SETTING UP AN AMATEUR WORKSHOP

CHAPTER 3B

Techniques for building and trouble-shooting circuits

Every homebuilder has his own methods of constructing and trouble-shooting his electronics. My methods won't be the same as yours, but hopefully you'll find some useful ideas in this chapter. I thought about writing this chapter years ago, but a reader, Matt Gibbs, inspired me to actually write it. He pointed out that I had not discussed the difficulty of trouble-shooting "dead" circuits when the builder has little or no test equipment. Many guys face that challenge. I certainly did, long, long ago.

Trouble-shooting with minimal equipment

The most important tool for trouble-shooting is an **understanding of how the circuit works**. If you don't understand how the circuit works, a schematic diagram is just a pattern of lines on a piece of paper. With luck, a circuit might work OK if the pattern of wires and "electronic thingies" seems to match the drawing.

When I was 12 years old, I was impressed by the small size and simplicity of a crystal set schematic that I found in a book. I thought it would be fun to conceal it inside a book. Before transistors, portable radios had large vacuum tubes and were NOT small. They were also complicated and expensive. I imagined that having a secret radio at school would be very cool. I could listen to the World Series when the teacher's back was turned. Real portable radios were too big to hide at school. I carved out a cavity inside the pages of an old, unwanted book and installed the crystal set. Unfortunately, a proper 30 or 40 foot long wire antenna wasn't going to fit inside that tiny compartment inside the book. I never heard the slightest whisper of sound out of the single earphone.

By age 12, I was living 2,000 miles away from Mac MacKenzie and could no longer ask him for advice. If I been able to ask someone, the crystal set would never have been mounted in a book and probably would have succeeded. Are you interested in crystal sets? Read Chapter 4A.

Basic trouble-shooting strategies

If you have no measurement equipment at all, you will have to invent ways to test circuits and components. Before you assemble or solder anything, make a careful inspection of each component. Are you sure you're using the right value resistor? Review the resistor color code in Chapter 2. If you read the colors backward, your resistance will be ***way*** off. Now inspect your capacitors. If the schematic calls for 22 **pF** and your capacitor is 22 **µFd**, it definitely won't work. Again, review the capacitor advice in Chapter 2. If the circuit has a diode or a transistor, make sure you have the correct component type number and understand how to orient the component leads correctly in the circuit.

After you have assembled and soldered a few of the parts, review the connections. Check again to be sure the diodes and electrolytic capacitors are connected with the correct polarity.

Look for loose wires. Tug on any connections that look suspicious. A frequent difficulty is weak batteries. To test batteries without a voltmeter, put them in a flashlight or other device that uses the same size battery.

A simple continuity tester made out of a flashlight bulb and two 1.5 volt batteries or a single 3 volt lithium battery is easy to understand. Mechanically, this may not be so easy to construct. If you have an old flashlight with a plastic body, holes could be drilled in the body to solder two wires across the ON/OFF switch. The idea is to apply the two wires to connections or components you wish to test. If the light goes ON, the connection is intact. If the light remains OFF, the circuit is open - not connected.

The first test instrument you should own is a multi-meter to measure voltage and resistance. Start with an inexpensive multi-meter. For $20 or less, you can buy a multi-meter at the hardware store that will still be useful long after you've graduated to $400 meters and oscilloscopes. When I was young, I never had more than a multi-meter and a low frequency 5 MHz oscilloscope. However, I also had a ham radio receiver so I could hear oscillators and get some idea about my signal quality. I used light bulb dummy loads for my transmitters. If a 25 watt, old-style filament bulb glows at full brilliance, the transmitter probably has about 25 watts output. Other than my poorly calibrated short wave receiver, I had no way measure frequency.

Beginners often don't notice obvious mistakes. Are you ***sure*** nothing is shorted? In Chapter 4A I tell a story about the young grandson of a friend building a crystal set. He forgot to carve a gap in a copper trace on his printed circuit board.* He had inadvertently shorted out the crystal. His craftsmanship *LOOKED* beautiful. It's so easy to focus on the difficulty of *CONNECTING* a wire, that we often become confused about where it was supposed to go.

