Kit 48. Introduction To Audio Power Amplifiers

Using integrated amplifier chips like the LM386, TDA2004, etc. are modern, quick and easy but it doesn't teach you anything about how power amplifiers actually work. Here is a Class AB amplifier made from discrete components. It will deliver a couple of watts of power into an 8 ohm speaker. It provides hands-on learning about audio topics such as cross-over distortion, bootstrapping, and push-pull. We have included a description of these topics.

Assembly Instructions :

Solder in the lowest height components first, then work up to the highest. The 10K pot is connected to the PCB by some 3 strand cable which you have to supply to the length you require. Preferably use shielded cable for this as well as the input. If it's easier, run the input direct to the pot, and then to the pot terminals on the PC board. Alternatively you can mount the pot on the PC board, by using pcb pins or wires for the input instead of the plastic terminal block.

Add the power transistors Q5 and Q6 last. Make sure to get the BD139 & BD140 in the correct way around and in their correct positions - the metal back of the package goes in above the bar marked on the overlay. Screw on the heat sinks **before** you solder them into the board. You will find that both transistors must be soldered some distance above the board so the heat sinks do not touch any of the other components. The metal plates of both power transistors are joined to their collectors so the heat sinks should not touch anything else, unless you insulate them.

Join the two 9V battery snaps together in series to make the 18V DC. (Solder together one red lead to the black lead of the other snap.) Alternatively you may provide any suitable supply of 9 - 18V D.C at greater than 500mA.

Setup :

The first step is to adjust the trim pot to remove any crossover distortion in the power transistors. Because the amount of bias applied to the transistors increases as the resistance increases, start by rotating the pot **fully clockwise**. This should give a resistance of zero. Do this before turning on the power to avoid giving too much bias. Then turn on the power and allow a couple of minutes for the transistor temperatures to stabilise.

Ideally to do this adjustment you should apply a 1 kHz sine wave input, and monitor the distortion level. Adjust the input level to give about 0.5V output. Gradually rotate the trim pot RV2 counter clockwise until the distortion reaches a minimum. The reduction in distortion should be quite obvious. However check that you have not set the bias too high which will cause excessive quiescent current to flow. If the power transistors feel hot to touch without any input signal, then the bias is set too high.

A second method is to measure the bias current, or the supply current drawn by the amplifier as the bias is increased. Use an ammeter in series with the power supply, or a voltmeter across R6 or R7. We found minimum distortion at approx 20mA bias current, which translates to 24mV across each of the 1R2 resistors. This is equivalent to approximately 30mA total supply current.

What to do if it does not work :

Poor soldering is the most likely reason that the circuit does not work. Check all solder joints carefully under a good light. Next check that all components are in their correct position on the PCB, and the transistors and electro's are correctly orientated. If you experience instability (high frequency oscillation) you can try a capacitor across the input terminals of about 220 - 330pF. This might be necessary if the leads to RV1 are long for example.

Circuit Description :

The power module has been designed for a maximum input signal of about 50mV. For signals larger than this the 10K volume control acts as a potential divider to reduce the input and prevent over-load. For smaller signals you will need to use a pre-amplifier. Or you could increase the value of the 10K feedback resistor R5 and so increase the amplifier gain above 101 (the ratio of (R3+R5)/ R3.) Do not reduce R3 which will also affect the frequency response of the amplifier.

There are various classes of amplifiers which can be used to drive a loud speaker. The text books list them: class A, B, AB, C etc. These classes are defined in terms of the amount of bias which is applied to the transistors. Class A is permanently and fully biased on, while Class C only conducts for a small part of the input cycle. In this design we have used Class A for the input pair, and Class AB for the output.

First Stage. Q1 & Q2 are arranged as a complementary pair in a common emitter mode. This gives a high voltage amplification. However, it has a high output impedance which means it is not suitable for driving an 8 ohm speaker directly. R1 & R2 apply sufficient bias to keep the transistor pair permanently turned on. The amount of bias places them in the middle of their conduction range so that they react to both positive and negative swings of the input signal. There is continuous current flowing whether or not a signal is actually present and being amplified.

