



Department of Electrical and Computer Engineering

AUDIO EQUALIZER

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Description

Students build a 3-channel audio equalizer, consisting of a low-pass filter, a high-pass filter, and a band-pass filter (more or fewer channels can be built if desired), Figure 1. They connect the equalizer to their mp3 player, phone, or laptop--any device having a standard audio jack, and play the filtered music through an amplifier and speaker, Figure 2. The amplifier can be provided or can also be constructed by students. The parts are reusable.

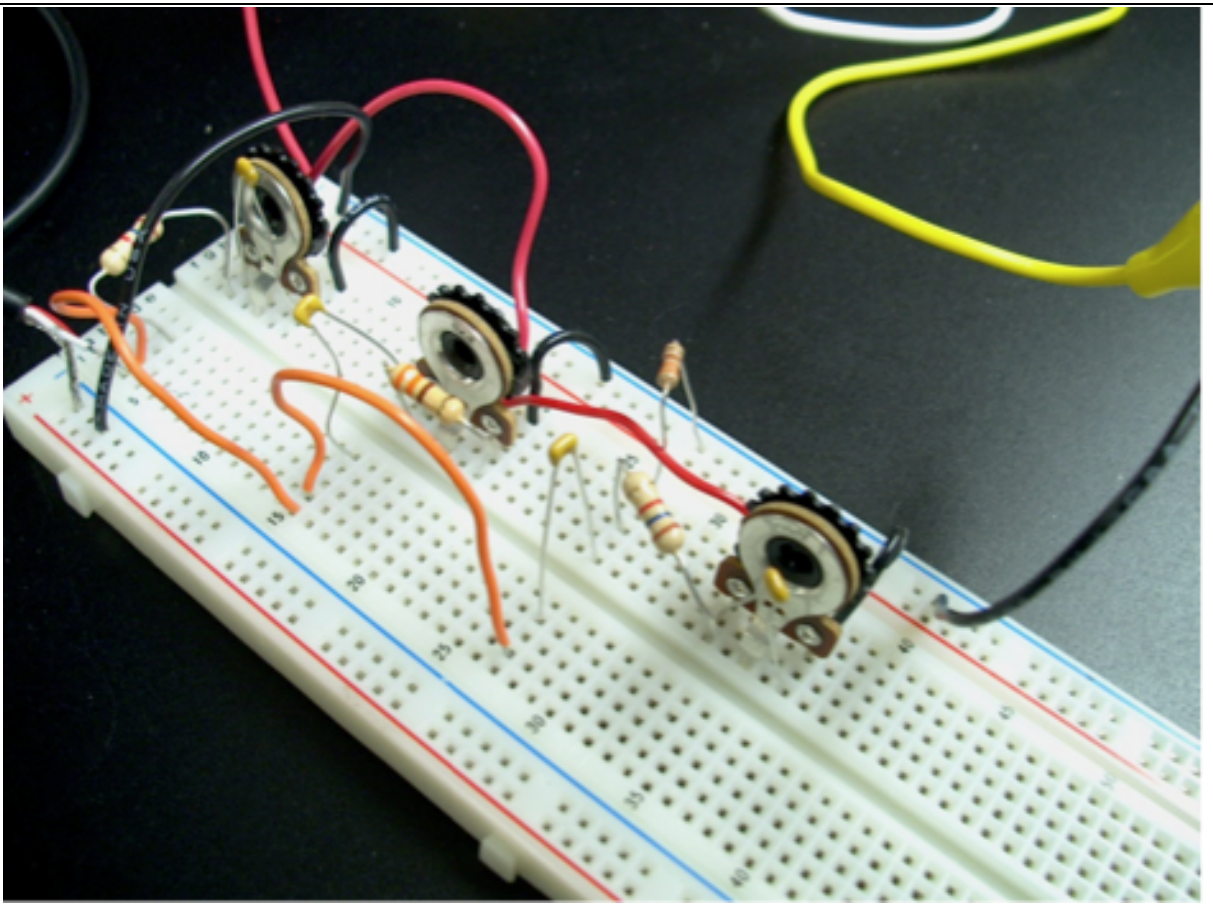


Figure 1. The 3-band equalizer circuit.

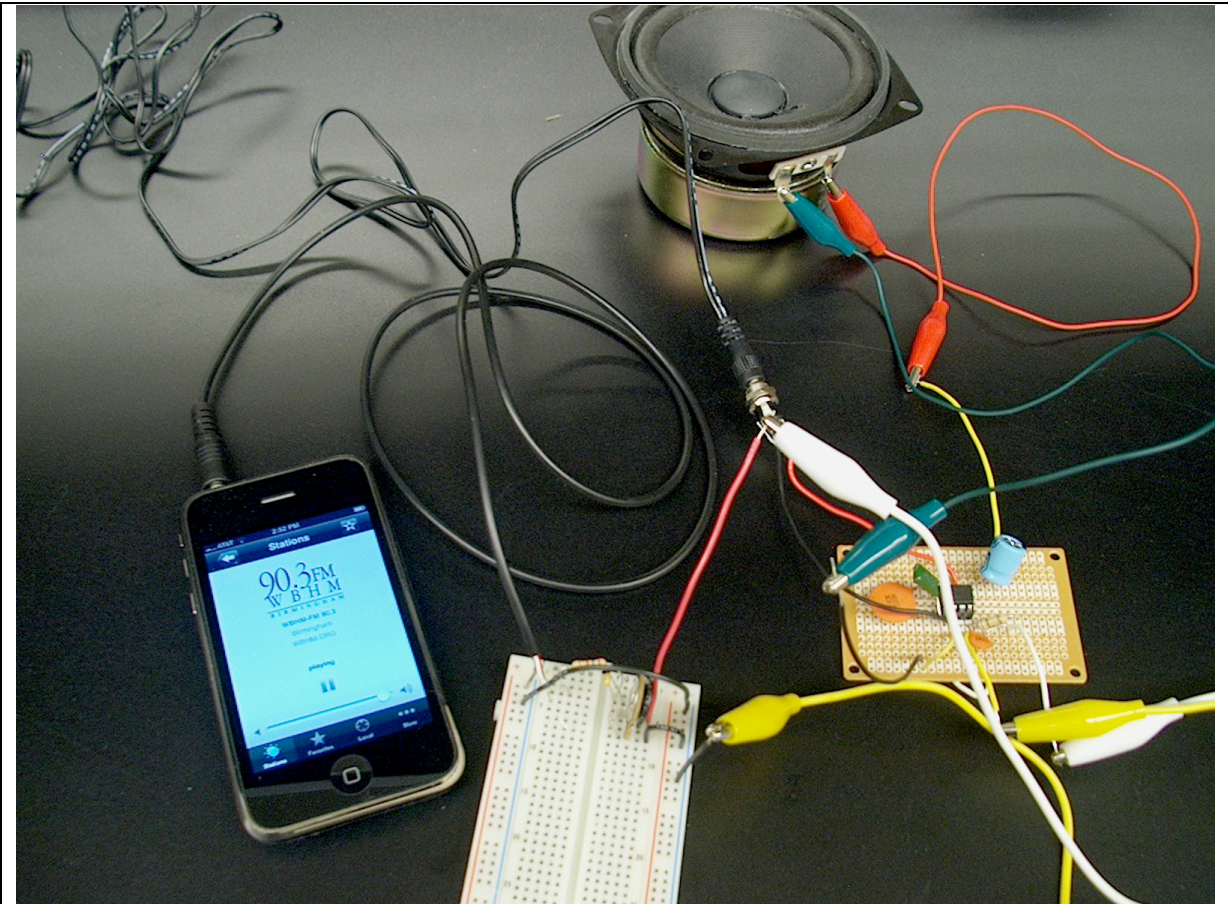


Figure 2. The filters (high-pass only shown here) is connected to a music source, and the output goes through an amplifier to a speaker. The amplifier can be built ahead of time or the students can build it with re-useable parts.

Audience

This discussion is aimed at an audience already familiar with sound waves, the concept of frequency, amplitude, and period. In the electrical section, the reader is assumed to recognize circuit symbols for resistors, capacitors, signal sources, and ground. The electrical operation of the circuits will be discussed in detail. An understanding of the circuit operation is not actually needed to build it, however.

Principle of operation

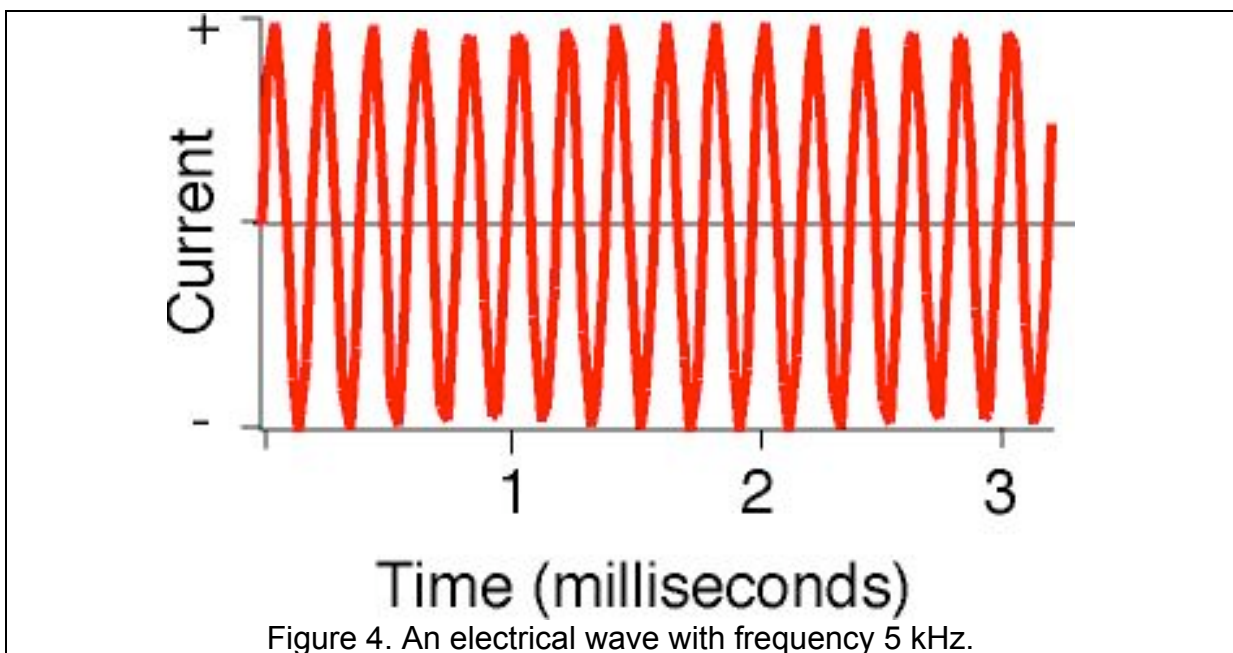
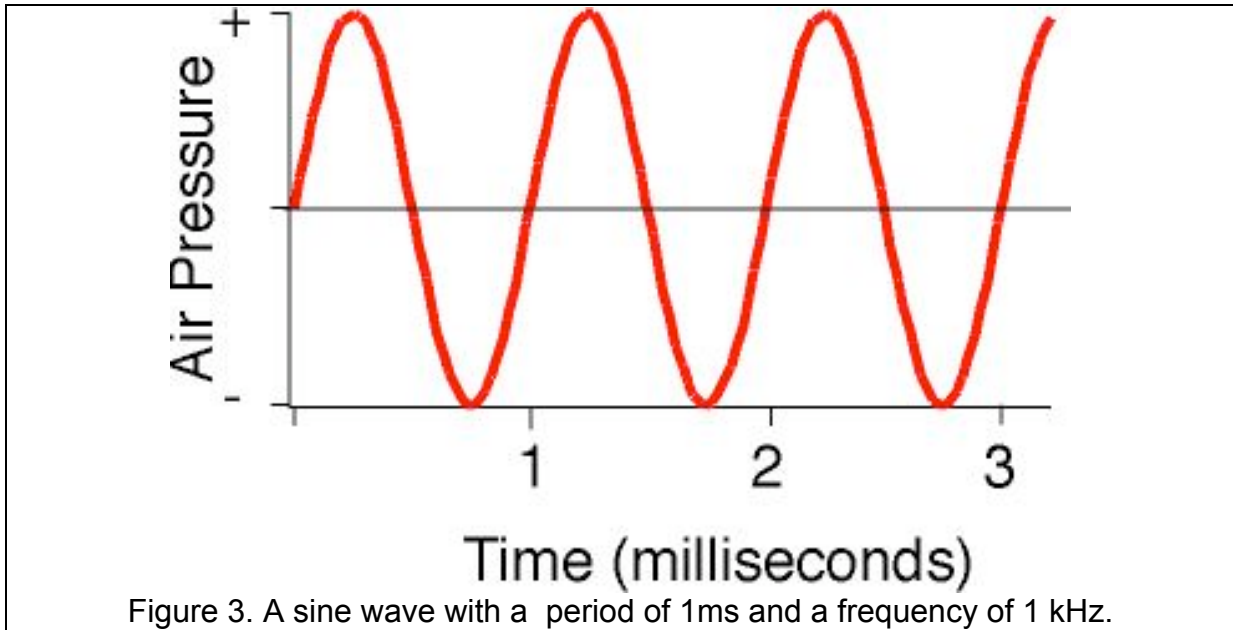
This section is in 3 parts. First, we discuss the frequency components of music and sound, and their relationships to the signal coming from an mp3 player. Second, we discuss the effects of a low-pass, high-pass, and band-pass filter on sound (and electrical signals). Third, we present the three simple filters' electrical schematics, and describe how they work. The actual building of the project is reserved for a later section.

