# Wiring for Contraptions

The circuits required for simple interfaces and art contraptions are generally quite simple, but that does not mean that they can be tossed together without a care for reliability. You can't depend on a circuit that's not properly built. I have seen many a project crash due to the failure of some simple bit of electronics.

## *Making schematics real*

Circuits are presented as schematics, a kind of short hand diagram of where the current flows. Figure 1 is an example:

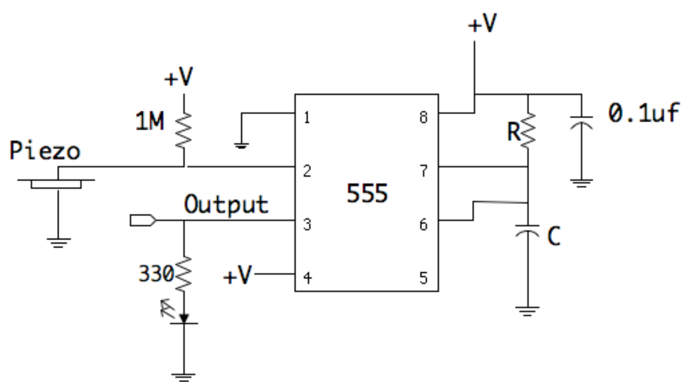



Figure 1.

This circuit senses a tap on a piezo transducer and produces a single positive pulse. It is useful for drum pads and other impact sensors. It can be connected to an Arduino, although I have included an LED for testing. The schematic really only communicates what is connected to what. The routing of the lines has no relation to the routing of actual wires. For instance, pins 6 and 7 are both connected to R and C. That could as easily have been drawn as shown in figure 2. All points on a line are the same point, as far as the circuit is concerned.

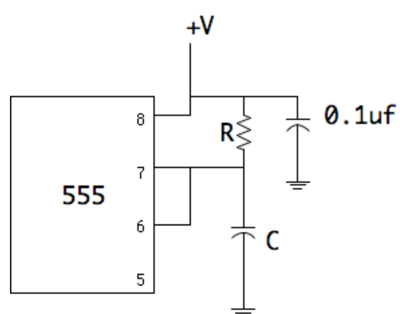



Figure 2.

Many connections are not shown as lines, just indicated with labels. The most common is , which indicates a connection to ground. Ground is a very important concept:

- It is the point from which all voltages are measured.

- It is a connection to the power supply, usually (but not always) the most negative lead from the power supply.
- It is the connection to any RF or hum shielding.
- It is NOT a connection to the power cord (mains) ground, or (even worse) the power cord neutral.

Connections to the positive power supply are also very commonly shown as labels. Sometimes a schematic won't even show these at all. This is particularly common when several devices share the same package as in logic elements and opamps.

When you look at a lot a schematics, you will see many styles. For instance, here is a similar circuit taken from a British web page:

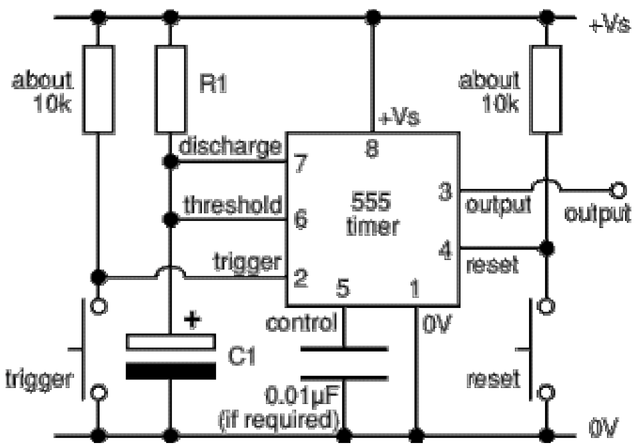



Figure 3.

Many of the symbols are the same, but some are different-- for instance, resistors are represented by rectangles instead of the wiggly line usually used in the US. The most potentially confusing difference is the treatment of lines where they cross. If the cross represents a join, there is a dot-- if two lines cross without connection, there is a little jump in the line. In US conventions, lines that make a T are always connected, so the dot is left out. You seldom see crossing lines in US schematics, but if they cross without connections, the jump is used.

Converting a schematic into a real device is a multi-step process. The first is to gather the parts and learn their physical qualities. The most common parts are ICs, resistors and capacitors.

## ICs

The big square in figure 1 represents an integrated circuit, identified by its part number 555[1]. The small numbers represent pin numbers. They are in different order on the two

[1] This is an abbreviation-- the part number is actually LM555CN from most manufacturers. The extra letters indicate the family and package design. Other letters may be added to indicate temperature range, reliability factor and so on.

versions; this again is a matter of style. The designer of 1 wanted to maintain the numbering of the pins as they are on the IC (top view), the designer of figure 2 prefers to show the power supply at the top and the ground at the bottom, and to run signals left to right. You won't see any pin numbers on an actual IC- the most you will get is a dot by pin 1 or a notch on the pin 1 end. Since you usually look at ICs from the bottom, you have to learn a sort of deliberate dyslexia-- everything is reversed left to right.

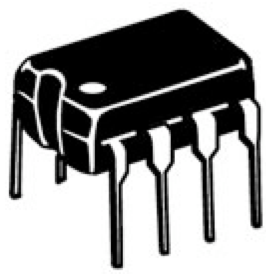


Figure 4. An integrated circuit in a DIP package.

When you order integrated circuits, you will find they come in a variety of packages appropriate for different manufacturing techniques. For hand built circuits, always order Dual Inline Packages or DIPs. The leads are spaced at 10 to the inch, and will neatly fit the holes in breadboards or punched circuit board.

Be sure to get a data sheet for each IC in your project. At the minimum, this will identify the pins, and you will learn something new about the part each time you look at the sheet.

## Resistors

Figure 5.
Resistors come in a variety of shapes, but the most common is illustrated in figure 5. Figure 5 is more or less actual size. There's no room for numbers, so the value is indicated by a series of stripes. You must memorize (or keep handy) the meanings of the numeric colors.

0. Black
1. Brown
2. Red
3.Orange
4. Yellow
5. Green
6. Blue
7. Violet
8. Grey
9. White

It may help to know that they are in the order found in the spectrum, or it may not.

Usually there are four stripes with a big space between the third and fourth. The first two colors are the value digits and the third represents the number of zeros[2]. Here are some examples:

Green, green, black = 55 ohms.
Brown, black, red = 1000 ohms
Brown, green, orange = 15 k
Brown, black, yellow = 100 k

The fourth stripe represents tolerance. The resistors we use will be either 5% (gold fourth stripe) or 10% (silver). More precise resistors are available, but we won't bother with those. (They have more stripes.)

It's also important to be aware of the power rating of resistors. That's the number of watts (voltage times current) the resistor can carry. For most situations, 1/4 watt is perfectly adequate. 1/8 watt resistors would work, but they a kind of small to work with. Motor circuits and power supplies may require 1 or 2 watt resistors. The power of small resistors is indicated by their size- high power resistors are big square things and have the wattage printed on the side.