*(Printed circuit boards are sometimes abbreviated as "PC board" or "PCB.")

The necessity of oscilloscopes and frequency counters

Once you progress past crystal sets and simple circuits with 2 or 3 transistors, diagnosing faults becomes increasingly difficult. To be blunt, before I had a calibrated oscilloscope that could cover ham frequencies, I really wasn't very competent. I did have a short wave receiver to hear the signals, but it wasn't always obvious what I was hearing. Was it a harmonic or the real frequency? If the signal sounds rough instead of a pure whistling tone, maybe my signal isn't a sinewave. Maybe the rough note is caused by my line-operated power supply.

I remember several of my high school projects that might have succeeded if I had had some way to analyze waveforms and frequency. If you are generating signals in specific ham bands, a good frequency counter is essential. Sixty years ago a first rate, professional quality oscilloscope cost $10,000 or more. Today a scope like that can be replaced with a digital scope costing a few hundred dollars. Remember too that, back then, a can of soft drink cost 5 or 10 cents, but now costs over a dollar. Modern electronics are assembled by machines in minutes. They are no longer hand assembled over days, the same way we now build projects in our basements.

Most modern oscilloscopes have a built-in frequency counter. An oscilloscope with a frequency counter is much better than a simple frequency counter. The scope picture will show you exactly ***what part*** of the waveform you're measuring. The triggering level can be adjusted up or down within the positive or negative portions of the waveform. For example, if your waveform is complex, it might have smaller, higher frequency components superimposed on it.

When the trigger is set near the peak amplitude of the varying voltage it will only "see" the highest frequency components. It only counts the pulses the trigger level passes through. The number it displays may be higher than a low voltage AC component but lower than the high voltage component. If the sinewaves are occurring in bursts, "motor boating," a simple counter will only count the waves it sees. With a simple frequency counter, you won't realize that the sinewave frequency is actually much higher. It is simply isn't seeing pulses much of the time.

Simple frequency counters and oscilloscope/counters have a response voltage threshold. They don't register signals that are lower than this minimum amplitude. On the oscilloscope you can often see the low amplitude waveform, even though it's too weak for the counter function to respond. If the AC waveform is below the voltage threshold of the frequency counter function, you may still be able to see the small sinewave and estimate its frequency.

Some transistors have very high gain and are capable of oscillating at extremely high frequencies, over 50 MHz. It is not unusual for a transistor to start oscillating in addition to amplifying the desired lower, ham band frequency signal. For example, a 7 MHz signal may still have its sinewave form, but the slower sinewave "hills" will be pierced with much higher frequency spikes.

You can often count how many waves per calibration square there are on the screen. If the scope is set to 1 microsecond per square, the frequency will be 1 million times that number. In other words, "invert" the number (divide it into one) to change microseconds-per-cycle into cycles-per-second, megaHertz. By ignoring low voltage noise spikes, the counter can then display the dominant waveform frequency. In short, oscilloscopes give you the whole story.

Constructing transistorized circuits

As Mac McKenzie, W2SOU, taught me, we need to build ***and test*** our circuits one small piece at a time. Building and trouble-shooting should happen simultaneously. ***Trouble-shooting begins with the first solder connection.*** Make your circuit easy to trouble-shoot by establishing your own standard ways of locating the power leads, color coding wires, orienting transistors and so on. Transistors are tiny and fingers are relatively fat. Soldering components together requires patience and care.

My method of building circuit boards often requires several components to be soldered to the same small circuit node. My technique is a kind of "surface mount" construction except that nearly all my components are large, old-style parts with wire leads. Node junction points are simply small patches of intact copper surface on a large circuit board. Frequently, when I'm soldering the second or third component, the first wire lead pops free. Then I have to go back and figure out how to hold one part down while soldering another. It doesn't help that the node is often buried between the inductors or capacitors that I'm soldering.