Frequency components

All sound consists of compressional waves that travel in air, liquids, or solids. A microphone converts these compressional waves to an electrical signal, whose

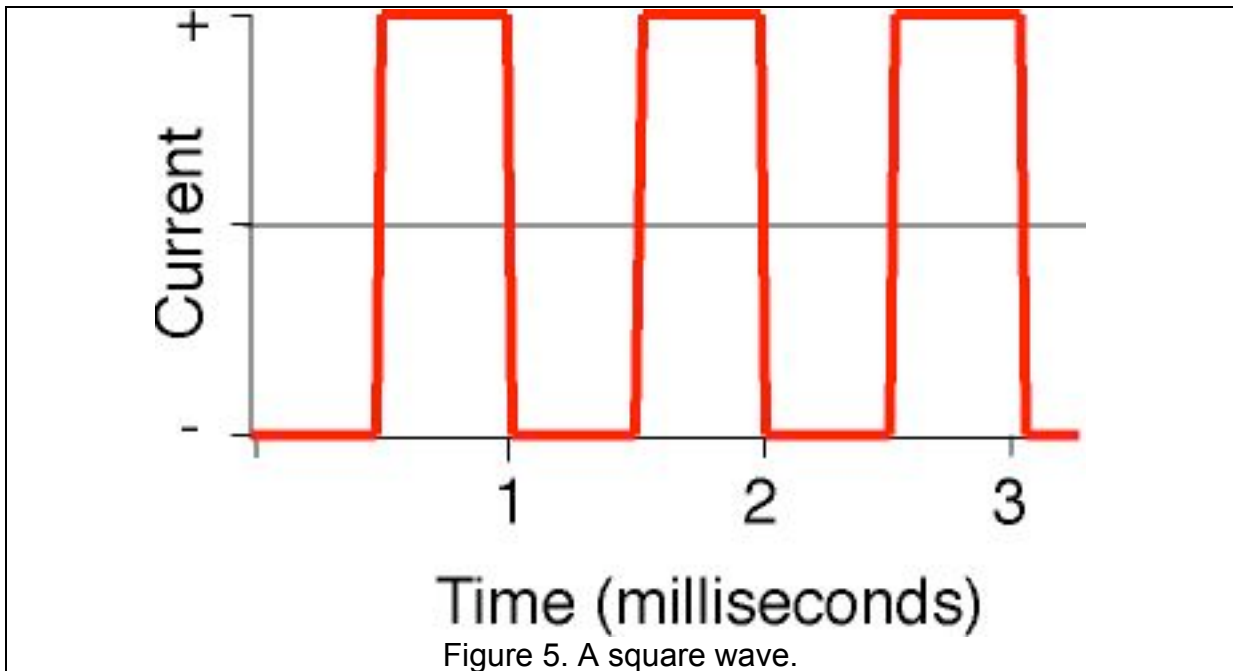
amplitude and frequency are proportional to the sound. Similarly, a speaker's cone vibrates proportionally to an input electrical signal and produces a compressional wave (sound). In our ears, compressional waves impinge on tiny hairs that move with the moving air, and nerves in our ear detect this motion and send signals to our brains.

The fundamental wave is a sinusoidal wave, whose amplitude is either a sine or a cosine (whichever you prefer), and that has a given frequency, Figure 3. Here the amplitude is air pressure, so the graph represents a sound wave. The period T is 1 ms, so the frequency $f=1/T=1$ kHz. Figure 4 shows an electrical wave, in which the vertical axis is current. This wave has a period of 0.2 ms and frequency of 5 kHz.



The frequency relates to pitch, with lower frequencies relating to lower pitches. The audible range for humans is about 20 Hz to 20 kHz (the upper end decreasing with age). The lowest note on a piano, A0, has a frequency of 27.5 Hz, and the highest note, C8, has a frequency of 4,186 Hz. Thus we cannot hear much lower pitches than a piano can play, but we hear a much higher range. Blue whales make and hear sounds down to 10 Hz, but some toothed whales use frequencies above our hearing range, for echolocation.

Figure 5 shows a square wave. It has a frequency of 1 kHz, also. If you played this through a speaker, the pitch would sound the same as the sine wave of the same frequency, but the quality of the sound (what musicians call “timbre”) is different.



The reason is as follows. We said earlier that a sine wave was a fundamental wave. It's called that because every other wave can be thought of as the sum of a bunch of different sine waves. For example, Figure 6 (top) shows three sine waves, of different frequencies (and different amplitudes). The bottom of the figure shows the sum of these. We notice that the sum is closer to a square wave, and in fact if we added up an infinite number of these frequencies, we would obtain exactly a square wave. The fundamental frequency (the lowest frequency, highest amplitude part) is what we primarily perceive, because its amplitude is largest, and that's what we perceive as the pitch. We do hear the higher frequencies, too, however, which is why this does not sound the same as a square wave. Other common waveforms are triangle waves and sawtooth waves, and each sounds different in timbre even when the fundamental frequency is the same. That's because it takes a different set of sine waves added to p make these different shapes.

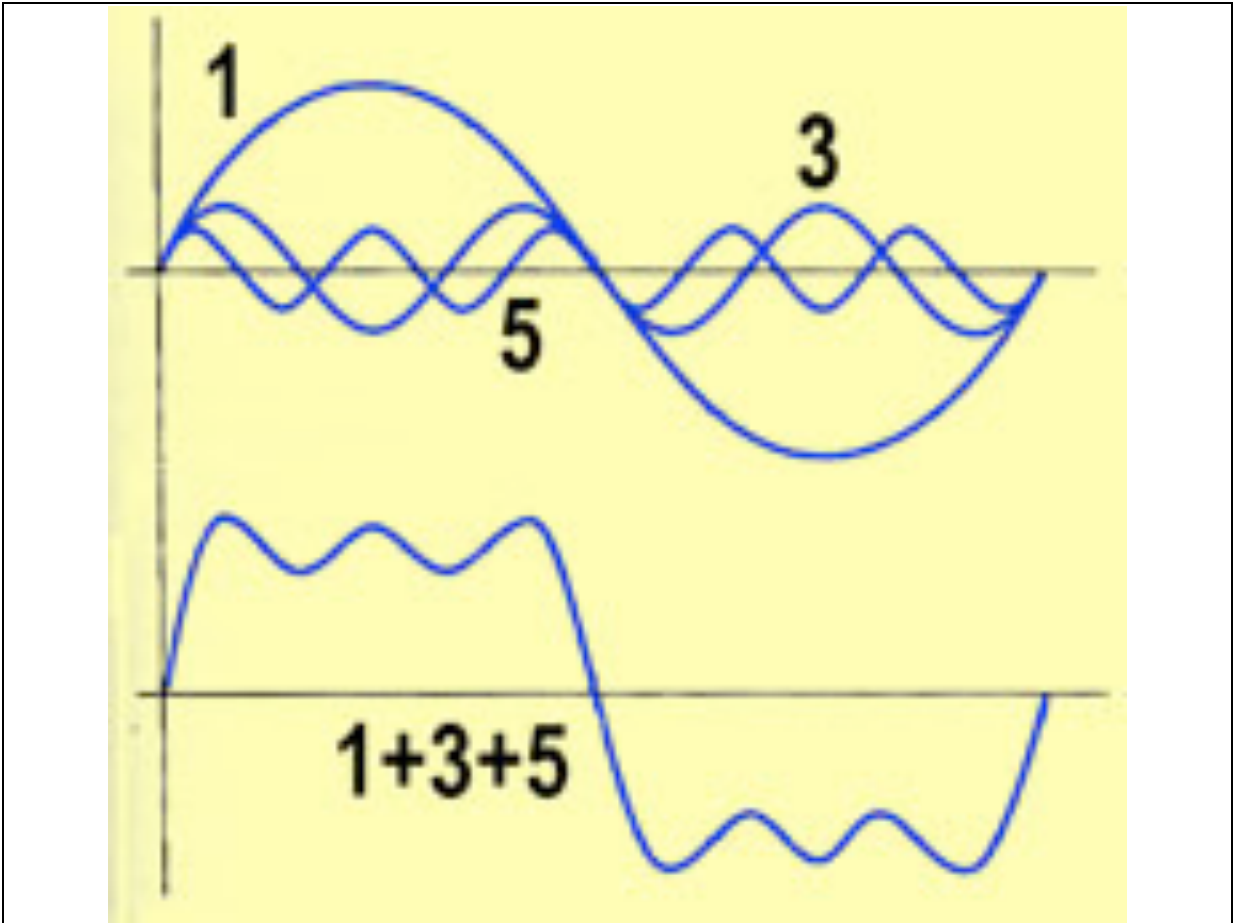


Figure 6. A square wave is an infinite sum of sine waves of different frequencies and amplitudes.

http://sirius.ucsc.edu/demoweb/images/waves/sound/fourier%20analysis_schem.jpg

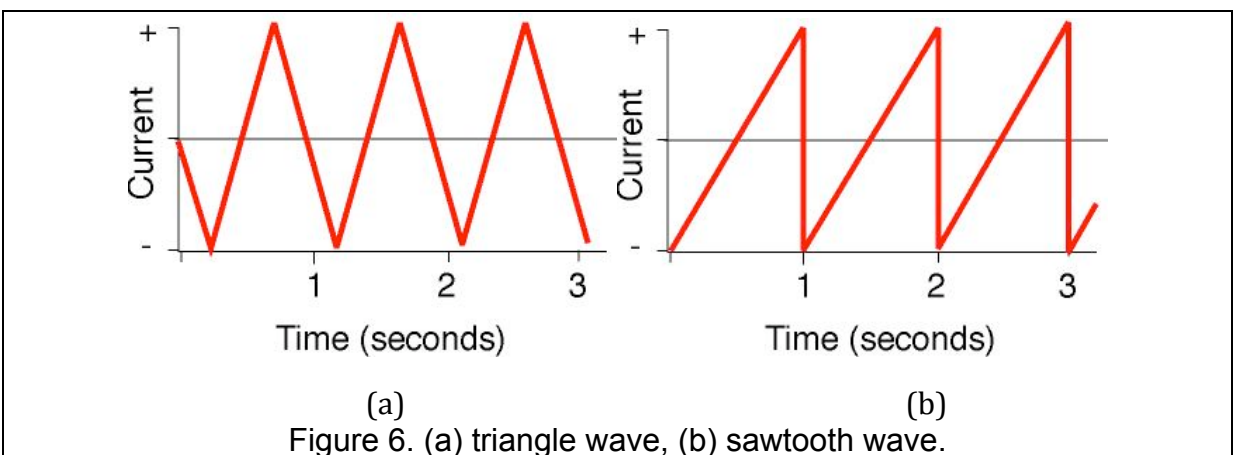
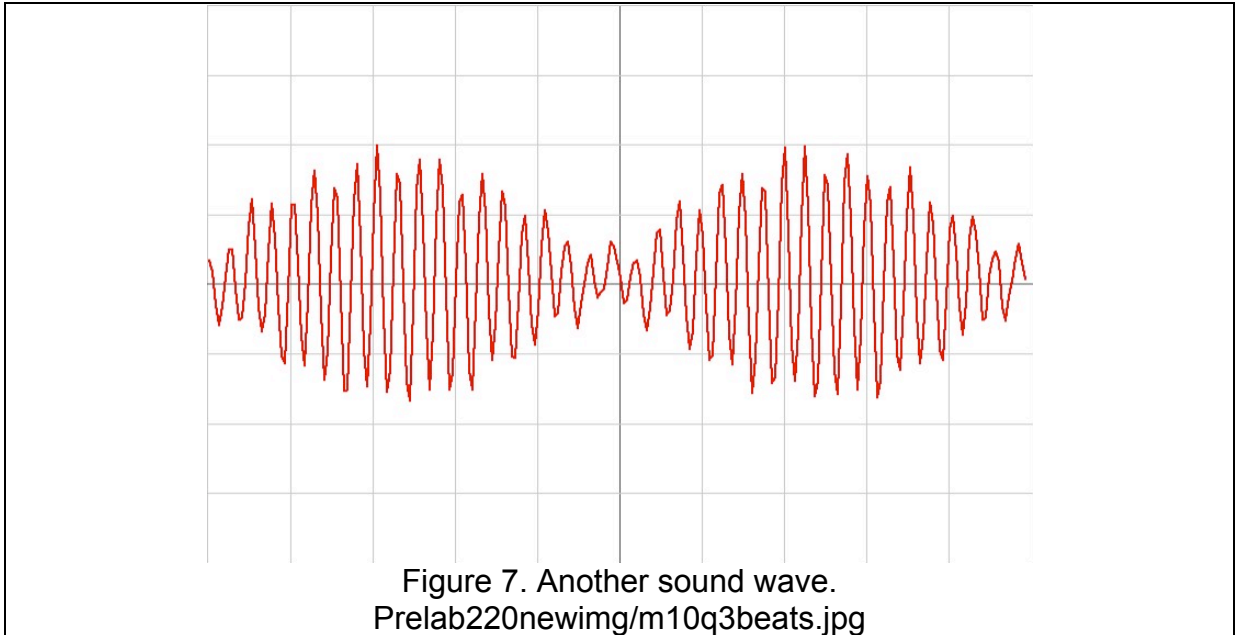


Figure 6. (a) triangle wave, (b) sawtooth wave.

Figure 7 shows the sonogram of another sound. In this case, the fundamental frequency (the one we perceive as pitch) may actually be the high frequency component, if the slowly varying envelope is below our frequency threshold. In this

case we might hear a single pitch that is throbbing in intensity. Or if both frequencies are in our hearing range, this might sound like a chord.

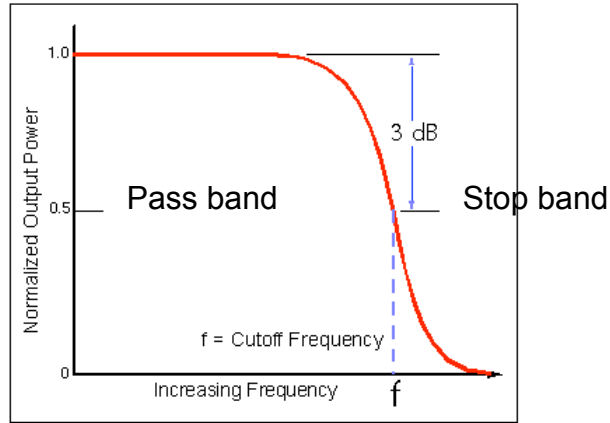


Electronic filters

We will discuss here three different simple electronic filters, the low-pass, high-pass, and band-pass.

Low-pass filter

Figure 8 shows the frequency response of a low-pass filter. Here transmission (fraction of signal passed) a function of frequency is plotted. This is called the “transfer function” of a circuit. Low frequencies are completely passed (fraction=1), but high frequencies are not passed. In the middle is a transition range. The transition may be slow or abrupt, depending on the filter design. Ideally the cutoff would be very sharp, but the sharper the curve the more electrical components are required to implement it.



low pass filter

Figure 8. The transfer function of a low-pass filter. After <http://www.its.bldrdoc.gov/projects/devglossary/images/lpfiltec.gif>

The “cutoff” frequency is usually defined as the point at which the throughput is reduced to half of the maximum. The transfer function has the value 0.5, or expressed in decibels is 3 dB. The decibel number of a power signal is given by

$$dB = 10 \log \left(\frac{Power\ out}{Power\ in} \right) \quad (1)$$

That is, the output is down 3 dB when the power out is half of the power in. The “pass band” is the range of frequencies that pass through the filter, and frequencies that not passed are in the “stop band.”

Figure 9 shows (bottom) a sound signal with many frequency components, and (top) the result when all frequencies except the fundamental are filtered out.