## Capacitors

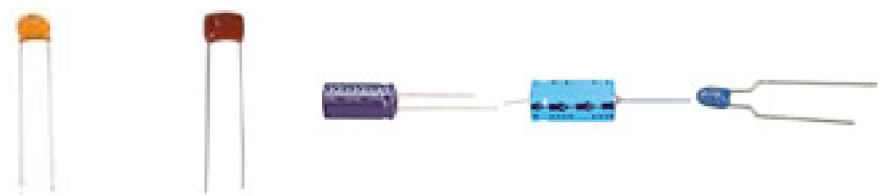


Figure 6. Capacitors: Ceramic, mylar, radial electrolytic, axial electrolytic, tantalum.

Capacitors come in a wide range of types and shape.

*Ceramic* capacitors are the smallest, shaped like a hairpin with a small disc of clay in the bend. They are identified by a number code that is similar to the resistor coding: two digits, then a number that is the number of zeros. If there is no third digit, the two digits give the value. Ceramic capacitors have tiny values-- the numbers are pico-farads. That's $10^{-12}$ farads. Sometimes you see larger ceramic capacitors labeled in microfarads-- those will have a decimal point such as 0.1. Schematics almost always give capacitance in microfarads, abbreviated µf or uf. Here's a chart to help convert the picofarad (pf) code.

[2] Technically, it's a multiplier. To represent small values a gold third stripe multiplies by 0.1 and silver multiplies by 0.01. A one ohm resistor is brown, black gold.

| Marking | Value |
|---|---|
| 1 | 1 pf |
| 10 | 10 pf |
| 100 | 100 pf |
| 101 | 1000 pf or 0.0001 µf |
| 102 | 0.001 µf |
| 103 | 0.01 µf |
| 104 | 0.1 µf |
| 105 | 1 µf |

*Mylar* capacitors are similar to ceramics in use and labeling. There are usually more precise in value than ceramic and are used in critical applications such as audio amplifiers. They are larger and more expensive, so we use ceramics in applications like digital logic decoupling where the precise value is not terribly important.

*Electrolytic* capacitors provide the large values. These can run up to 100,000 µf. They are also physically large, although the size is related to the voltage rating. You must use electrolytics with a voltage rating at or above the voltage that will be applied. If you don't the capacitor will fail in a messy and possibly dangerous way. The value and rating are printed on the side. There is also a marking for polarity-- this is a stripe usually indicating the negative lead. Electrolytic capacitors must be hooked up so the + lead has a positive voltage relative to the - lead. Getting these mixed up will also lead to failure. If the two leads are the same voltage, the capacitor will quit working after a while.

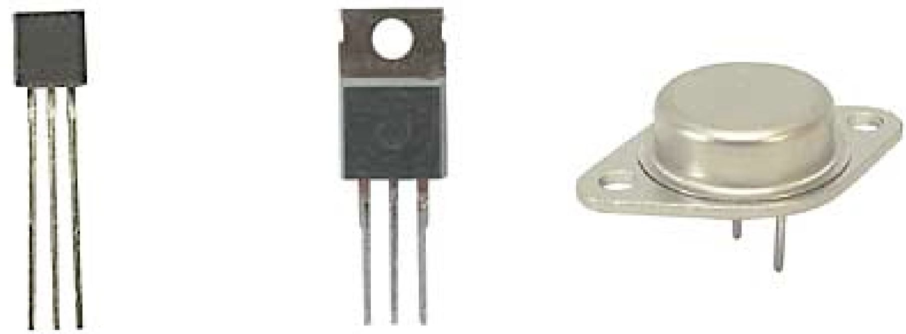
*Tantalum* capacitors are similar to electrolytic in most ways (including spectacular failure modes). They are smaller and more expensive. They are marked with numeric codes like ceramic, but the numbers go up to 107 for a 100µf value. One lead will be marked with a +, a dot or a splash of paint. This is the positive lead.

## Diodes

Figure 7. A diode

You will occasionally need a diode, especially if the circuit involves motors. Small diodes are resistor shaped, but have the part number stamped on the side. (Diode part numbers usually begin with 1N.) The cathode end is always marked with a stripe. This matches the bar on the schematic symbol.

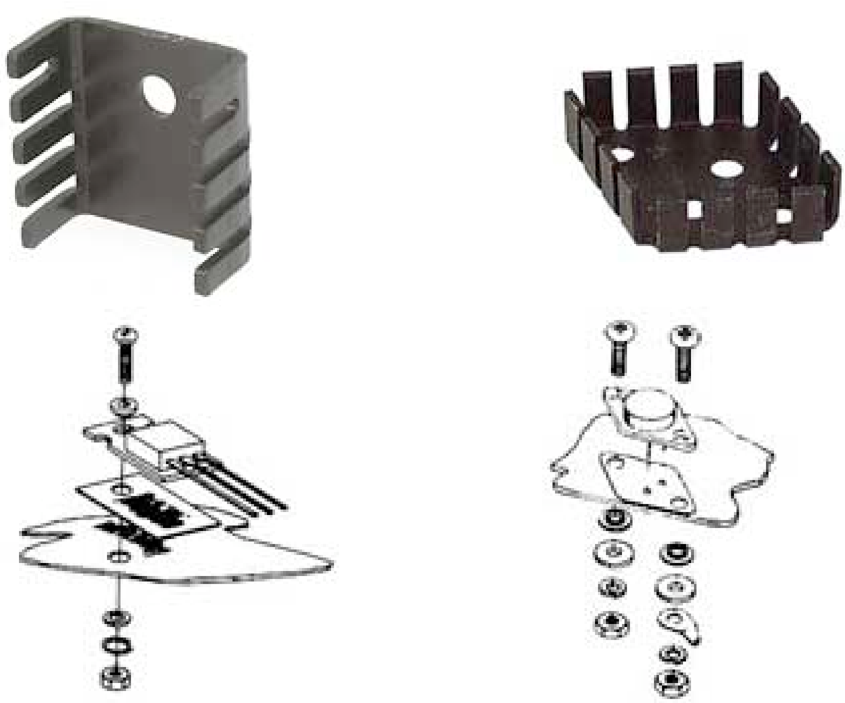
## Transistors



TO-92 TO-220 TO-3

Figure 8. transistors

Transistors come in a variety of packages, depending on power capability. The most common are illustrated in figure 8. The TO-92 has a rounded back and flat front. Whatever package they come in, transistors have three connections, collector, emitter and base. These are occasionally identified, but you usually have to check the data sheet to see which is which. The case of the TO-3 package is a connection-- a wire must be bolted to one of the mounting holes. Both the TO-220 and TO-3 should be mounted on a heat sink if they are used at the top half of their rated power. The transistor usually must be electrically insulated from the heat sink-- this is provided by a mounting kit, which includes a thin insulating wafer, screws, solder lugs and plastic inserts. The heat transfer will be most efficient if the insulator is coated on both sides with a silicone heat sink compound.



TO-220 TO-3

Figure 9. Heatsinks

## Other Parts

No general description can cover the amazing range of electronic components available. The connections will almost always be a lead (like resistors and capacitors) a pin, or wires. In many cases, the device can be mounted with a socket with pins or leads. The only odd part for this project is the piezoelectric transducer, which has two long wires attached. These can be soldered to lead clippings for insertion directly into a breadboard, (see figure 10) and will ultimately be connected with an audio connector.