To reduce the power wasted by Class A, another class of amplifier, Class B, uses a pair of complementary transistors which are not biased on. The signal is amplified by using the NPN transistor to react to the positive voltage side of the input signal while the PNP reacts to the negative side. At any instant only one transistor is turned on. This is called push-pull; when the NPN transistor (like our Q5) turns on the output voltage is pulled up towards the positive supply rail, while turning on the PNP (Q6) pushes it towards ground. Class B solves the quiescent current problem of Class A amplifiers, but introduces another - crossover distortion. Because the first part of the signal is used to complete the turn-on bias for each transistor you introduce distortion in the output whenever the input signal swings between positive and negative, or negative to positive. Enter Class AB Amplifiers.

Second Stage. Class AB also uses a pair of complementary transistors acting in the same push-pull arrangement, but it adds sufficient bias between the base-emitter junctions to just turn on both transistors when there is no input signal. When a signal is applied, one of the transistors will turn on more and the other will turn off. A diode in series with an adjustable resistance (an LED in our circuit), or the controlled output voltage of another transistor or zener, is normally used to apply precise bias. If the bias is too small then there will still be some distortion; but if it is too large an increased quiescent current will flow, which will waste power.

In the schematic you can see that the second stage of our amplifier is set up as an emitter follower with the load connected to the emitter of the transistor rather than the collector as in the first stage. The voltage at the output 'follows' the voltage at the input. They are the same value except for a 0.6V drop across the base-emitter junction. The advantage of the arrangement is that it produces a large output current at a low output impedance. This is ideal for driving a speaker.

Now let us look at the bias needed to remove the crossover distortion which is the special feature of Class AB amplifiers. Because our circuit uses four output transistors arranged as two darlington pairs in the final amplifier stage, the bias needed to just turn on Q3 - Q6 should be about 2.4V (4 x 0.6V.) This is supplied by the voltage drop across the green LED and that across the trim-pot.

Overall Description. Q1 & Q2 form a complementary pair for the audio voltage amplification. The advantage of using two transistors for this stage is that the arrangement has a very high input impedance and hence does not load down the input signal. That means it draws very little current from the previous stage. The load for transistor Q2 is the green LED, the resistance of RV2, plus R4. Note that R4 is not joined directly to the ground rail (as you might expect) but indirectly via the speaker. This is called bootstrapping, a topic we will shortly return to.

The pairs of transistors Q3/Q5 & Q4/Q6 form a current amplifier. The small value resistors R6 & R7 help to stabilise the circuit. Voltage changes across these resistors act as local negative feedback and help to counteract any alteration in current caused by temperature, or different current gains in the transistors. There is also a global negative feedback loop provided by R5.

Bootstrapping. This is a technique which allows you to unlock or separate the AC & DC operations of an amplifier in order to get an increased power output. In some ways it is like the operation of an inductor which has a low DC resistance but a high AC impedance. The smaller DC resistance of the bootstrapped load does not restrict the current flow, while the higher AC impedance results in a large voltage being generated across the load. And combining high current with high voltage gives high power (P = E * I).

In general, bootstrapping provides positive feedback from the output to the input of a unity gain amplifier in such a way that a particular point of the circuit is 'pulled up by its own bootstraps'. The signal voltages at the opposite ends of the bootstrap rise & fall together, with virtually the same AC signal appearing on both sides, providing a higher impedance load for the driver transistor than its ohmic value would indicate. Let us look at how this works for our circuit.

Resistor R4 is the bootstrapped load. Because it is connected after the capacitor C3, the bootstrap is effective only for the AC signal and the extent of the multiplying effect will be determined by the true voltage gain of the nominally unity gain amplifier. Suppose the amp has true unity gain. Then the voltage gain at both ends of resistor R4 would be exactly the same. With no AC voltage drop across R4 no current would flow through it so it would have an effectively infinite resistance. Now suppose that the voltage gain is a more realistic 0.9. This means that the voltage at the top & bottom of R4 would be 1V and 0.9V respectively making the voltage drop across it 0.1V. This is only one-tenth of the full V which would occur across R4 if it were connected directly to ground. Hence, R4's 'bootstrapped' resistance is 10 times greater than its 1K5 value. So to the driver transistor Q2, R4 now provides an AC load impedance of 15K. The closer the gain approaches unity the greater the effective impedance provided by the bootstrap.