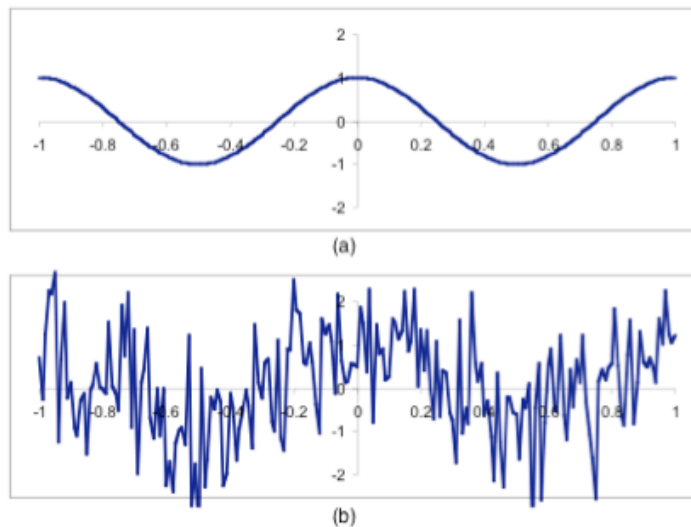
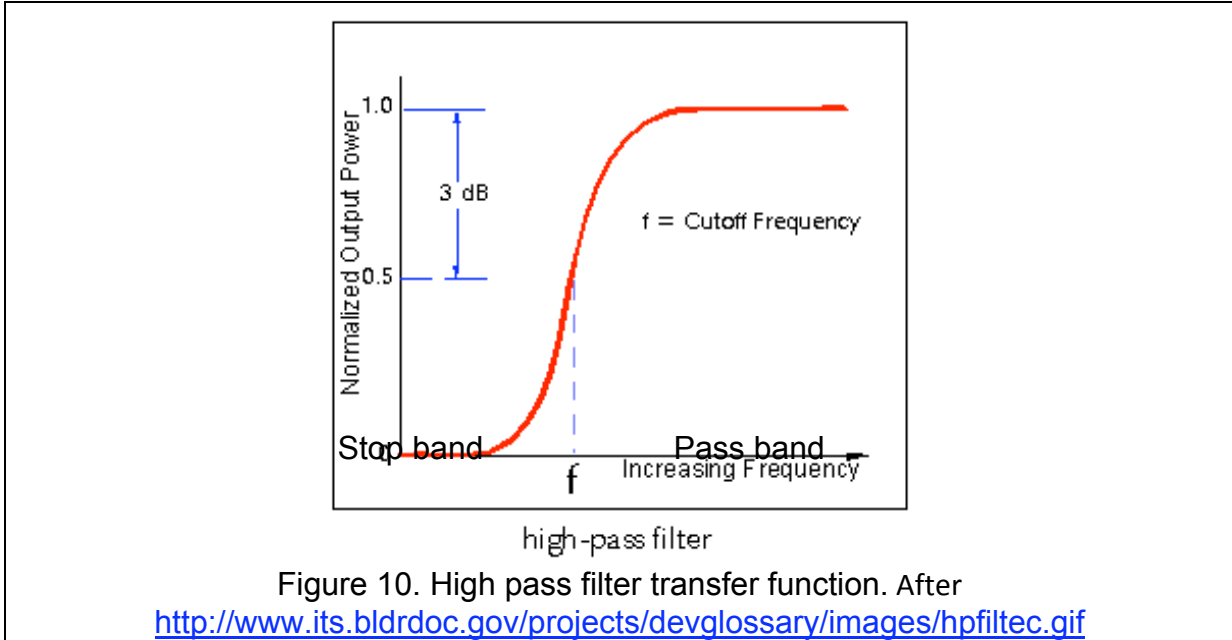


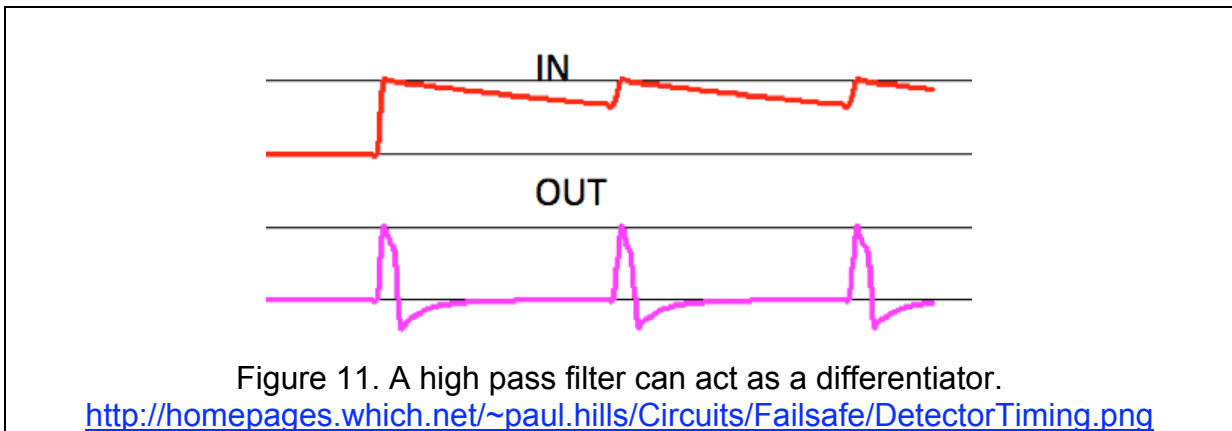
Figure 9. The effect of low pass filtering. Bottom: original wave. Top: filtered wave. <http://www.its.bldrdoc.gov/projects/devglossary/images/lpfiltec.gif>

High-pass filter

Figure 10 shows the transfer function of a high-pass filter. Now the low frequencies are in the stop band, high frequencies are in the pass band, and there is still a cutoff frequency.

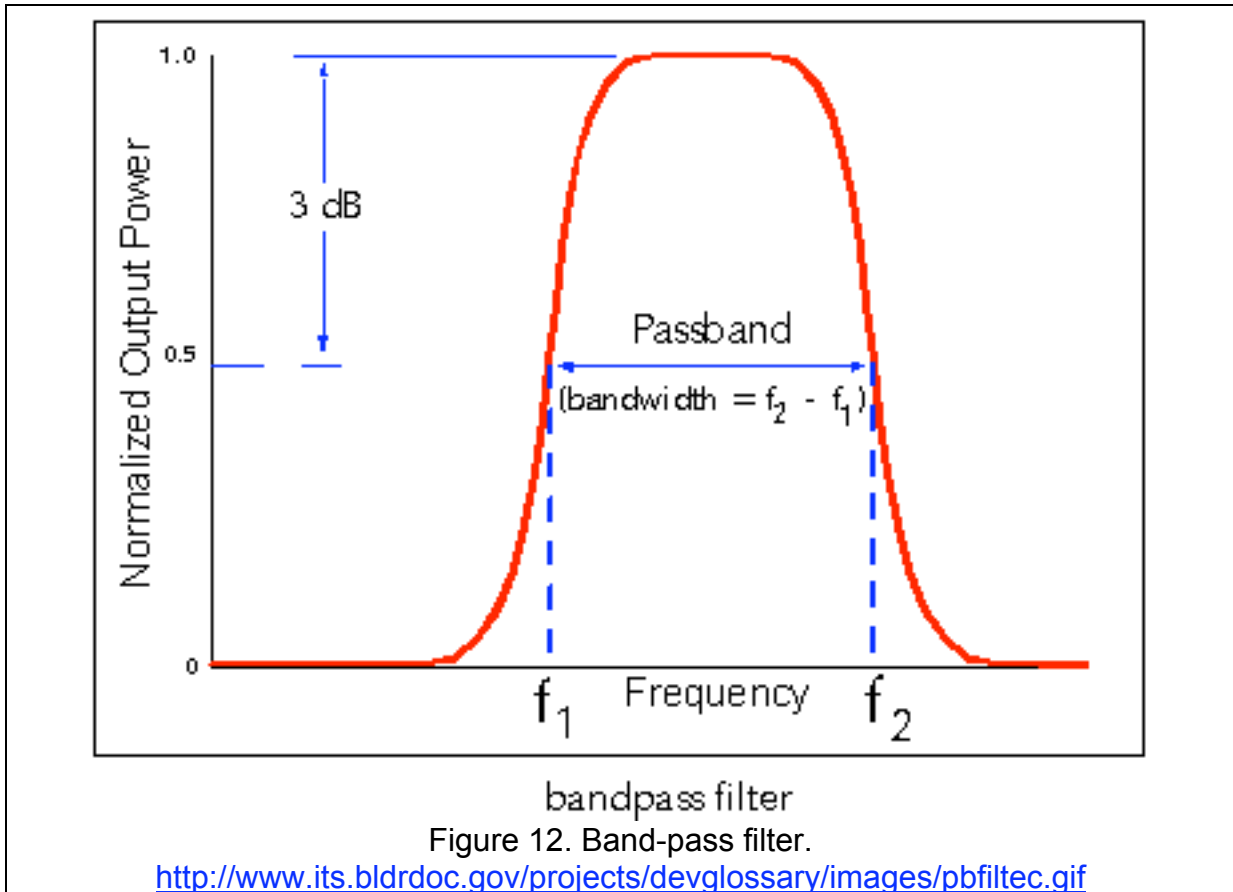


Another way to think of the effect of a high-pass filter is that only parts that are changing rapidly can get through. Consider Figure 12. On the top is an unfiltered signal. On the bottom is the high-pass-filtered result. In fact, this filter is behaving much like (not exactly like) a differentiator. The first part of the signal has zero slope, and the output of the filter is zero. When the slope increases suddenly, the output likewise goes to a high positive value. When the signal degrades slowly, that is where it has a small, negative slope, the filter output goes to a small negative value. The analogy breaks down because this is an imperfect circuit, but we leave the reader with the thought that certainly circuits related to our low-pass and high-pass filters are used as integrators and differentiators for analog computing and other uses.



Band-pass filters

Finally, a bandpass filter's transfer function is shown in Figure 12. This can be thought of as a low-pass filter combined with a high-pass filter. In the next section we will introduce the circuits for each of the three filters we have discussed.





Electrical filter schematics

In this section we discuss the three filter circuits and their operation. They are all RC (resistor-capacitor) circuits. A resistor responds identically at all frequencies (ideally). They are typically made of carbon mixed with an insulating ceramic, where the ratio of the two materials determines the resistance. The resistor symbol, Table 1, is meant to suggest a path that is difficult to get through (compared to a conductor).

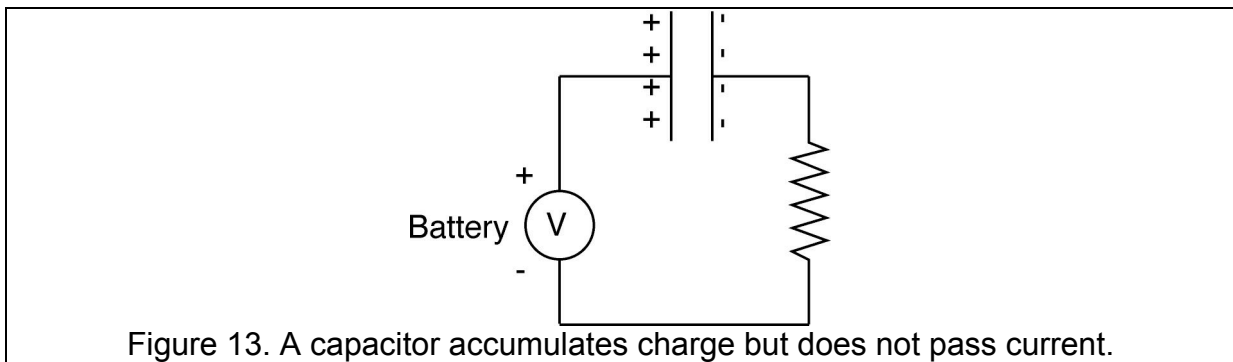
A capacitor is made from two parallel conducting plates, with an insulating material between them, a structure that is suggested by its symbol.

Table 1. Some circuit elements, their symbols, and what they look like.

Resistor		
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Capacitor		
Inductor		
Ground		

Clearly no current can pass through a capacitor because of the insulating layer. When a voltage is applied, positive charges accumulate on one plate, and negative charges accumulate on the other, Figure 13. If left alone, the charge would accumulate until the voltage across the capacitor equaled the voltage across the source. *While* the charge is accumulating, the charges are flowing out of the battery. Once the steady-state is reached, no current is flowing. Notice the time-sensitive words “while” and “steady.” When things are steady (DC), no current flows through a capacitor. While the capacitor is charging up, no current is flowing through the capacitor, either, but current is flowing through the circuit, so from the circuit’s point of view, a time-changing current is flowing.



Thus, *a capacitor blocks DC and passes AC*. This is simplistic, of course. The rate at which the capacitor charges is related to how fast the frequencies are that it will pass or block. The *RC time constant* is given by

$$\tau = RC \quad (2)$$

where R is the resistance and C is the capacitance.

The other symbol in Table 1 is the symbol for ground. In a house or building, the ground is literally connected to the ground, usually by connecting to a cold water pipe that actually goes into the earth. This is for safety- if any electrons get unruly in a house

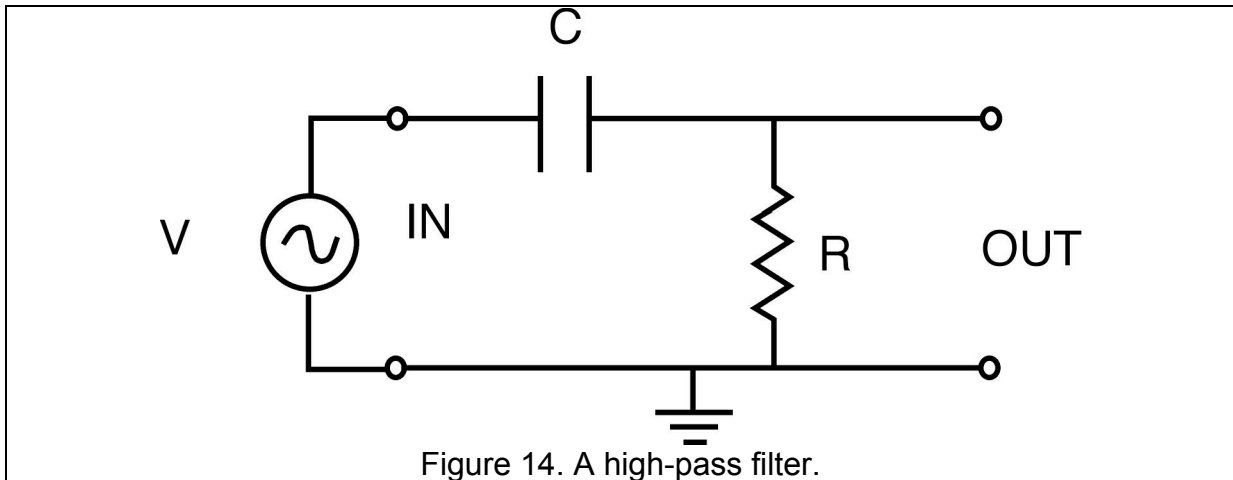
¹ www.suntan.com.hk

² <http://www.powerlabs.org/railguncurrent.htm>

circuit they can be shunted to ground without hurting anybody. Our circuit is portable, and doesn't generate dangerous currents, so for us the term "ground" really means "common." Any point in a circuit diagram connected to the ground symbol is understood to be physically connected to all other points with the ground symbol, even if the connection is not explicitly shown.