## *Breadboarding*

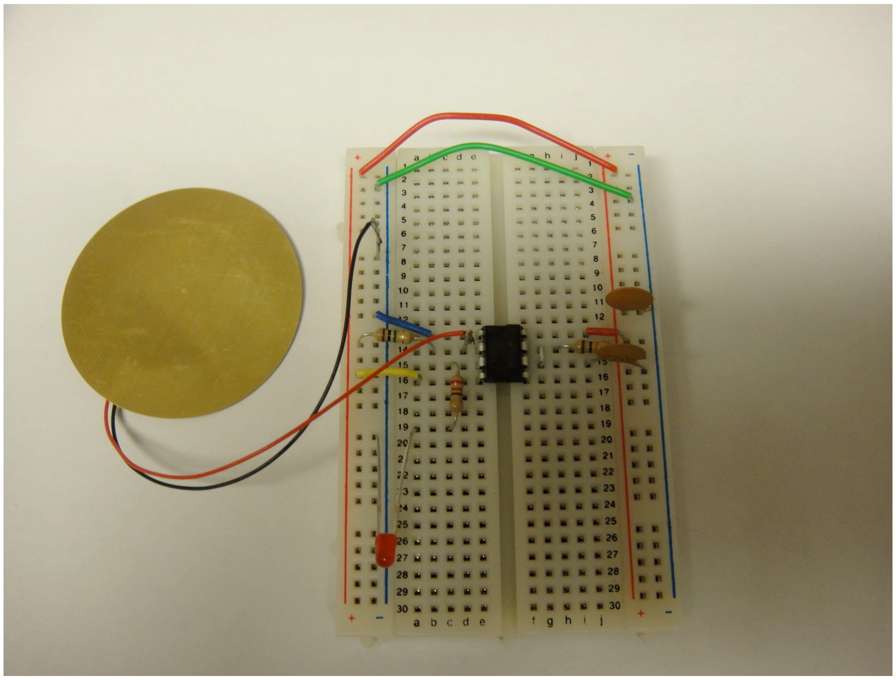


Figure 10.

The next step to building a circuit from a schematic is to assemble the parts on a temporary breadboard. I've been building circuits since you really could cut bread on the board[3], and I've learned the hard way not to skip this step. Schematics have mistakes in them more often than you would think. The breadboards we use today are the solderless kind, where you stick the leads into holes in a plastic block. Most have the holes grouped together in horizontal rows of five, with a space between rows wide enough for a DIP IC to straddle. There are also a few columns that are connected all the way down for power and ground busses.

The most elaborate breadboards are mounted on boxes with power supplies and signal generators. We can usually make do with smaller ones for Arduino projects. In fact, I often mount an Arduino and breadboard next to each other on a block of plastic. This makes an excellent development environment.

[3] You bent the wires around brass nails stuck in a piece of wood.

I assembled the circuit on the breadboard as shown in figure 10. The process is really simple:

- Place the IC on the breadboard.
- Use jumper wires to connect all powered pins to the V+ buss and ground pins to the ground buss.
- Take the remaining pins in order, and connect the associated components, including components the components are connected to.

The next step is testing. Connect the V+ and ground busses to the power supply and check the voltage on each pin of the IC. Confirm that the proper pins have V+ or 0V present. Next, try to activate the circuit to see if it behaves properly.
If not:

- Check that everything is shoved well into the breadboard.
- Systematically check all connections against the schematic, pay particular attention to power to the IC.
- Make sure the ground and V+ busses are connected to the power supply. (Many breadboards have two busses marked +, but these are not connected together. Note the red and green wires across the top of figure 10.)
- Check the values of components.
- Check the orientation of components like diodes and polarized capacitors.

If the parts are new, the chance of a bad part are remote, but a misconnection on the breadboard can blow an IC. If you discover a power connection was wrong, the IC may need replacement if fixing the connection does not fix the problem.

Once the circuit is working, experiment a bit to see how its behavior changes when the circuit is modified. For instance, in this project the time constant of the parts marked R and C are critical. If the time constant is too short, the pulse will not be visible on the LED. If the time constant is too long, the pad will not repeat fast enough. A bit of experimentation showed the best values for R and C are 10k ohms and 0.1 µf respectively.

## *Final construction*

### The Prototype Board

Once the schematic is shown to work on a breadboard, its time to make a final version. Never trust a breadboard circuit in a show. Wires will work loose every time you move it, and you will spend hours trying to fix them in the field. We don't have to manufacture a circuit board (although that's a good idea if you need lots of copies). You can buy a prototype board with the same sort of layout as the solderless breadboard. Figure 11 shows a nice one from GC Electronics. (Jameco part 616649).

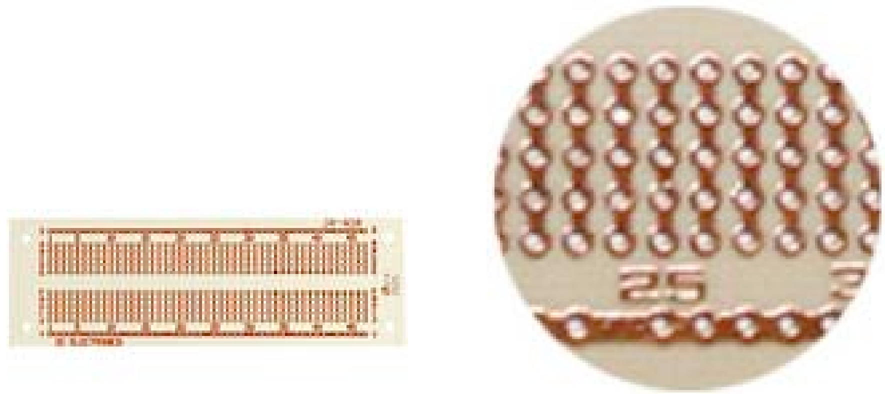



Figure 11.

If the board is too large for the space you have, it is easily cut. Then you can do two projects. There is one irritant in using these boards. Whereas the solderless types have five holes in a row, many solder versions other only have three or four, forcing some minor changes in the layout. There are also prototype boards with rows that go the complete width of the board. (Veloboards) You have to cut the strips to the length you need with an X-acto knife. The cheapest prototype boards do not have a real pattern to them, just individual solder pads on each hole. I find these rather difficult to work with, but they are good for projects that are almost all chips. I use very thin wire that is designed for wire-wrap construction and work on the back of the board. Two or three of these can be soldered in a single hole.

The cheaper prototype boards have untinned copper pads. These usually must be sanded with light sandpaper before solder will stick properly to them.

## Layout

Its a good idea to make a sketch of the board layout before you begin. That way you won't find you have crowded too many parts in the same space. Graph paper makes it easy-- just scale things so the grid spacing represents 0.1", which is the lead spacing for ICs and the spacing of the holes in the prototype board. Lightly sketch the foil pattern. Measure all of your parts to see how far apart the leads will be. Keep these clearance issues in mind:

- Resistors can be mounted flat to the board (4 holes), or with one end sticking up (2 holes).
- Capacitors are mounted sticking out from the board.
- Very short jumpers need not be insulated. (Clippings from resistors work well)
- Jumpers that are longer than about 0.4" must be insulated.
- Jumpers can run under other parts, but never over anything.