The advantage of such a setup is that Q1 & Q2 achieve a higher AC voltage gain because their output is developed across a higher value load resistor. If R4 were not bootstrapped but simply connected to ground the value of R4 would have to be increased to 15K to achieve the same effect. But such an increase would result in the base currents of Q4 & Q6 (which also flow through R4) developing a far larger voltage across the resistor. This voltage could easily be large enough to turn off Q2 on the negative sections of the signal preventing its voltage swing going anywhere near ground.

Calculation. An 8 ohm speaker dissipating 1W of power draws an RMS current of 354mA ($P = I^2R$), or a peak current of 500mA (354 x sqrt2). If the current gain of each transistor Q4 & Q6 is 30 (typical) then the base current of Q4 is 556 uA. This small current still produces a voltage drop across 15K of 8.3V, restricting the negative output voltage swing to only 0.7V (9 - 8.3V). Clearly the driver transistor Q2 will shut down long before the amplifier delivers a peak load to the speaker.

Hence the advantages of bootstrapping - the multiplied resistance of the load resistor - gives us an increased AC voltage gain from the first stage of the amplifier without decreasing the AC current from the second stage. This results in higher output power.

Supply Voltage. This calculation also explains why increasing the supply voltage will increase the volume of the output. A higher supply voltage means that the input signal to the power stage can have a greater voltage swing before clipping which results in a greater swing for the output. For the same current flow in the load, doubling the voltage will double the output power. However for a constant load resistance, the output current will also increase. The power output of the module was measured at various supply voltages. To do this the speaker was replaced by a 5W, 8 ohm resistance, a 1kHz signal was applied to the input and the output viewed on a CRO.

Next the amplitude of the input signal was adjusted to achieve the maximum output signal prior to clipping (by looking at the output on the CRO.) Then the AC voltage across the load resistor was measured using a voltmeter. The power dissipated in the load was calculated from $P = V_{rms}^2/R$. This gave the following results:

Vcc (D.C.)	**V out** (RMS)	**P out** @8 ohm
9V	2V	500mW
12V	2.7V	0.9W
15V	3.3V	1.4W
18V	4V	2W

So it can be seen that the increase in supply voltage gives a substantial power increase. Doubling its value gives four times the power. This is why very large power amplifiers (hundreds of watts) need much higher supply rail voltages.

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See our Web page at :

http://www.kitsrus.com

Specifications :

D.C. input :	9 - 18V at 500 mA
Idle current	~ 30 mA
Power output	~ 1 Watt RMS @ 12V, 8 ohms
	~ 2 Watts RMS @ 18V, 8 ohms
Freq. Resp.	< 200 Hz, >20 kHz, –3dB, 8 ohm
THD	< 1 % @ 1 Watt, 18V DC
S/N ratio	> 60 dB, ref. 1W output.
Gain	~ 40 dB maximum
Input Z	~ 10 k ohm

Components :

Resistors, 5% carbon:

R1	820K	grey, red, yellow	1
R2	1M	brown, black, green	1
R3	100R	brown, black, brown	1
R4	1K5	brown, green, red	1
R5	10K	brown, black, orange	1
R6,R7	1R2	brown, red, gold	2
R8	2K7	red, violet, red	1
RV1	10K log. pot		1
RV2	200R trim pot		1

Capacitors :

C1	10uF 25V	1
C2	47uF 25V	1
C3, C4	100uF 25V	2
C5	0.1 uF mono	1

Transistors :

Q1, Q3	BC 548B	2
Q2, Q4	BC 558B	2
Q5	BD 139	1
Q6	BD 140	1

Misc. :