High-pass filter

The circuit of Figure 14 is a high-pass circuit, if we consider the voltage source to be a time-varying signal input and take the output across the resistor, Figure 15. The small circles indicate "terminals" where the input and output are connected. For example the input might be an mp3 player and the output might be connected to a speaker or an amplifier. The symbol at the bottom of the circuit is the "ground" symbol. In this circuit, low frequencies cannot pass through the capacitor, so they are blocked. Only high frequencies make it to the output. High frequency currents do flow through the resistor, and since current (I) times resistance (R) equals voltage (V), a high-frequency voltage appears at the output.



The frequency response of this circuit looks something like Figure 10 presented earlier, and the cutoff frequency is given by

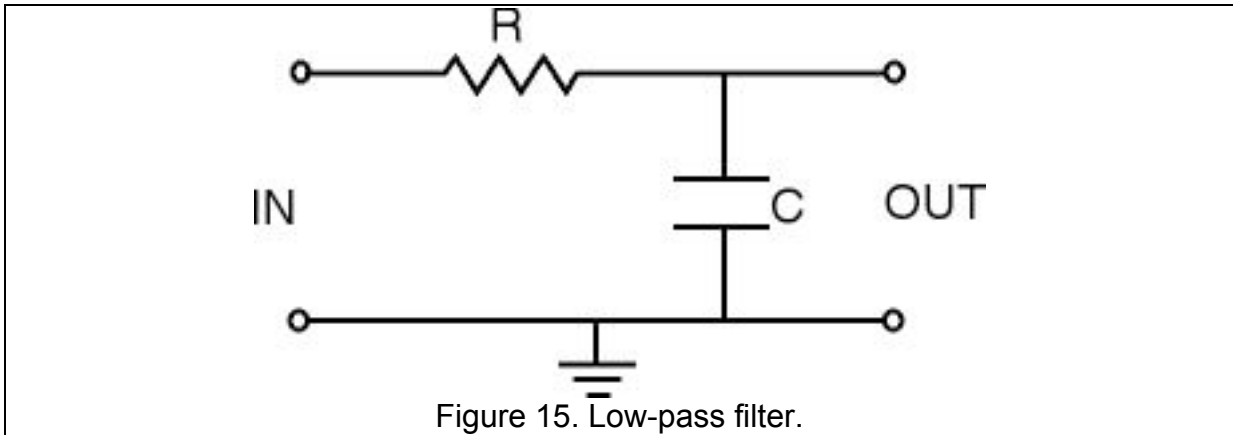
$$f = \frac{1}{2\pi RC} \quad (3)$$

For example, in the circuit we will build, $R=680 \Omega$, $C=0.2 \mu\text{F}$, and $f=2.5 \text{ kHz}$. Thus this circuit will generally pass frequencies above 2.5 kHz. Note the frequencies *near* 2.5 kHz are "sort of" passed.

Low-pass filter

Figure 15 shows the schematic for a low-pass filter. It looks the same as the high-pass filter, except the resistor and capacitor are swapped. In this case, all frequencies make it past the resistor. The low frequency currents cannot flow through the capacitor; they have no choice but to flow to the output (when one is connected). High

frequencies, on the other hand, pass very easily through the capacitor, and go directly to ground. They don't make it to the output, so this is a low-pass filter.



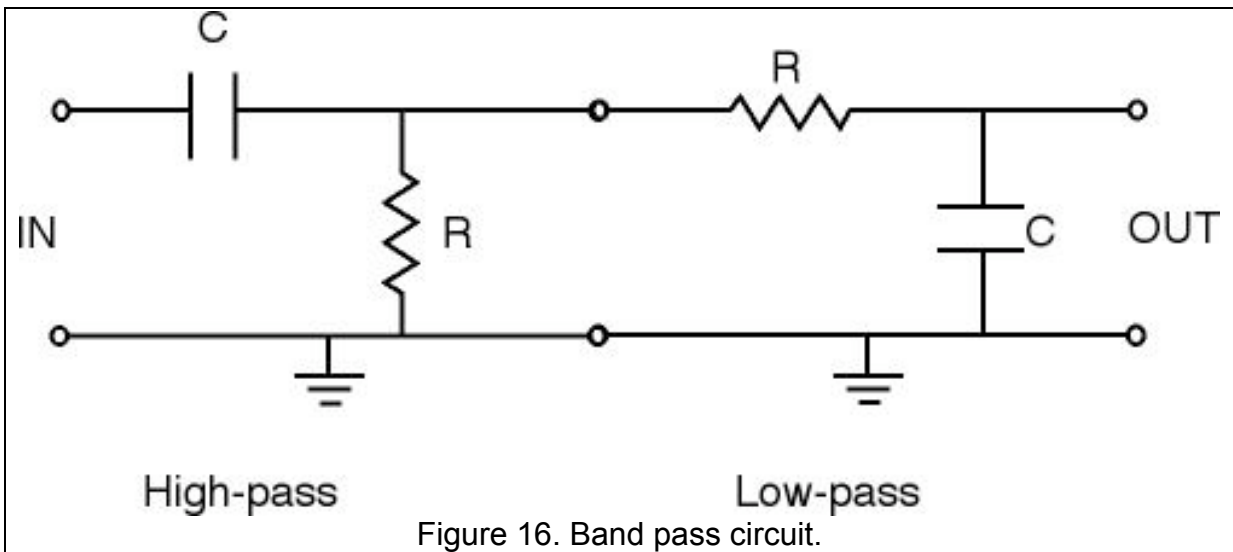
The cutoff frequency is still given by

$$f = \frac{1}{2\pi RC} \quad (4)$$

except that in this case frequencies below the cutoff are passed. In our circuit, we will use $R=1.6 \text{ k}\Omega$, $C=0.1 \text{ }\mu\text{F}$, and thus $f=1 \text{ kHz}$.

Band-pass filter

The bandpass filter is just a high-pass filter followed by a low-pass filter, Figure 16. If we use the same component values as above, this circuit will pass frequencies between 1 kHz and 2.5 kHz. Frequencies near those limits are partially passed.



Combining the filters into an equalizer

Currently we have seen how to build individual filters. Now we will show how to combine them into single circuit to make an equalizer. First, we will add a volume

control to each filter to allow the student to control the power in each frequency band. Then we will add an amplifier that also acts as a current summer.

Figure 17 shows the low pass filter with a potentiometer (variable resistor) added. The potentiometer has three leads. The two ends have a resistor between them. The center lead is a moveable wiper that makes physical contact with the resistive material. If the wiper is at the top, there is no resistance between the top terminal and the wiper, and the entire resistance between the wiper and the bottom terminal. As the wiper moves (through a knob, thumbwheel, slider, or other mechanism) the resistance seen by the output varies. Recalling again that the voltage is proportional to the resistance ($V=IR$), we see that the level of the output voltage changes as we adjust the knob. Thus the potentiometer acts as a volume control.

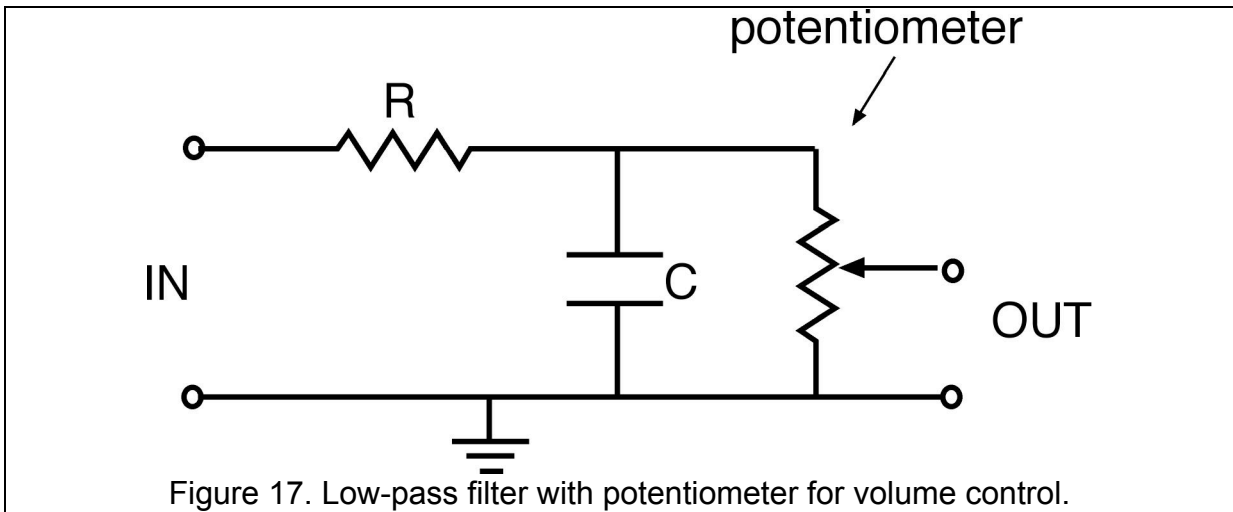


Figure 18 shows all three filters combined in parallel into a single circuit. Each has its own volume control. Notice that the input is connected to each of the three filters, the ground lines are all connected together, and the outputs are all connected together. The solid black circle indicate connections. The semi-circles in the ground leads indicate that these wires do not make connection with the wipers.

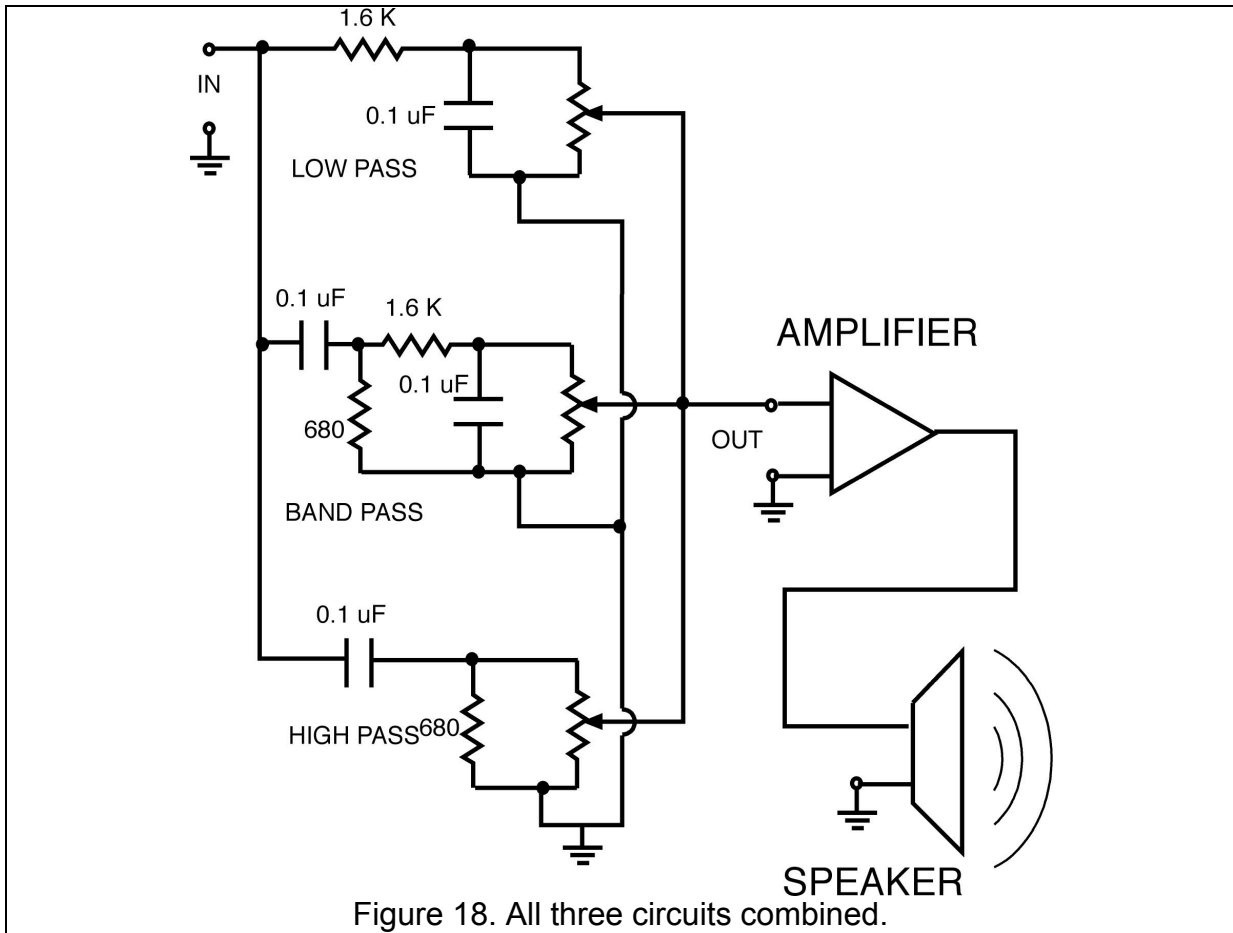


Figure 18. All three circuits combined.

Also shown is the amplifier, indicated as a triangular block, without going in to the details (the details are in Appendix A). The amplifier is needed because the average mp3 player doesn't have enough power to drive a big speaker. It also acts as a current summer, summing the currents from the three filter circuits. Notice that the amplifier and speaker each have two terminals- one is connected to ground, the same electrical point as the filter grounds and input ground.

Building the circuit

This section discusses the details of how to build the circuit. We assume that the students will build the filters, and that the amplifiers will be pre-built and supplied. It is also possible to have the students build the amplifiers as well. The instructions for the amplifier are in Appendix A.