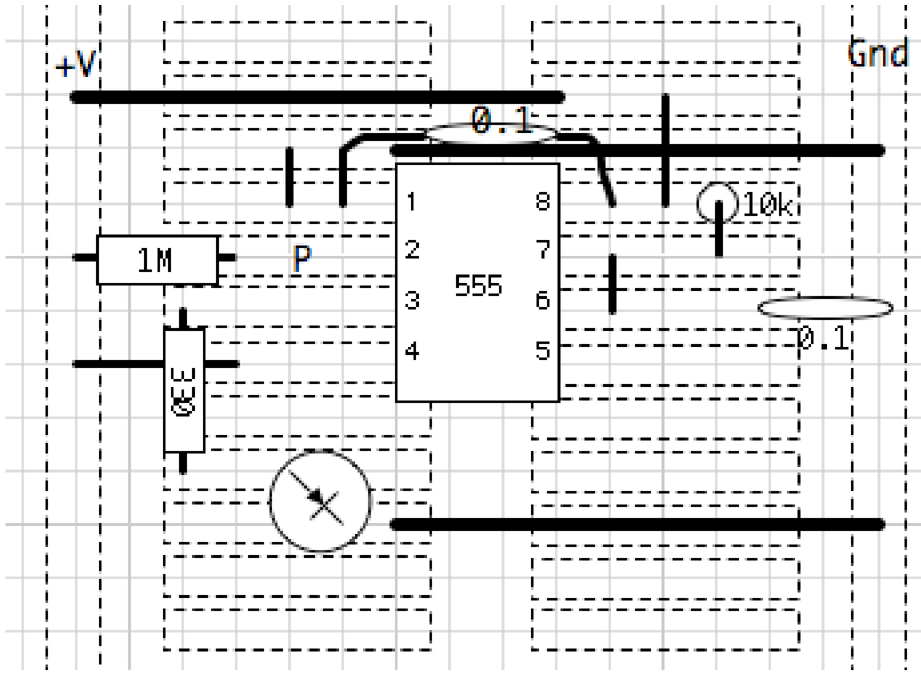



Figure 12.

Figure 12 shows a layout almost identical with the breadboard. The only real modifications deal with the fact that there is only one buss on each side. The thick lines represent jumper wires, and the thickest are the insulated ones. The letter P indicates where one lead of the piezo connects. The other goes to any ground point. The 10k resistor is mounted sticking out of the board- this exposes a bare wire. If you mount many resistor this way, make sure the exposed wires cannot touch.

The parts are now soldered to the prototype board.

## *A Necessary Digression on Soldering*

Soldering is a subtle art. It's not difficult to master, but it's also not difficult to create solder joints that are time bombs, prepared to let go at the most embarrassing moment. You can do it right if you just keep a few concepts in mind.

### Cleanliness

When two pieces of metal are soldered together, the solder forms an alloy with the metal that is actually stronger than the metal alone. This can only happen if the solder and metal come into chemically pure contact. Any dirt, grease or oxide on the pieces will prevent this bonding. The materials should appear clean to start with. If there is the slightest doubt, use a piece of fine grit sandpaper to make the contacts shiny. If you are using untinned prototype boards, develop the habit of sanding the entire board before you start.

### Flux

Soldering flux is a liquid or paste that becomes a very aggressive detergent when heated. It is the flux that removes the last layers of dirt and oxidation, leaving the metals ready for the alloy bond. You can apply flux before soldering, or (more commonly) simultaneously with the solder. Solder sold for electronic work has flux in the core of the solder wire itself-- that is all you need. There are two kinds of flux- the proper flux for electronics is rosin flux. Flux used for plumbing is made from an acid. If any is left over, it will eat right through the circuit traces in a year or two. (Plumbers solder with blowtorches- excess flux is burned away.)

## Heat

It's important to remember that heat is different from temperature. Heat is the energy required to do a certain job, such as raise the temperature of one gram of water by one degree. It takes more heat to solder two large pieces of metal than two small ones. The heat available from a soldering iron is determined by the mass of the tip. Use a small tip for delicate jobs like soldering components to a board and a larger one to solder big things like the pins of XLR connectors. The rate of heat transfer is determined by the contact area between the soldering tip and the work. Sometimes we can speed up the transfer by placing one drop of solder between the joint and iron.

## Temperature

The traditional lead based solder (now illegal in California) would melt at 361°. The new lead free solders melt at a somewhat higher temperature. Melting solder uses up heat, and will cool down the metal the solder is in contact with (just as melting ice cools your soda). It is thus important that the metal you intend to solder be well above 400° before you apply the solder. The temperature of the soldering iron also affects the rate of transfer of heat from the iron to the work, so it is a good idea to use a higher temperature iron on heaver jobs. If the iron is too cool or too small for the job, the joint may dissipate the heat faster than the iron can supply it, and never get hot enough to melt the solder.

On the other hand, various parts close to the solder joint can be damaged by heat. This includes the insulation on wires, the internal workings of transistors and the like, and in extreme cases the material the circuit board is made of. It's important not to let things get too hot. Sometimes this can be prevented by clamping  pliers or a hemostat a half inch above the solder joint, but the best approach is to work quickly[4].

## Soldering Irons

Soldering irons come in two types. Your basic woodburner consists of a handle with a heating element in it and a replaceable tip. The heating element has a specified wattage. This determines how fast the tip heats. It does not determine the temperature. When the iron sits idle, it gets hotter and hotter, and may be 1000° when you touch it to the work. As you hold the iron against the work, the heat is dissipated, and the work may never get hot enough. If you use this kind of iron, you should have two; one about 20 watts for light work and one of 40 watts for bigger jobs.

[4] It also helps to buy good wire. I swear the insulation on Radio Shack wire will melt on a hot day. The best has Teflon insulation-- that's hard to strip, but soldering is a snap. Unfortunately, it costs $0.60 a foot. (Watch for bargains at surplus stores.)

Woodburner Temperature Controlled

Figure 13. Soldering Irons

A temperature controlled iron is more expensive, but much easier to use[5]. You set a target temperature of 600 to 800 degrees, and the iron heats quickly to that temperature. Once that temperature is reached the iron shuts off and turns on only enough to maintain the temperature. The temperature is set by a dial or by changing tips.

The soldering process is summed up like this:

- Clean iron on sponge.
- Touch iron tip to both parts of joint.
- Count to 3 to 10, depending on mass of joint.
- Touch solder to joint-- it should melt instantly.
- Pull solder away, leaving a drop on the joint.
- Remove iron.
- Work should not be disturbed until solder turns gray.

It is OK to place a drop of solder on the iron to speed up heat transfer to the joint, but don't let solder build up on the iron. If you do, everything will wind up soldered in a big lump.