Kit 48 PCB	1
Speaker, 3”, 8 ohm	1
5mm Green LED	1
5mm Red LED	1
9V battery snap	2
SPDT PCB switch	1
2 Pole Terminal blocks	3
Heat sinks HS103	2
Nut & bolt set	2

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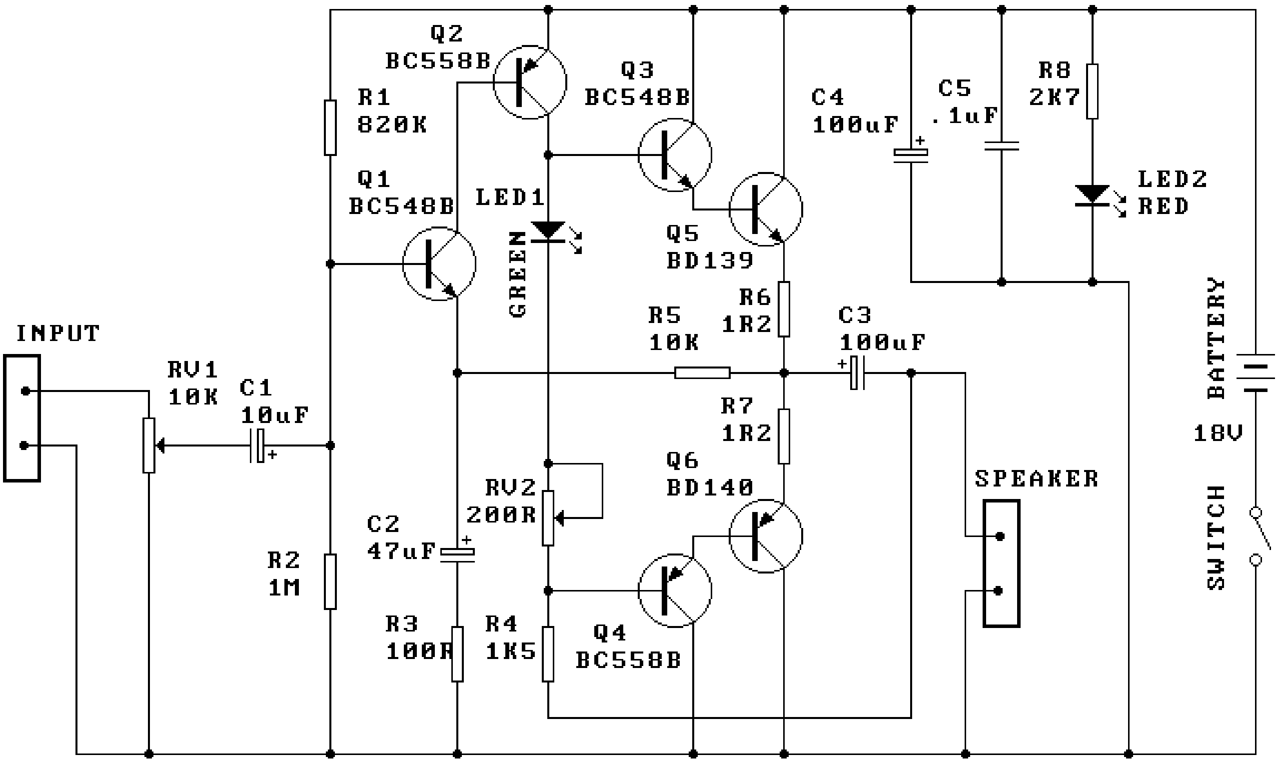
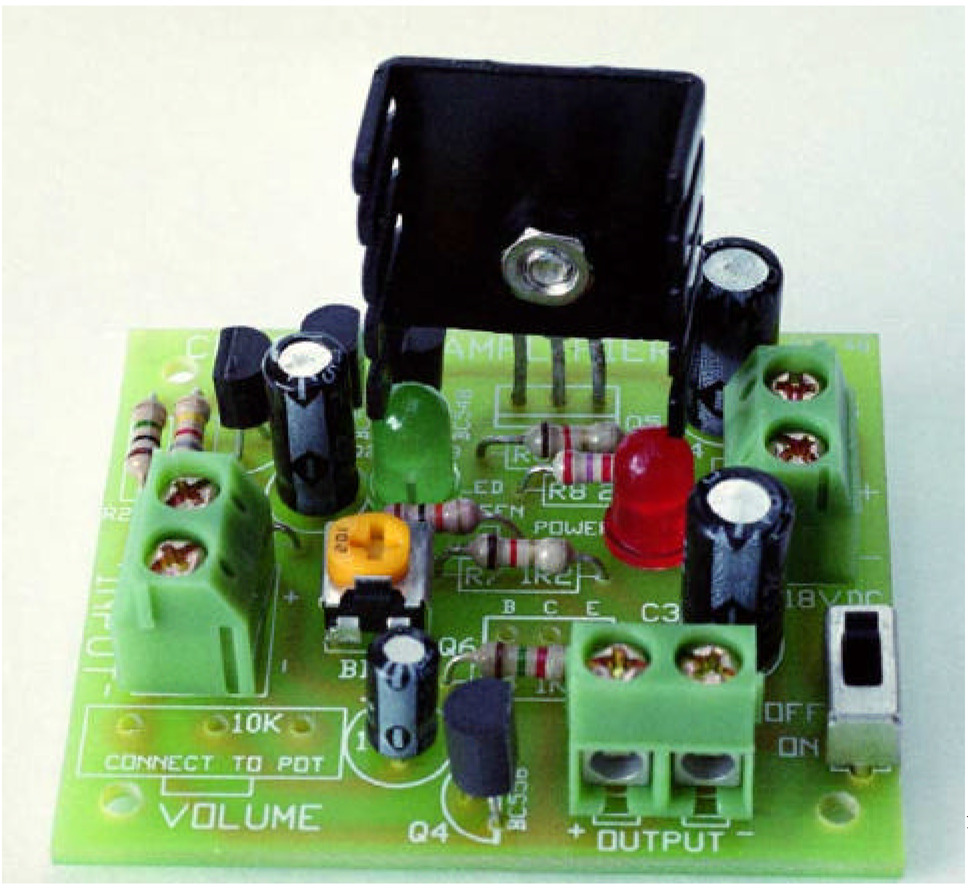
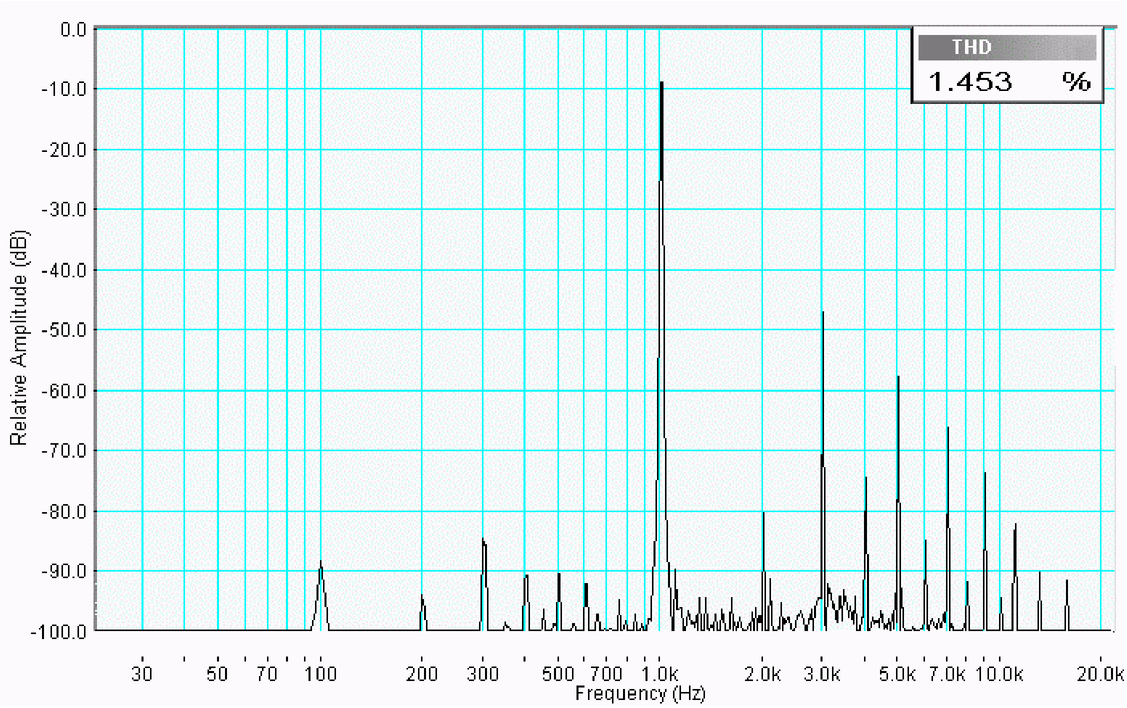