Materials:

For each circuit you will need: (prices circa March 2009)

#	Unit	Description	Vendor	PN	Unit Cost
1	Ea	Solderless breadboard	Digikey	438-1045-	\$8.73

				ND	
3	Ea	Potentiometer (100 K Ω vertical mount trimmer)	Circuit Specialists	32QV501	\$0.59
4	Ea	Capacitor, ceramic, 0.1 μ F	Digikey	P4910-ND	\$0.56
2	ea	Resistor, carbon film, 680 Ω , ¼ Watt	Digikey	680QBK- ND	\$0.064
2	Ea	Resistor, carbon film, 1.6K Ω	Digikey	1.6KQBK- ND	\$0.064
		Jumper wire*	Radio Shack	276-173*	\$6.49
1	Ea	Amplifier circuit and power supply	See Appendix A		
1	Each	Mp3 player or equiv			
0.5**	Each	Audio cable	Digikey	AE9918-ND	\$3.76
1 ***	Ea	Speaker	Digikey	GF0876- ND	\$5.53
4	Each	Alligator-alligator clip leads	Digikey	GC396-ND (pkg of 10 leads)	\$6.44

* This is a kit with assorted jumper wires. If you will be doing much breadboard work, it's cheaper to buy spools of jumper wire, e.g. Digikey C2004B-100-ND, black, 100-foot spool, \$16.24; red: Digikey C2004R-100-ND. Make sure the wire is solid, not stranded, and 22 AWG (that's the wire gauge). Jumper wires can be cut and stripped ahead of time for a group.

** Each cable as purchased can be cut in half, creating two usable cables.

*** For larger groups it is possible for people to share speakers in the interest of cost. In this case, one set of 4 alligator leads is needed for each *speaker*.

You will also will need: If buying spooled wire, you'll need wire strippers, wire cutters.

And once only: Wire cutters, wire strippers, and soldering iron to tin leads of audio cable .

First time: Preparing the audio cable

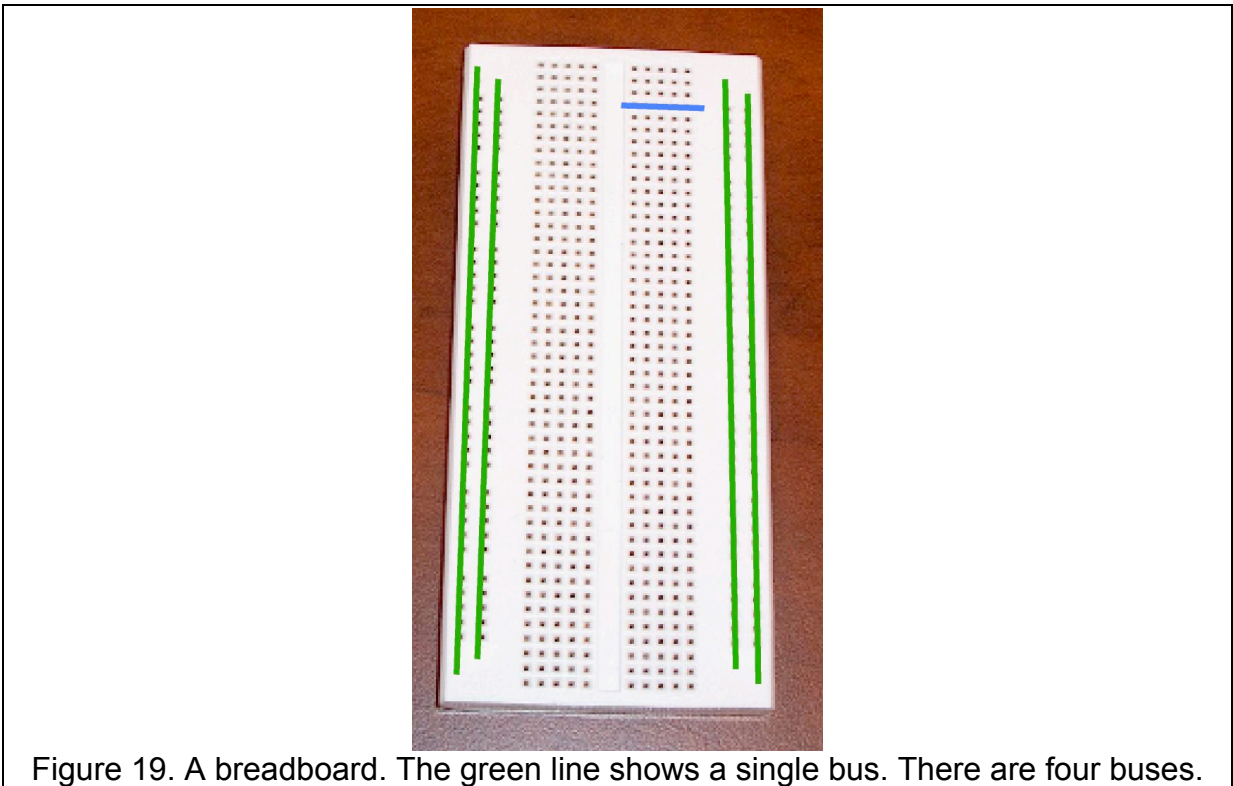
Using wire cutters, cut the audio cable in half. Remove the cable jacket for an inch or two to expose the wires. There will be three wired inside, one that's not insulated and two that are. For the bare wire, twist the strands together. Heat a soldering iron, and apply just enough solder to keep the wires from untwisting. This is called "tinning" the lead. If you apply too much and make the wire too fat to insert into the breadboard, reheat.

Strip one of the insulated wires back a quarter inch or so and tin the end. It doesn't matter which wire. These wires are so fine you may want to fold the end back on itself to double the thickness.

Construction of the Audio Equalizer

Breadboard

The breadboard, Figure 19, consists of four long columns of holes (two along each long edge) and many pairs of rows. The holes in each column are connected together, such that a wire inserted in any hole in a column will be electrically connected to any wire connected to any hole *in the same column*. Each column is called a "bus." Each row of five holes is also connected (blue line in the figure). The rows are *not* connected across the trough down the middle of the board.



Low-pass circuit

We'll start with the low-pass circuit, Figure 20. The green lines on the schematic show which connections we'll make.

- We'll use a bus for ground, so insert the uninsulated wire from the audio cable into one of the buses, as shown in the figure.
- Take the insulated wire that is partially exposed, and insert it into any convenient row. (The third wire won't be used. If it is also exposed, make sure it doesn't touch any other wires.) The wire you're using will be called the input.

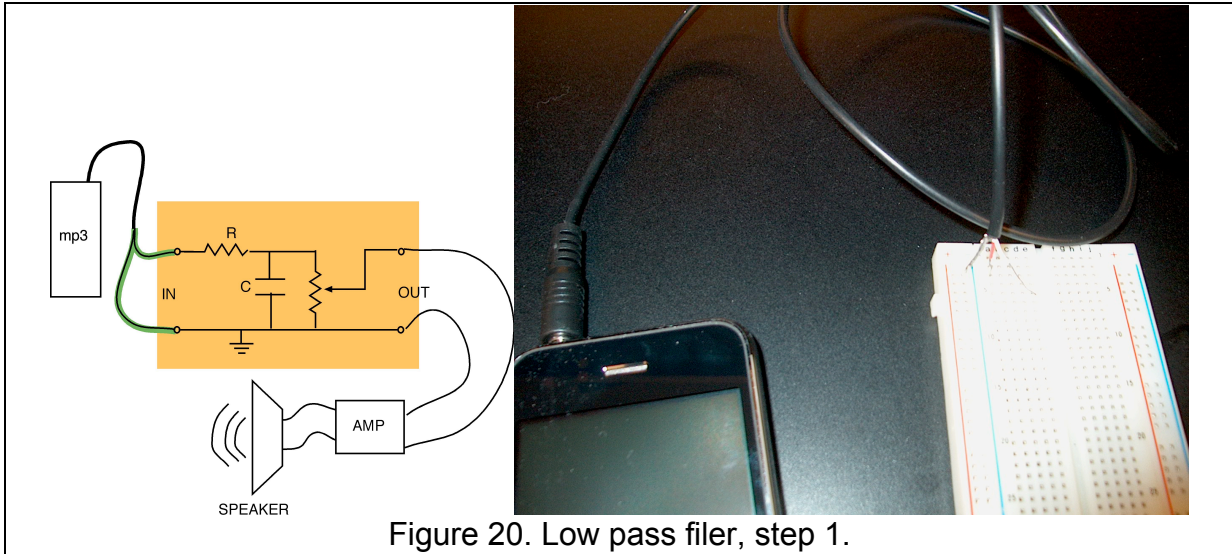


Figure 20. Low pass filter, step 1.

- Next, find the resistor labeled “R,” which we’ll assume here to be the 1.6K Ω resistor. The color stripes from the end of the resistor in go: brown, blue, red. If there is a fourth stripe, ignore it. If you are changing the component values to vary the frequency ranges, Appendix B shows how to read resistor and capacitor codes.
We see from the schematic that one end of the resistor is connected to the input, so insert one lead (either one) of the resistor into the *same* row of five holes that has the wire from the audio cable, Figure 21. That is the input.
- Insert the other end of the resistor into a *different* row of five holes. It will be convenient if it is on the other side of the central trough. The rows are not connected across the center trough. One the schematic, we show the previous connections in blue and the new ones in green.

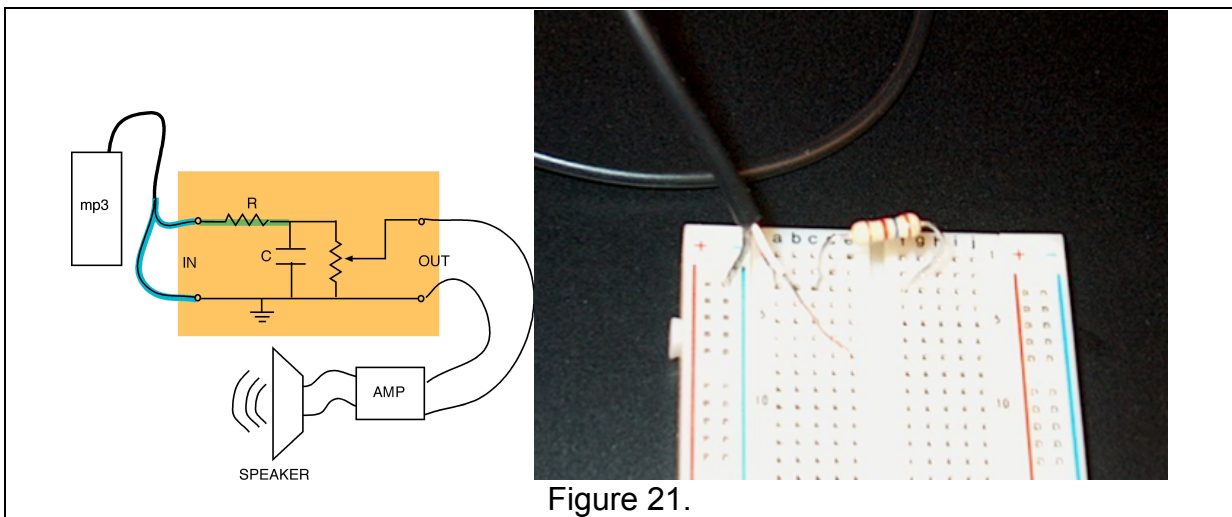


Figure 21.

- Next, we’ll install the potentiometer, the capacitor, and make an output lead. Referring to the schematic, we see that one of the end leads of the

potentiometer is connected to the resistor. Thus we should insert the potentiometer with one lead in that row, and the other two leads in two different rows, Figure 22.

- We next connect the capacitor. It goes from one end of the potentiometer to the other. Insert it such that its leads are in the same rows as the two outer potentiometer leads. Note that in one of the rows, there are now three leads: the resistor, the capacitor, and the pot. From the schematic we see these three things are connected to a common point.

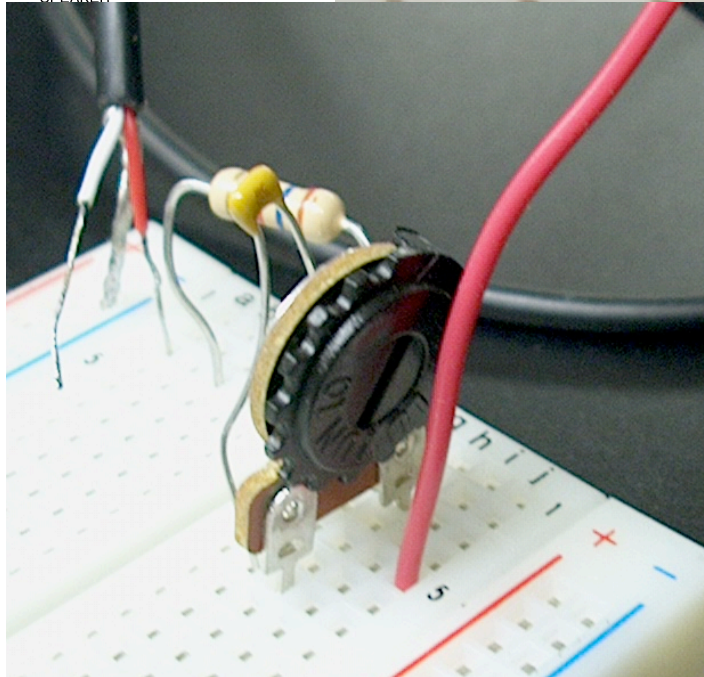
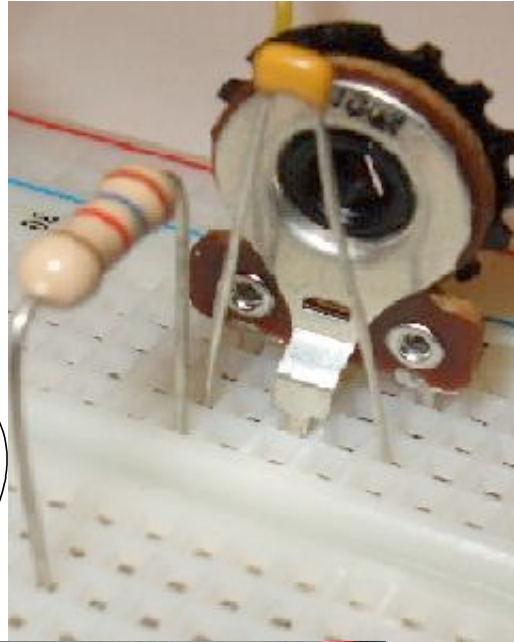
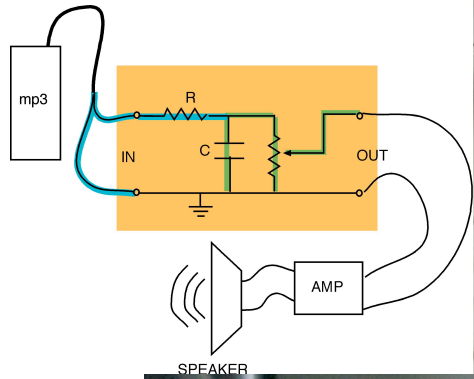


Figure 22. Upper photo courtesy A. Bowser, M. Frankart, T. Lee, P.Lundstrom, and B Reed, Ohio State University 2008.