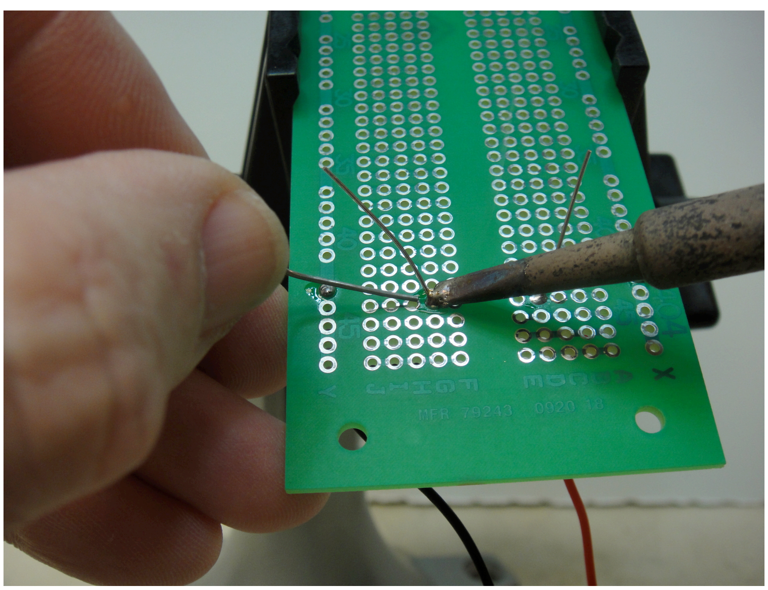


Figure 14.

A lot can go wrong when you solder. Figure 15 shows some common problems:

[5] They also last longer. I have two irons that I have been using for 30 years.


Figure 15.-- this is stolen from an excellent tutorial on soldering at www.curiousinventor.com

Common mistakes are:

- Dirt or oxide on the parts or iron.
- Too cold- both parts of the joint must be hot enough to melt solder. Adding solder chills the joint and iron, so don't touch the solder to the joint too soon. If you touch the solder to the iron, it will melt, but won't stick to the joint.

- Too hot- holding the iron down too long will melt insulation, damage chips, separate traces from the board, even burn the solder! This usually results from trying to cook a dirty joint until the solder flows.
- Not enough solder. First time solderers are often timid. You have several seconds before the heat damages anything.
- Too much solder. Excess solder can short out adjacent traces. The most common cause of this is letting solder build up on the iron.
- Letting the wire move before the solder freezes. This crystallizes the solder, and it will only hold for a day or two.

Sometimes it is necessary to remove solder-- you may find a faulty part, change your mind about the design, or solder something in the wrong place. The best tool to remove small amunts of solder is "solder wick", which is braided copper that is impregnated with flux. If you lay the wick across the joint and heat the joint through the wick, most of the solder will be absorbed by the wick. The part will be left very lightly connected and will break free easily.

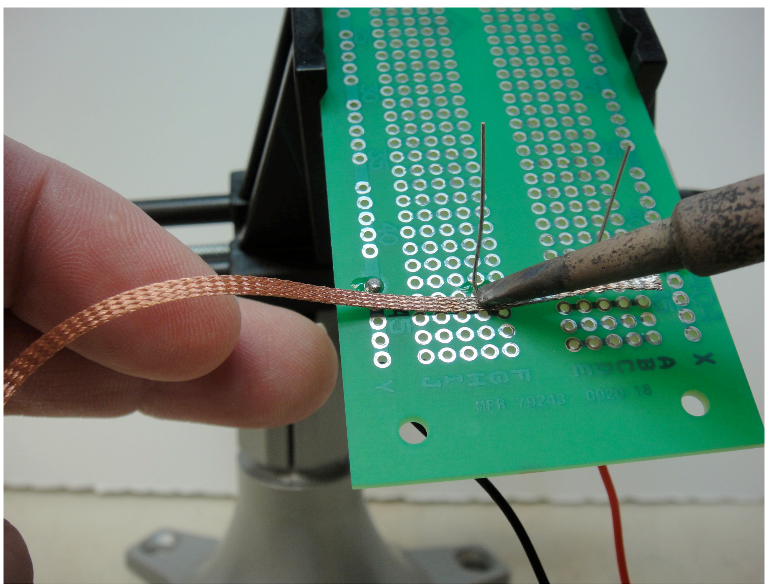


Figure 16.

### Soldering headers

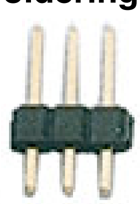


Figure 17.

The Arduino board uses 0.1" header blocks for connections to the outside world. While it is possible to try things out by stuffing wires directly into these blocks, that is not secure enough for a finished product. Matching header pins come in strips of many lengths. I buy strips of 8, which are easily cut to supply the number of pins you need. Soldering to these pins is a special technique:

- Support the strip in a header block so the pins don't get out of alignment as things heat up.
- Tin the stripped wire and the back end of the pin.
- Touch the wire to the pin and hold it against the pin with the tip of the solder iron. This will re-melt the solder.
- Hold the wire steady as you pull the iron away.

With such a tiny pin, the whole process takes less than a second. The joint will be stronger if you use a bit of 1/8" Teflon heat shrink. Cut a piece about 3/8" long and slide it over the wire and joint.[6] Use a heat gun[7] to shrink the tube into place.

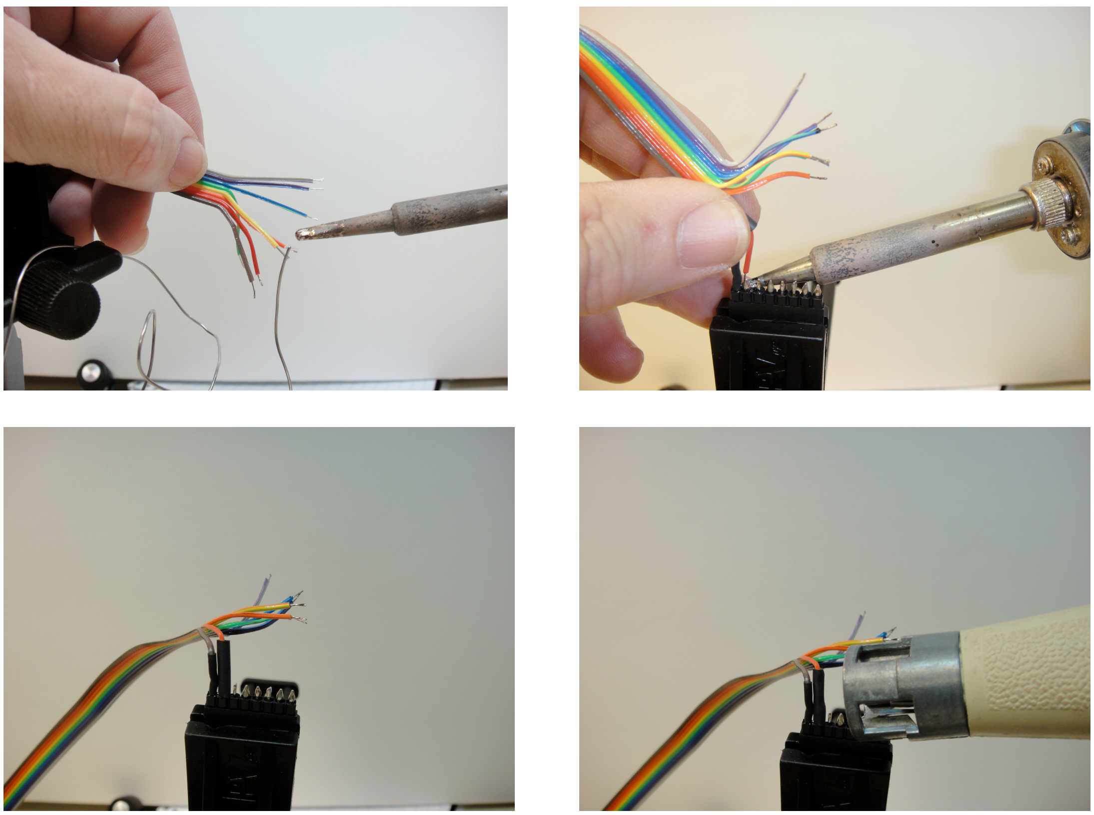


Figure 18.