Circuit Diagram

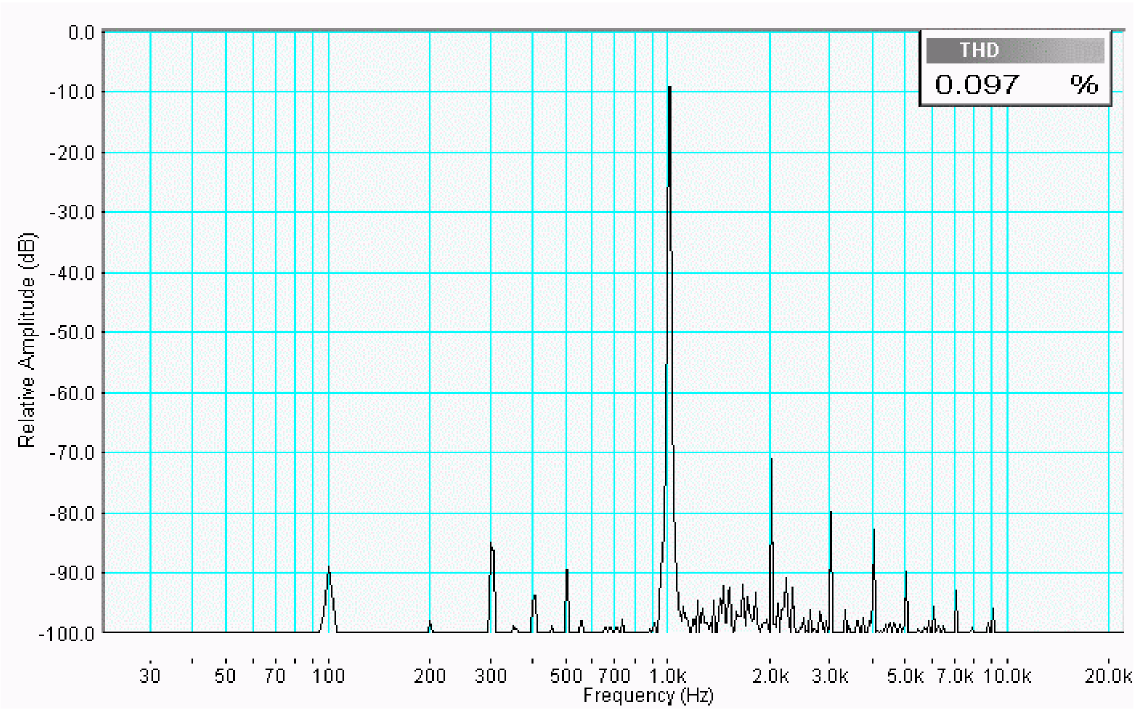
Photo of amplifier minus Q6 and RV1.



THD @ 1kHz, 30mW output, showing effect of
bias adjustment on distortion at low levels.



5 mA DC bias
(approx. 15 mA quiescent supply current)



20 mA DC bias
(approx. 30 mA quiescent supply current)