- Finally, we'll create an output lead to connect up to later. Take a piece of hookup wire and insert one end into the row containing the center pin of the pot (the wiper). We'll connect up to the other end of this wire later.
- Before going on, check your circuit against the schematic and verify that you have made the connections highlighted in blue and green so far.
- The last thing to connect is the grounds. We have a ground bus on the left side of the circuit board, but we need to connect from ground to the output, too, so it would be handy to have another ground bus. So, using a piece of black hookup wire, connect the original ground bus to another bus on the other side, Figure 23.
- We also have to connect the bottom end of the pot and capacitor to ground, so a second jumper wire is used. One end goes in the same row that already contains the pot and cap, and the other end goes in the ground bus.

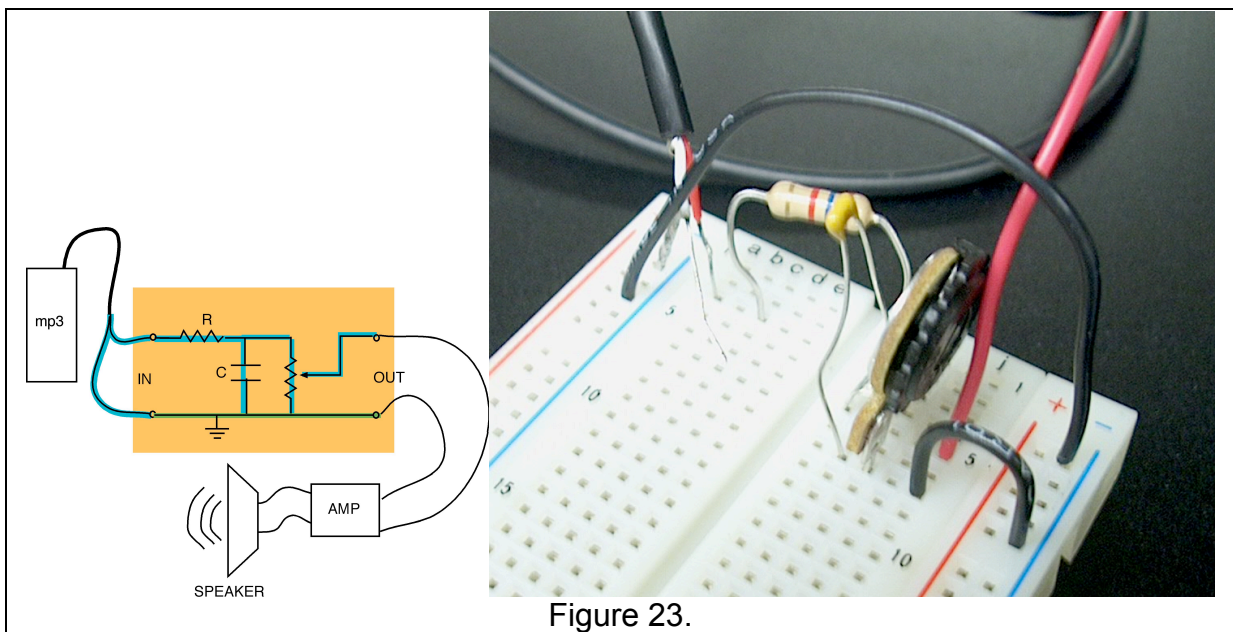


Figure 23.

- Finally, make a second output lead from a piece of hookup wire, with one end in the ground bus, Figure 24.

We may as well try out our circuit and see if it works!

- The amplifier has two input leads and two output leads. Using an alligator lead (so called because of its teeth- squeeze the alligator's head and the jaws open), connect on alligator clip to the output wire and the other end to one of the amplifier inputs (it doesn't matter which one). With a second alligator lead, connect the grounded output lead of you filter to the other amplifier input.
- Using the remaining alligator leads, connect each of the amplifier outputs to a speaker input.

- MAKE SURE NO WIRES ARE TOUCHING EACH OTHER.
- Plug in the transformer to the power input jack for the amplifier, and plug the wall wart into an outlet.
- Start your mp3 player. If you don't hear music, try turning the dial on the pot. If it's all the way to zero, you won't hear anything. If it still doesn't work, check all your connections, and make sure they're solid. The problem is usually a wire is not firmly connected somewhere.

Once it's working, move the filter output lead (red in Figure 24) back to the row with the input, so that the signal goes directly from the mp3 player to the amplifier. You should hear all the frequencies. When you put the filter back in, by moving the red wire back to the wiper, you should hear the lower frequencies much better than the higher ones.

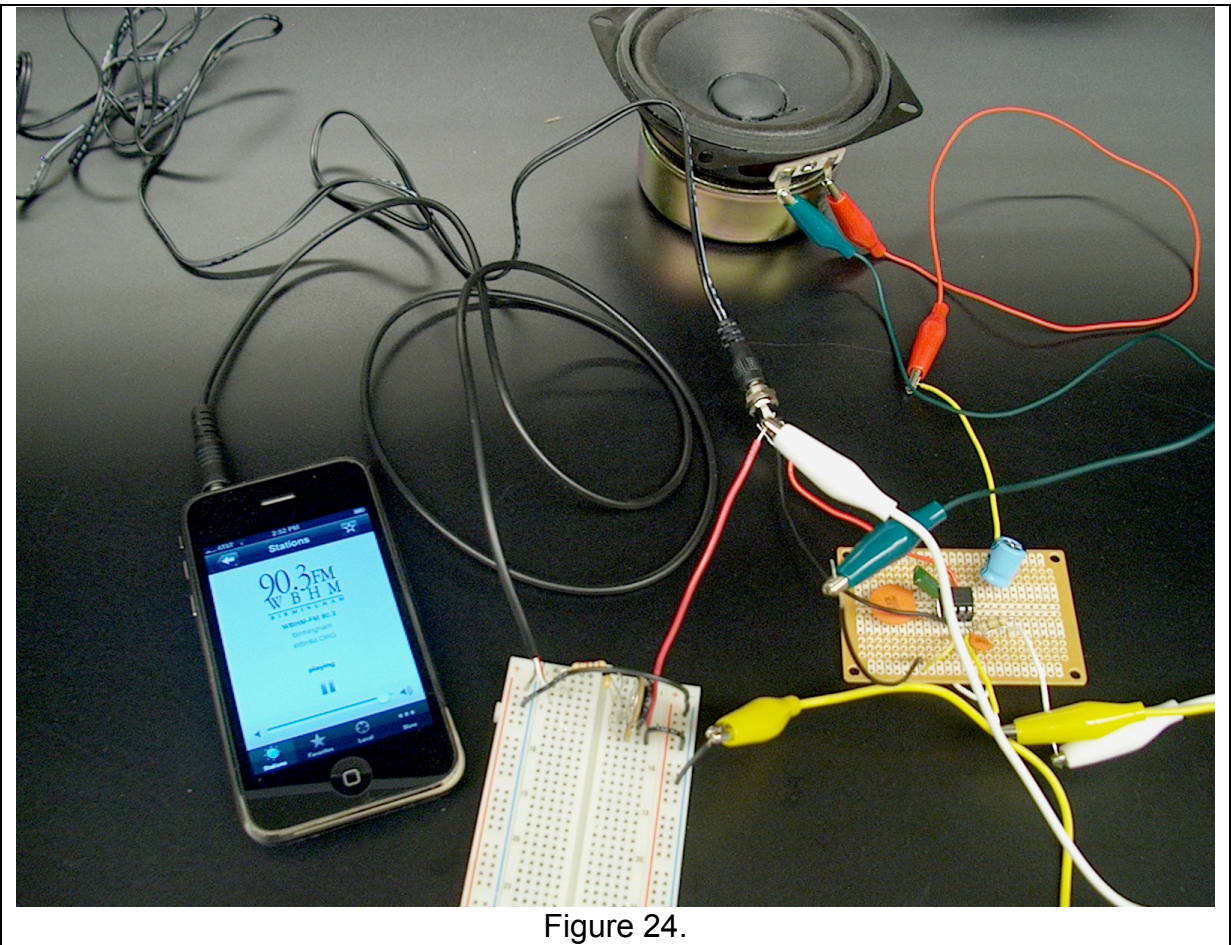


Figure 24.

- Before continuing, disconnect the amplifier and the power to the amplifier.

High Pass circuit

From Figure 25, we see that we need extend a line from the signal input to a new location to start the high-pass circuit, and that the input will connect to a capacitor this time.

- Use a jumper wire to connect the signal input to a new row (give yourself plenty of space).
- Run a capacitor from that row to a new row on the right hand side of the breadboard.
- Insert a potentiometer such that one of the end leads is in the same row where the capacitor ended, and the other two leads are in separate rows.

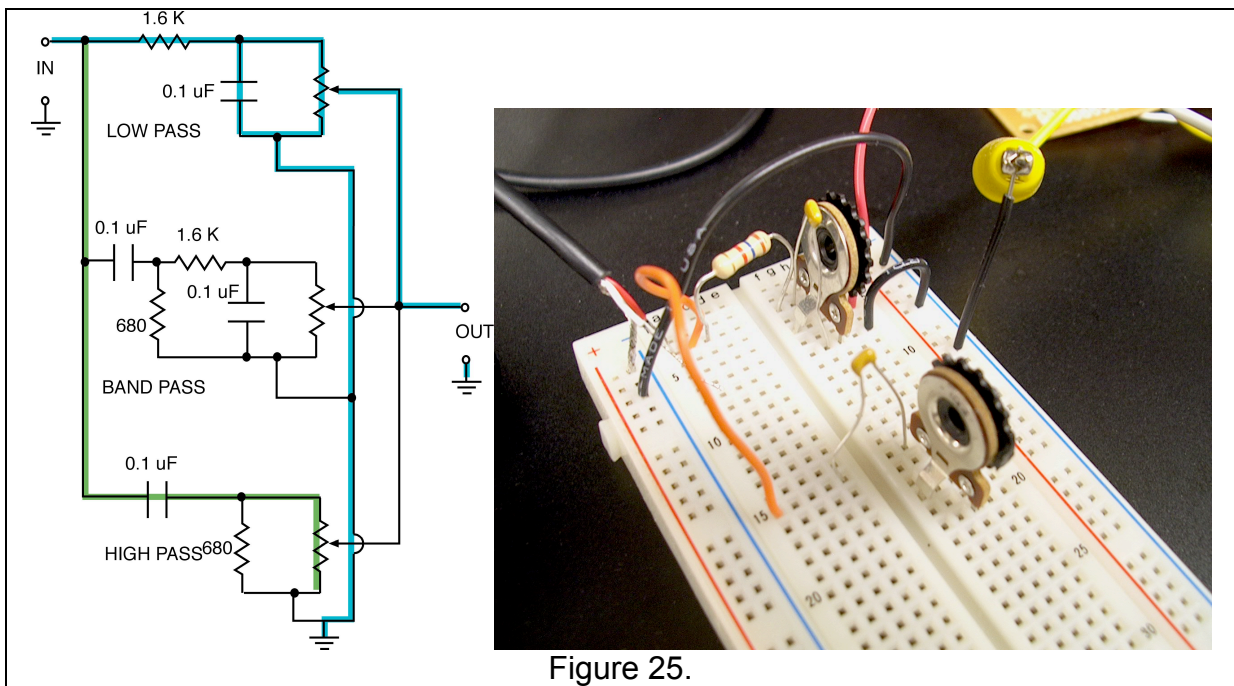


Figure 25.

- Connect the resistor (680 Ω , stripe colors blue, gray, brown) across the potentiometer.
- Connect the bottom of the pot to ground
- Run a jumper lead from the wiper to the wiper of the other potentiometer, Figure 26.

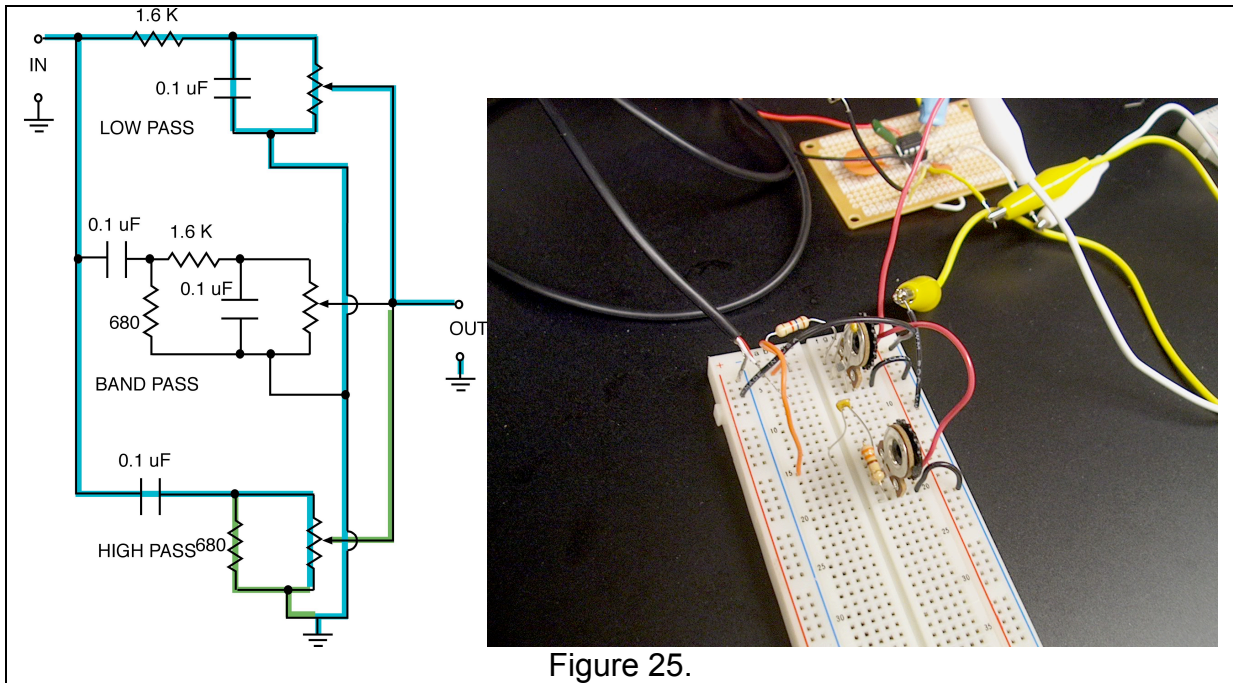


Figure 25.