[6] If the other end of the wire is already connected, you will have to do this before soldering. Hold it far enough away from the joint that it doesn't shrink prematurely.
[7] You can heat the shrink tube with the barrel of the iron, but it won't do as neat a job as a heat gun. Don't use a cigarette lighter, it will probably burn the insulation of the wire.

## *Back to the Board*

Figure 19 shows the circuit laid out in figure 12. The board is easy to assemble if you follow a logical order:

- Place the ICs first, to provide an easy reference for everything else. Feel free to mark reference points on both sides of the board. I like to identify the power and ground busses, you may also want to mark pin 1 of the ICs.
- If the ICs drop out when you turn the board over to solder, spread the pins slightly to provide more grip. Never bend a pin (or any lead) all the way against the board.
- Solder the ICs pins quickly, but be sure there is enough solder. A good joint is shaped like a Hershey's Kiss.
- After the ICs are in place, put in the jumpers. Make sure no insulation gets melted in the soldering process. Keep the jumpers as tight to the boards as possible. Clip the excess ends just above the solder with diagonal cutters (don't cut into the solder.)
- Next add resistors. Resistor bodies should touch the board-- no croquet hoops.
- Finish up with the big items like capacitors and the LED. The cathode of the LED is marked by a flat spot at the base.

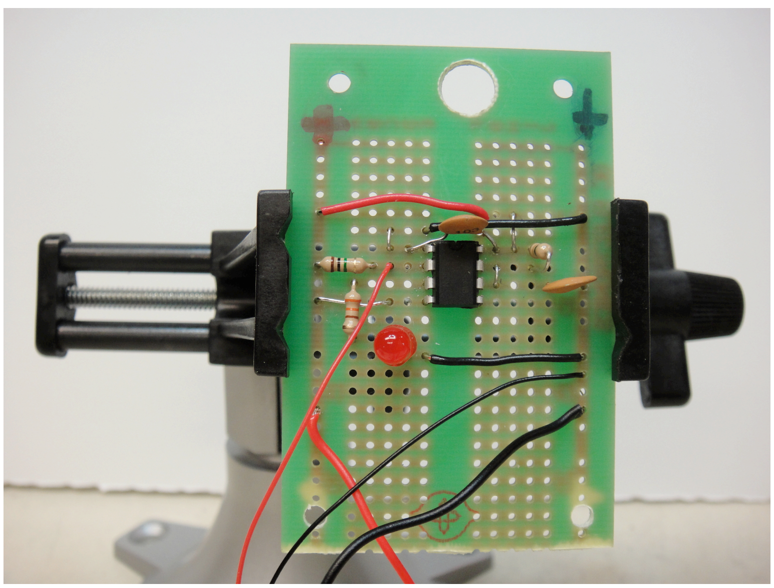


Figure 19.

The board can now be tested by attaching wires to run to the power supply. I like to color code these wires-- black or green for ground and red for +V. I use the same code for jumpers on the board. This is a personal habit. You should develop a similar habit, but the choice of colors is up to you. Test in the same way you tested the breadboard. In addition to mistakes in assembly, you have to look for bad solder joints.

## *Enclosures*

Now that the board is done, it should be put in a box. This is way too late to be thinking about a box- the board should have been chosen with the box in mind, and the box must be chosen with the board in mind. Boxes don't have to be purchased from electronics suppliers-- those are usually overpriced and often hard to work with. Nearly any box will do, as long as it is sturdy. Of course sturdy boxes are getting harder and harder to find. Many of the old standbys-- cigar boxes, cookie tins, lunchboxes, are now very flimsy and flexible. The box material must be rigid enough to support the controls and thick enough that a bolt won't pop through. Maybe the electronics store boxes aren't so bad after all.

[Note: the project we have been working on doesn't need a very complicated box. In fact, it will probably share a box with other things. To introduce basic element of box building, I'm changing projects here. This is just an Arduino enclosure with six potentiometers for analog input.]

The box size is determined by the controls that need to be mounted on it or the size of the circuit board, whichever is larger. If the space is mostly needed for circuit, it is possible to reduce the size of the box by distributing the circuit on two boards and mounting one above the other, but I urge you not to. You will be repeatedly taking the project apart to make adjustments and repairs[8]. The board can be mounted below the controls, as long as you remember to leave the wires long enough to pull the board aside and still operate the device.

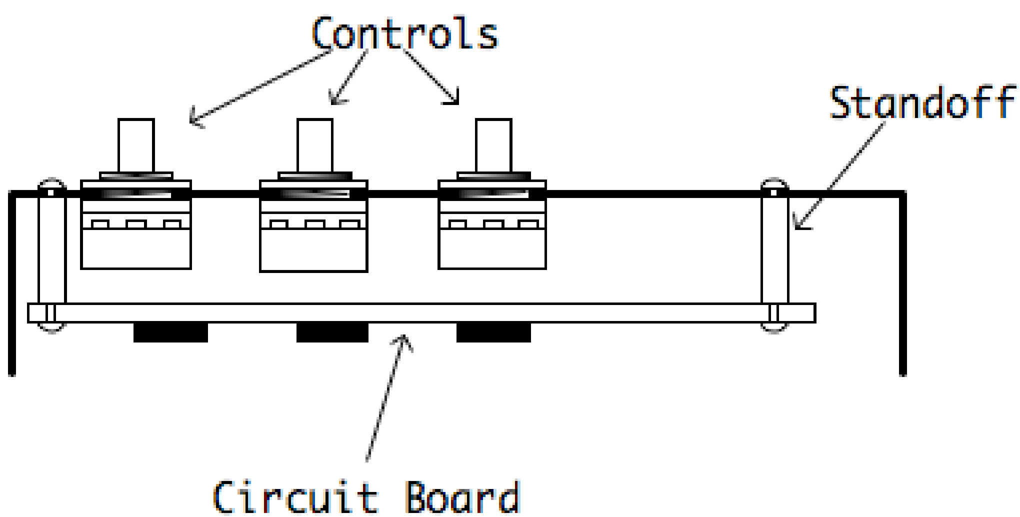



Figure 20.

## Mounting circuit boards

The board is mounted on standoffs, metal or plastic tubes that are tapped at each end for small screws. These cost about fifty cents in small quantities, but if you buy 100 for $35, you have a lifetime supply. I have seen many ingenious substitutes, but they take a lot more than 35 cents worth of time.

[8] There seems to be a rule-- the harder it is access a component, the more likely it is to fail.

