stage of this circuit but would be fine as a current buffer into headphones from 32 to 300 ohms.

Have fun. Good luck and check out our other kits from EPO.