Now, try the circuit again. As you turn the knobs, you should be able to go back and forth between low and high frequencies. If either pot gets turned all the way down, all sound will stop.

Bandpass circuit

- Start with another extension jumper from the circuit input to a new section of the breadboard (orange in Figure 26).
- Run a capacitor from the input to an unused row.
- Run a 1.6 K Ω resistor from there to another unused row.
- Run a 680 Ω resistor from the junction of the capacitor and first resistor to ground.
- Insert the potentiometer such that one end is connected to the unused end of the first resistor (the 1.6 K Ω), with the other leads in separate rows.
- Connect a capacitor across the pot.
- Connect the bottom end of the pot to ground.
- Connect a jumper from the wiper of the pot to the wiper of another pot (it might get tough to find a hole).
- Connect and test.

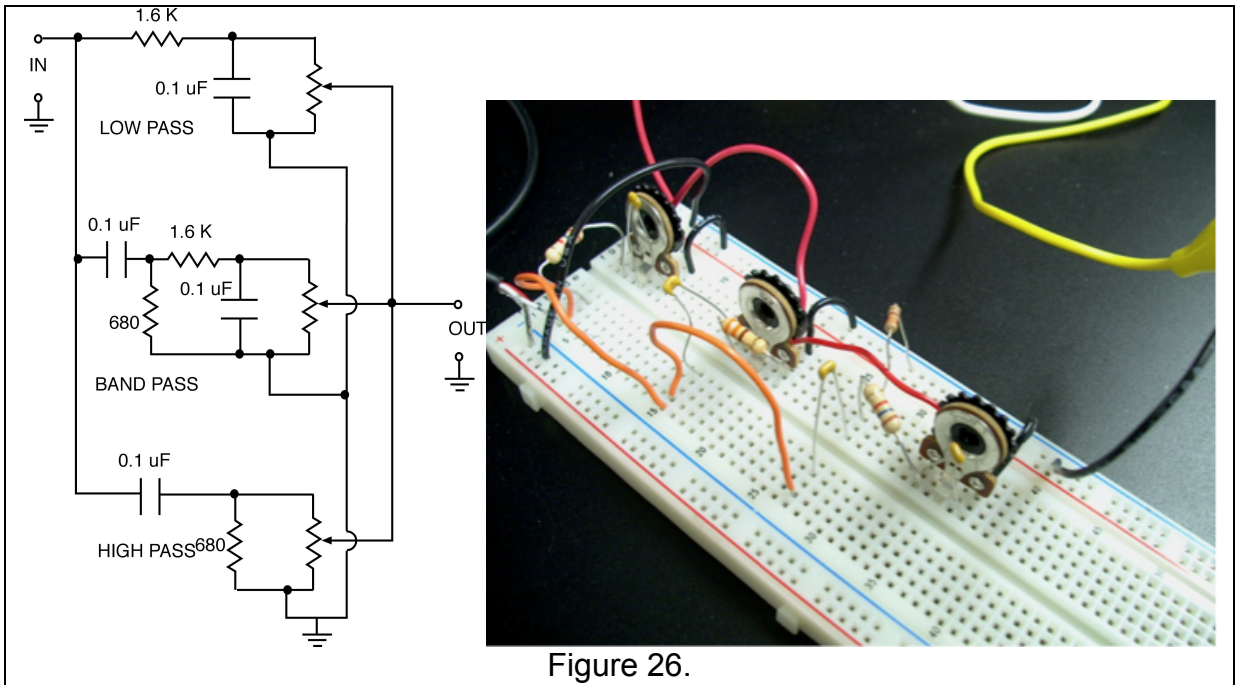


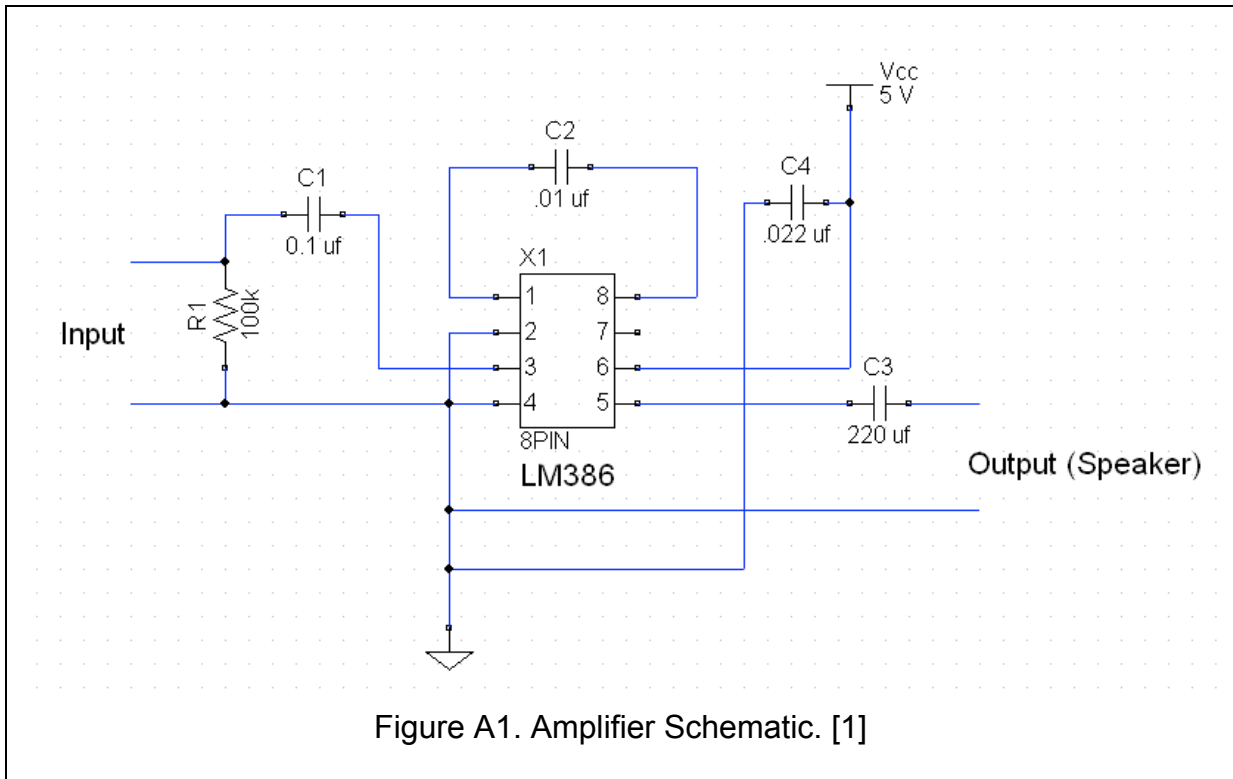
Figure 26.

Appendix A. Amplifier

This appendix gives a simple amplifier circuit, parts list, and instructions for building one on breadboard. It can also be soldered on a piece of vectorboard and mounted in a box for more ruggedness.

This circuit uses a low-voltage audio power amplifier integrated circuit, National Semiconductor LM386N-1.

Figure A1 shows the circuit schematic:



The power source is a 5V wall-transformer. The parts list is given in Table A1. Prices circa Feb 2009.

Table A1.

Quant	Unit	Description	Vendor	P/N	Cost
1	Ea	5 V wall transformer	Jameco	RDU050050C5031	\$10
1	Ea	breadboard	Digikey	438-1045-ND	\$8.73
1	Ea	100KΩ resistor	Digikey	OD104JE-ND	\$0.42
1	Ea	Capacitor, Ceramic	Digikey	399-4331-ND	\$0.16
1	Ea	Capacitor, Ceramic	Digikey	490-3812-ND	\$0.17

1	Ea	Capacitor, Electrolytic	Digikey	P51530ND	\$0.31
1	Ea	Capacitor, Ceramic	Digikey	399-4169-ND	\$0.22
1	Ea	Audio Amp Chip	Digikey	LM386N-1 ND	\$1.09
1	Ea	Power jack	Digikey	SC11510ND	\$4.56
		Jumper wire	Radio Shack	276-173*	\$6.49

*This is a kit with assorted jumper wires. If you will be doing a lot of breadboard work, it's cheaper to buy spools of jumper wire, e.g. Digikey C2004B-100-ND, 100 foot spool, \$16.24.

Tools: Wire strippers, wire cutters, soldering iron (first time)

1. Prepare the power jack by soldering two wires to it. Solder a black wire to the center lug, and a red wire to the lug on the right when viewing the jack from above (upper right hand corner of Figure A2).
2. Insert the amplifier integrated circuit (IC) into the breadboard such that it straddles the center trough, and each pin is in a separate row.
 - a. The small circle embossed on the chip in the upper right-hand corner indicates the location of pin 1. Figure A3 shows the pin numbering system.
 - b. Using short pieces of hook-up wire, connect pins 2 and 4 to one of the buses. We will call this the ground bus.

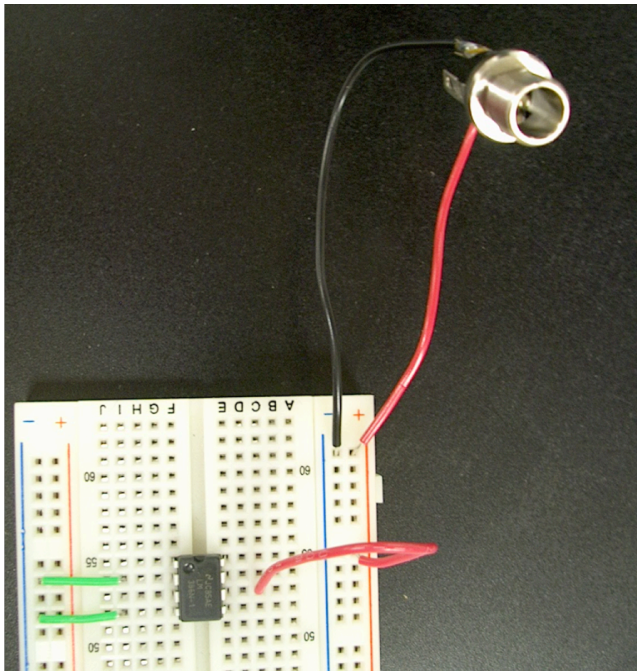


Figure A2. Step two of amplifier assembly

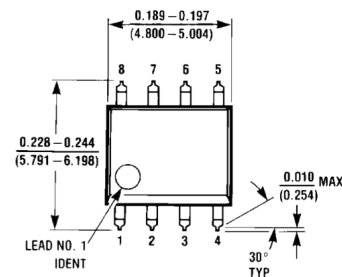


Figure A3. Pin numbering system.

- c. Connect the wires from the power jack to the two buses on the right. We will later connect the ground bus we started before to the bus with the black wire, making that bus ground also. The other bus, connected to the red wire, will be the positive bus.
- d. Connect a wire from Pin 6 to the positive bus.

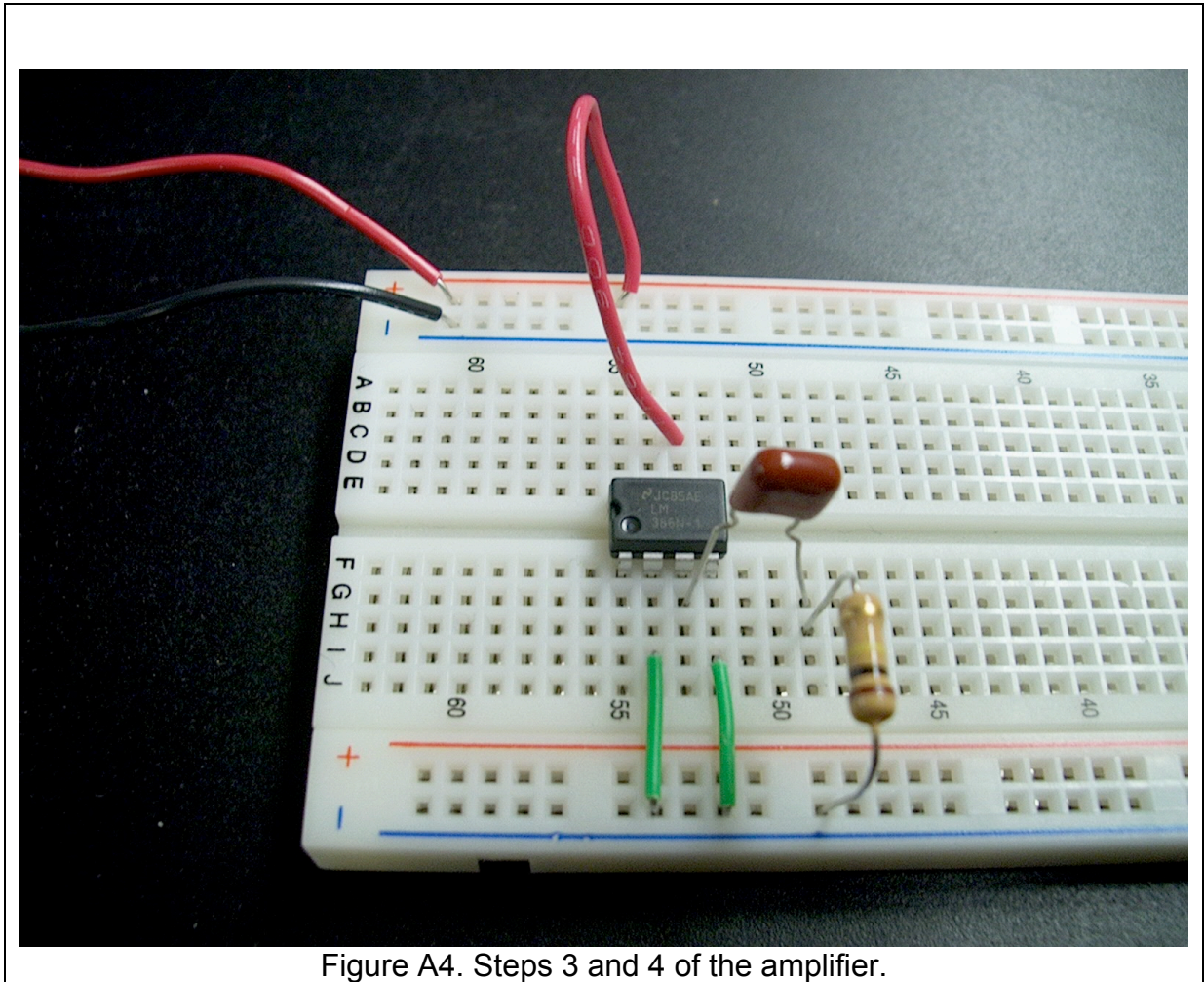


Figure A4. Steps 3 and 4 of the amplifier.