### Connectors

The box should have jacks for connection to the outside world. A box with wires that dangle out of it is usable, but the wires are at risk when you move the contraption around and annoying when you pack it away. Jacks may be attached to the enclosure or mounted to the circuit board (or both.) There are gazillions of connector types-- look at other devices you own for inspiration. For our purposes we can think of these basic types:

- Cable connectors for audio signals and the like are held in round holes in the enclosure with nuts that encircle the jack. Power connectors for wall warts are similar.
- Multi-pin connectors usually go into an oddly shaped hole and are held in place with small bolts. The most common of these are in the sub-D series. But these also include microphone and MIDI connectors.
- Cat-5 jacks and USB jacks are soldered to the board and stick out through square holes in the side of the enclosure. Make sure they are securely held to the board, because they take a beating when connections are made.
- Terminal strips are bolted to the outside of the enclosure and require a series of holes for the wires to pass inside. These are good for connecting bare wires such as speakers or alarm sensers.

## *Drilling*

Drilling the box is quite simple compared to the other jobs involved in building a contraption, but it is worth taking some pains to do a neat job. After all, you are going to be looking at the box for several years.

### Layout

To lay out the box, draw an outline of the inside dimensions of the box on a sheet of graph paper. Also draw any posts or braces in the box that could be in the way, and outlines of any connectors that will be mounted on the side of the box. Next place all of the controls on the paper. Include the knobs on the potentiometers. Align shafts and mounting holes on intersections of grid lines wherever possible. Be sure to leave adequate clearance to get in with a soldering iron to make connections. Keep an inch clear between any control and the side of the box, if you can. Once you have a layout that looks good, trace the outlines of each control and circle the grid intersections that need to be drilled. (Use pencil.) Note the drill size needed. Remove each control as you mark it.

Finally, lay the board over the drawing, and mark where the post holes can line up between the controls[9]. If the board includes connectors that should stick out the side of the box, make sure the connectors can reach.

[9] If you can't find a spot that clears all controls, try turning the board over.

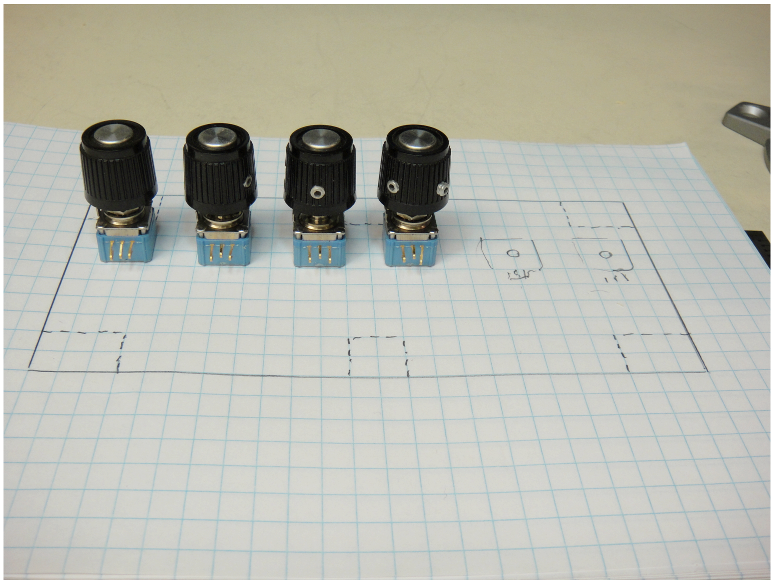


Figure 21.

Next cut the graph paper along the box dimensions. Tape this to the face of the box, making certain the graph lines are square with the box sides. Once it is in place, use an automatic center punch to mark the hole centers. Simply place the point of the punch on the grid intersection and press down-- the punch will go snap and mark the box, right through the paper. Remove the paper, but don't tear it. If the dimples are hard to see, circle them with a sharpie-- once you start drilling, the top of the panel will be covered in junk, and the dimples will be invisible.

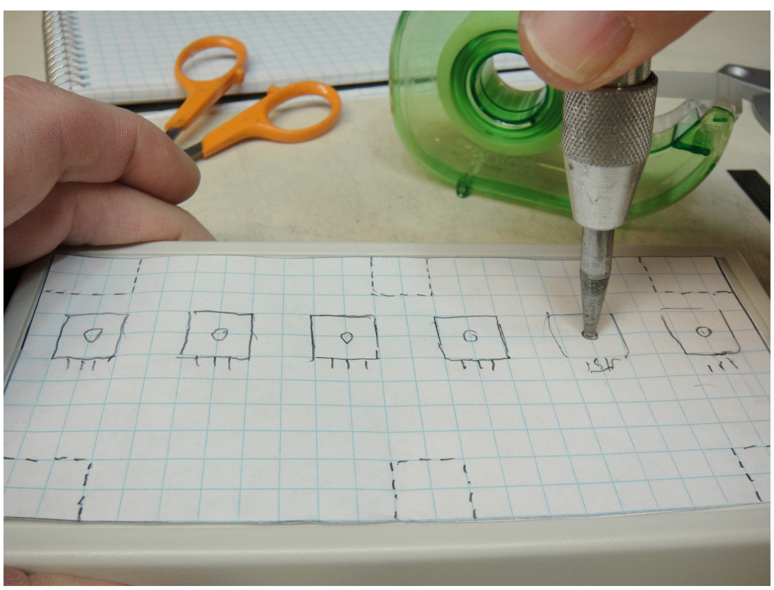


Figure 22.

The next step is drilling. The best job will be done in a drill press, but a good hand drill will do in pinch. Support the panel with a block of wood as you drill.  Start by drilling a 1/64" pilot hole on each mark. Note that the dimple made by the punch will keep this well centered. When you drill, don't try to force the bit through the metal-- take your time and let the bit do the cutting. If you press too hard, the bit will overheat and get dull or seize and break[10]. You don't need to lubricate the bit unless you are working with a steel box. If you are, lubricate it with a beeswax stick.[11] Next drill through the holes with an 1/8" bit. This is big enough for 4-40 mounting screws, if you are using 6-32 screws enlarge these with a 9/64" bit. For larger holes, increase the drill size in steps of 1/8". Slow the drill when the bits get large.

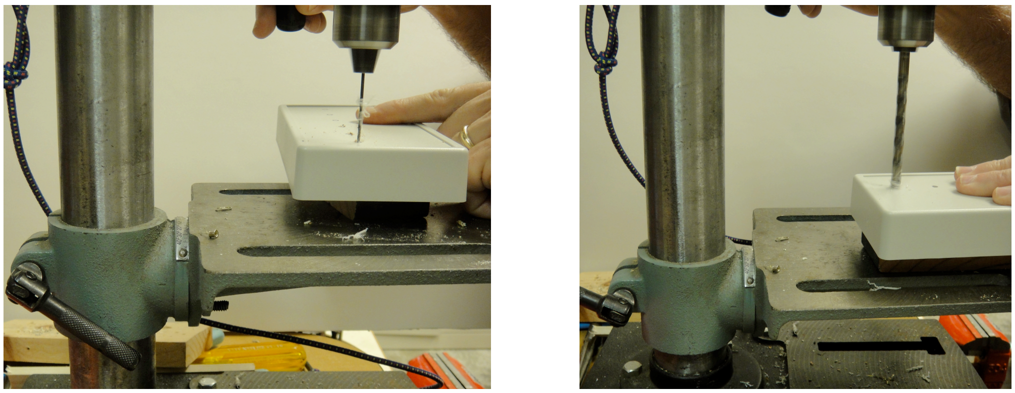


Figure 23.

After the holes are drilled, use sharp knife (on plastic) or file to remove any burrs.

## Other holes

If all we needed were holes for round controls and screws, life would be easy. Unfortunately, controls and connectors come in many shapes.

## Slots

The proper tool for making a long slot is a mill in a milling machine. A nice milling machine can be had for about $5,000. If you don't have one in your garage, you will have to improvise.

The simplest approach is to drill holes to mark each end of the slot and use a jeweler's saw or a coping saw to cut the slot. I only recommend this for plastic boxes-- you will break a lot of blades if you try to cut aluminum this way. After drilling the end holes, mark the edges of the slot (make it narrower than you think it needs to be-- the saw cuts on both sides of the line.) The box must be held solidly in a vise --use a block of wood to support the box face against the vice jaw. Remove the blade from the saw, pass it through a hole, and reassemble the saw. Now very carefully cut along the lines. Use a thin flat file to finish the edges of the cut.

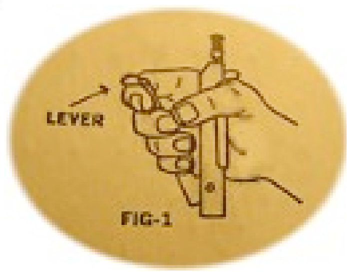
To cut a slot in aluminum, drill a series of touching holes for 3/4 inch[12] at one end of the slot. Use a flat file to open the holes and shape this to the width of the slot. Now use a

[10] Small bits are always sold in pairs. Now you know why.
[11] They are usually used to lubricate sticky drawers and doors.
[12] Use a bit just wide enough for your file- these holes will never be perfectly straight.

hacksaw in the manner described above to cut the slot. Sawing aluminum goes easier with a bit of beeswax on the blade.

The next step up is to use a power jigsaw. Since most jigsaws are bigger than the box you are working on, you will need to build a guide plate that will fit around the box and fit flush with the top[13]. Then you can clamp guides to the plate that will keep the saw cutting straight. Use a fine blade and move the saw slowly.

## Square holes




Square holes larger than 5/16" can be cut with a nibbling tool. As the name suggests, this removes a tiny bit of metal at each chomp. The bit is rectangular, and with patience (and an iron thumb) you can make any manner of hole with straight edges.

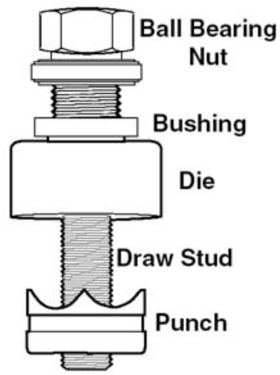
## Big Round Holes

You can only drill a hole up to 1/2" or so. Anything larger than that requires a hole saw[14]. A hole saw has three pieces-- a central arbor that fits in the drill chuck, a pilot drill, and the saw blade itself. Blades of various sizes can usually be interchanged on the arbor. The difficult thing about using a hole saw is getting the cut exactly where we want it. There are two ways to improve the odds. Number one is to use it in a drill press with the box clamped to the drill press table. This keeps the saw parallel to the face of the box. If there is any angle, one side of the saw will grab first and pull everything off center. Always clamp a piece of wood behind the hole location. This keeps the face of the box from flexing, which would have the same effect as drilling at an angle.

[13] It's not hard to build if you've got a jigsaw.
[14] There are milling tools for that job, but we already decided we can't afford one.

The second trick is to turn the pilot drill around and use the back of the shank to guide the saw. This means you have to drill a pilot hole first and lubricate it. When you try to drill the pilot and outer hole in the same pass, the edges of the pilot drill can enlarge the pilot hole and let the saw wander.

## Greenlee Punches



If there are a lot of odd holes in your life, it is worth investing in a Greenlee punch or two. These are heavy duty punch and dies that you  pull through the metal with a wrench. They come in many sizes and shapes, including a 1/2" x 1/2" square. Prices range from $30 to $1500 (really!). Luckily the more common holes tend to be the less expensive. It will last you most of your life, so it really is an investment. There are other brands, but the name Greenlee is almost synonymous  with punch.

### Labels

Each control should be labeled before anything is mounted in the box. Use as much or as little care as you feel this needs, but remember you will be looking at this for a long time. Here are some labeling systems that <u>don't</u> work:

- Pens and markers (They fade or rub off. OK for short term items.)
- Paper labels (They dry up and fall off. Probably tomorrow.)
- Dymo raised letter tape. (Falls off in a year or so. Corners apt to loosen and get caught on things. Can be reattached with double stick tape.)

These Do: (Ordered from pretty to ugly.)

- Dry transfer letters. These come in  big sheets and you rub them into place with a steel burnisher. A bit difficult to line up until you get the knack. Once in place, protect them with a layer of clear tape.
- P-touch Labels. These are labels printed on sticky tape (colored or clear.) A forty dollar gadget does the printing, but the tape costs about 50 cents a foot. (Tip: print several labels at a time and cut them apart. Each print job wastes a good 3 inches of tape.
- Paper labels printed on a computer. Cover the label with clear tape, then use double sided tape (Scotch is stickiest) to hold the label down.
- Scratching letters directly into the surface of the box. Ugly but effective in a good light. You can do a cleaner job with an electric engraver and a letter stencil. No room for mistakes.

You can also print a paper cover for the entire panel, with labels and other decorations. Tape this over the panel with a grid of double stick tape and cover it with a sheet of Cleer Adheer laminating film. Cut out the mounting holes with an X-acto knife. A layout program like InDesign is best for this. Cut slightly smaller than the panel so the laminating film will overlap a bit and stick directly to the metal.

Place labels under controls, in a clear relationship to the control they mark. Check your spelling carefully.

Don't forget to include your name and a name for the box.

### *Final Assembly and Wiring*

Once the box is drilled and labeled, final assembly is a snap.

- Mount all controls and connectors
- Run common wires (power and grounds) as needed. Look at figure 24 for a reminder of how to wire potentiometers to supply analog control.
- Solder lengths of wire to each point that will go to the board- that's the center taps of pots, switch terminals and so on. Don't forget power and ground wires. Use heat shrink tubing where wires are close together. Use stranded wire for this.
- Set the board alongside the box, propped up so the solder side is away from the box. It should be oriented so it can "fold" into position on its standoffs in the box.
- Solder the free ends of the wires to the board, or to headers stuck into the board. Leave the wires long enough that the board can lay flat.
- Test the operation of the contraption at this point. Once it works, fold the wires under the board and mount it on the standoffs. Test it again and put the cover on.

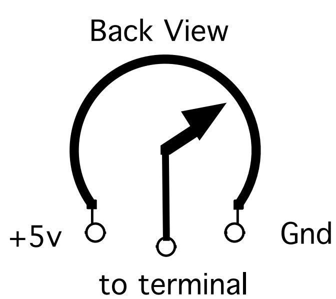



Figure 24.

Figure 25 shows the completed project.


Analog 0
Analog 1
Analog 2
Analog 3
Analog 4
Analog 5
Arduino NG
Standard Firmata
PQE 2010

Figure 25.