3. Connect the 0.1 μF capacitor from pin 3 to a row that you are not using, Figure A4. This row should have no other components in it (yet) and should NOT be a bus.
4. Connect the 100 $\text{k}\Omega$ resistor from the row with only the capacitor in it to the ground bus.

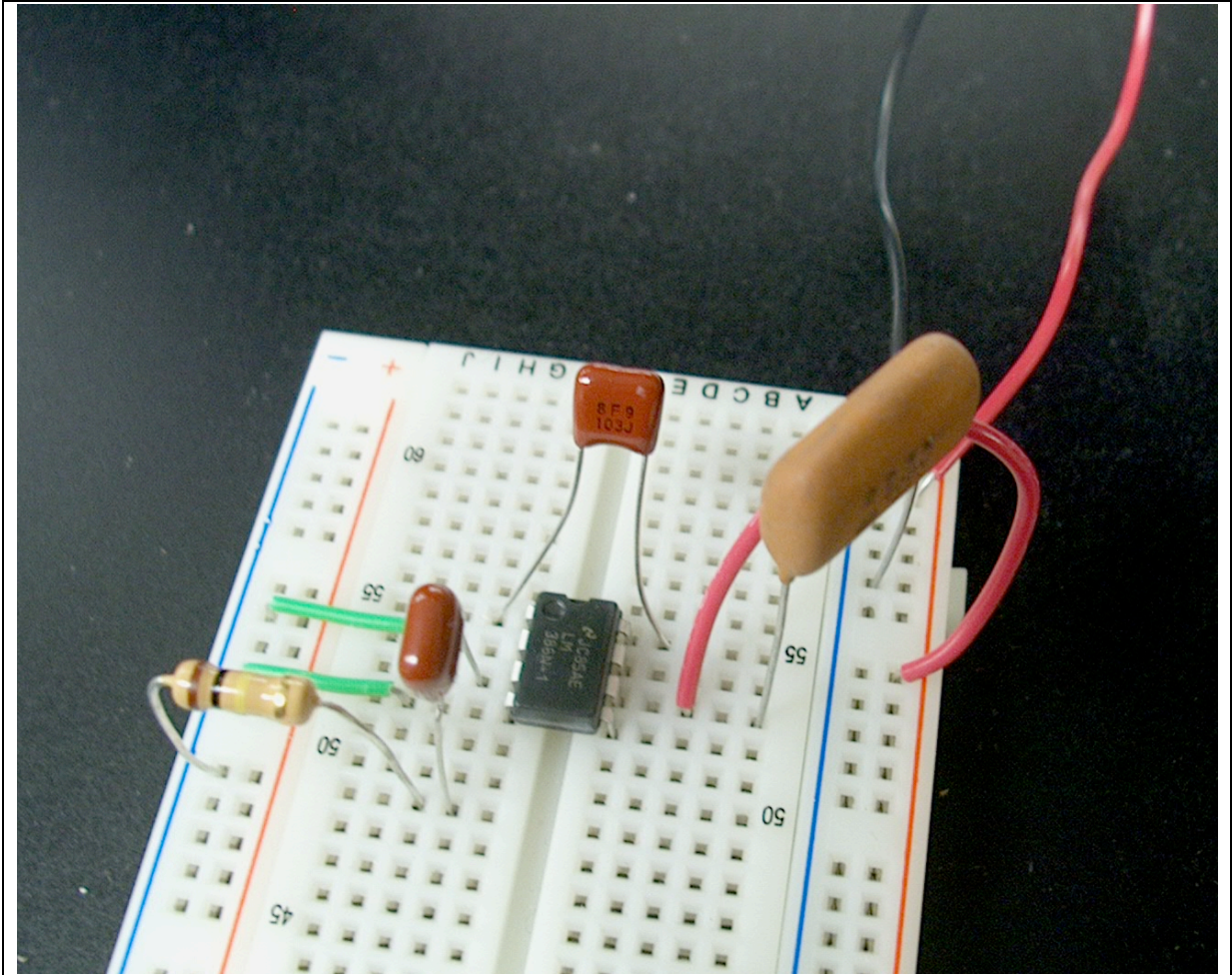


Figure A5.Steps 5 and 6 of the amplifier.

5. Connect the 0.01 μF capacitor from Pin 1 to Pin 8 of the IC, Figure A5.
6. Connect the 0.022 μF capacitor from Pin 6 to the right-hand ground bus. That is the bus with the black wire.

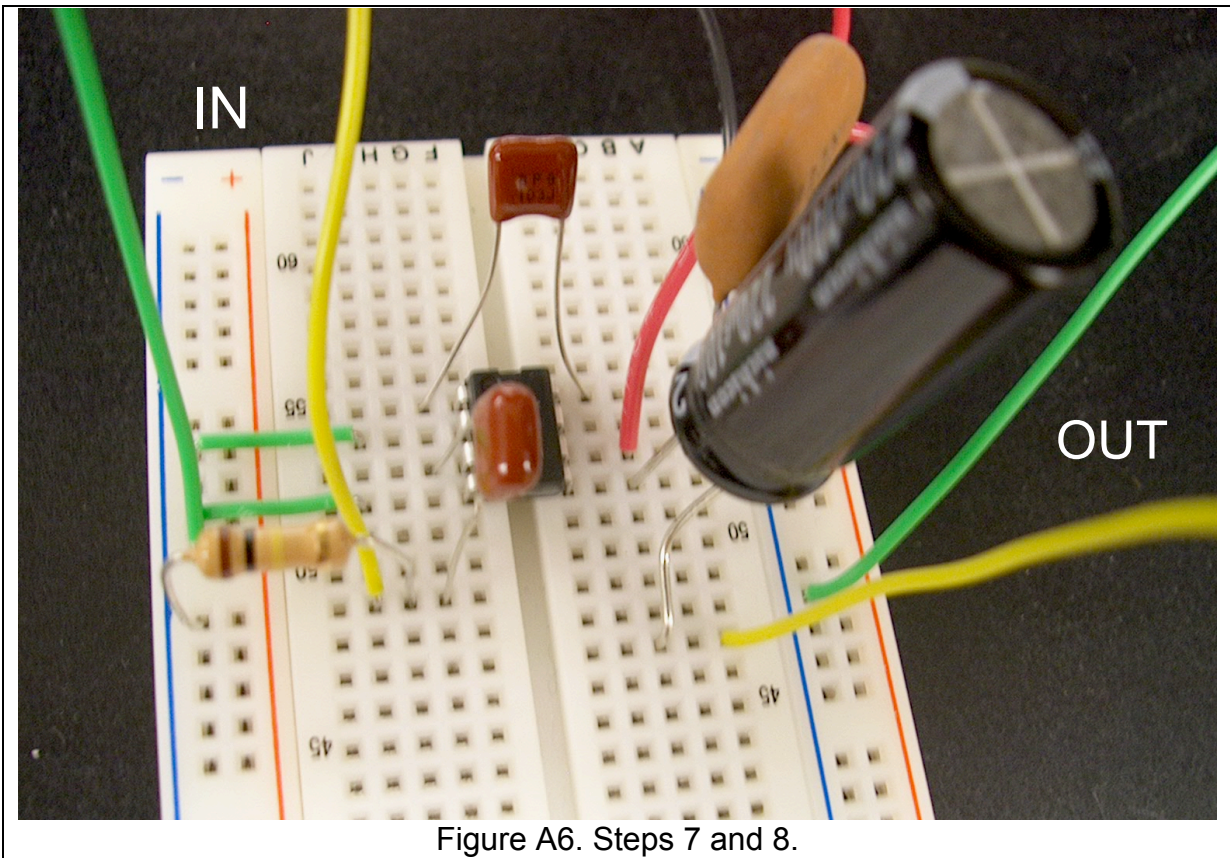


Figure A6. Steps 7 and 8.

7. Connect the 220 uF capacitor from Pin 5 to some row that you are not using (yet). An example is shown in Figure A6.
8. Create the output leads by sticking one end of a wire into the row where the capacitor of Step 8 ended (yellow in the picture). Stick another piece of wire in the ground bus. These are the output leads that you will connect to the speaker using alligator leads. (One alligator lead connects the yellow wire to one wire of the speaker, and another alligator lead connects the green wire to the other wire of the speaker.)
9. Create the input leads by sticking one piece of wire into the *same row* that is shared by the resistor and the 0.1 uF capacitor. There are now three connections in this row. Connect another wire to the left-hand ground bus. These two leads will connect to the output of your mp3 player.

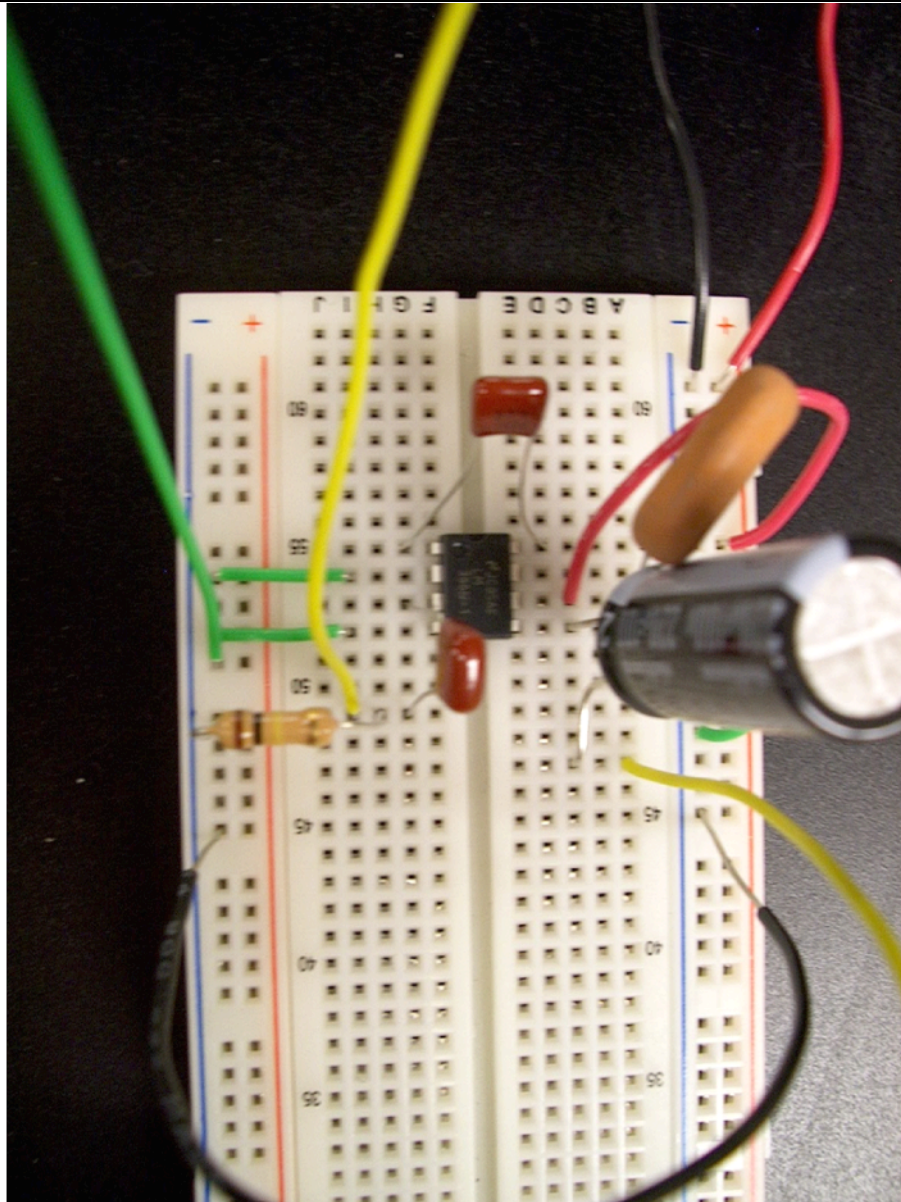


Figure A7. Step 11 of amplifier assembly.

10. Finally, connect the two ground buses together with a wire (black in Figure A7). Double check that you have not connected either ground bus to the positive (red) bus. The ground bus on the right is the one with the *black* wire.

This completes the amplifier assembly.

Appendix B. Reading component values

Figure B1 shows the color code system for reading resistor values. [2] There are three color bands that give the resistor's value in Ohms, plus a fourth band for tolerance.

Color	Digit	Multiplier
BLACK	0	_____
BROWN	1	_____0
RED	2	_____00
ORANGE	3	_____000
YELLOW	4	__0,000
GREEN	5	__00,000
BLUE	6	000,000
VIOLET	7	
GRAY	8	
WHITE	9	

EXAMPLE
47,000 Ohms
or
47-K Ω

1st Digit — 4
2nd Digit — 7
Multiplier — 0000
Tolerance — 2% - Red

5% - Gold
10% - Silver

The first two stripes give the first two digits of the value, for example, yellow-purple gives 47. The third band is a multiplier of 10^x , where x is set by the third band. If third band is orange, that is 10^3 , so a resistor whose colors are yellow, purple, orange has a resistance of 45×10^3 or 43k Ω .

There is a mnemonic to remember the order of the colors: "Boston boys respect our young girls because Violet graduated Wellesley." Each word's first letter is the same as the first letter of the corresponding color. One only has to keep straight black and brown, and green and gray.

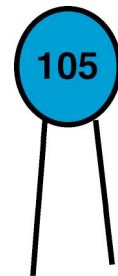
We do not care about the tolerance in the project, since we only have to come close to the correct cutoff frequencies. The cutoffs are pretty gradual.

Interestingly, if you buy ± 10 resistors, they will be within 10% of the correct value, but are virtually guaranteed to be outside $\pm 5\%$. That

is because the manufacturer likely screens the resistors, and the ones that fall in the $\pm 5\%$ range are put into that bin, and more can be charged for them. This is perfectly reasonable and helps keep costs down overall.

Capacitors, sadly, have a variety of labeling conventions. Caps that are physically small like ours don't have room for much information. A common code uses a three-digit number that works just like the resistor codes, except you don't have to convert colors to numbers. The units are generally in picofarads, at least for small capacitors like the ones we're using.

For example the capacitor at the right is labeled "105." Thus the value is 10×10^5 picofarads, or 10^6 picofarads, which is 1.0 μF .



References

- [1] A. Sinha, A. Luzader, and M. Lee, "STEM Outreach-- building a speaker," The Ohio State University, Columbus, Senior Design Project Final Report 2008.
[2] <http://www.finders.com.au/site-information/resistor-color-codes/>