Paradoxically, concentrating on soldering solid, clean connections means I pay less attention to following the circuit diagram. ***As a result, I routinely make wiring errors.*** In other words, my circuits frequently don't match the schematic. Decades of experience haven't changed that difficulty.

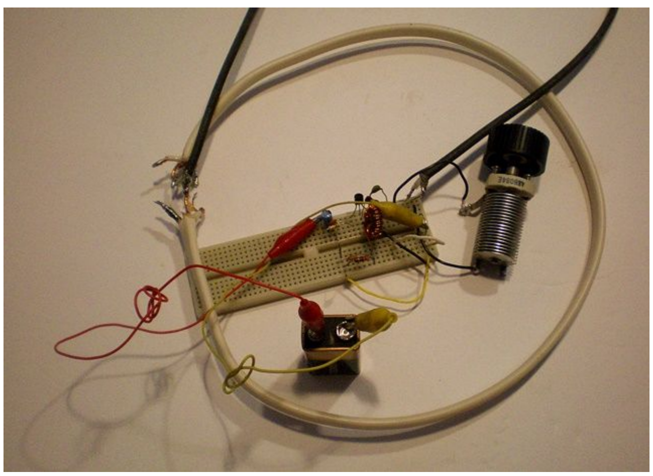
Knowing that I often make this error, I always look for mistakes. First I compare what I just built with the schematic diagram. Next I examine the solder joints with a jeweler's loupe or other magnifier. I'm always reasonably sure the circuit is correct before I turn on the power.

Because of this habit, I rarely turn on the power with my stupid errors still in place. If your circuit runs on more than a few volts, your error may damage a transistor, electrolytic capacitor or other part. That's why it's helpful to be able turn up the supply voltage gradually while watching the current drawn by the circuit.

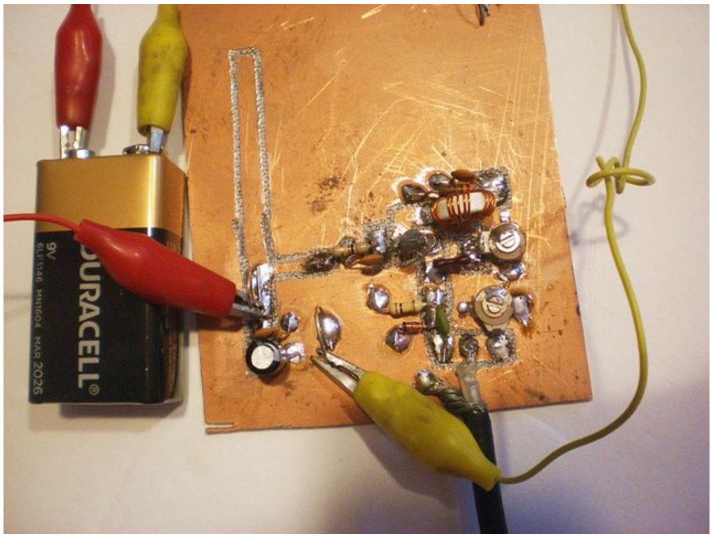
Bread-board prototype first

If you aren't certain that your circuit will work, start with a crude prototype. Don't start by building a high quality circuit board complete with all the connectors and shielding. Perhaps you can't find the parts called for in the original design. Maybe there are several values of components that you had to calculate for a specific frequency and you don't trust your numbers. With parts stuck together in a so-called "bread board," you can work out the basics of the circuit without wasting too much labor and time.

The picture below is a plug-in board prototype of an oscillator that drives a metal detector. The big loop of wire is the seeker inductor that senses a nearby metal object by a small change in resonant frequency. The variable capacitor in the photo adjusts the oscillator frequency to match a receiver circuit which listens for the subtle shifts in frequency.

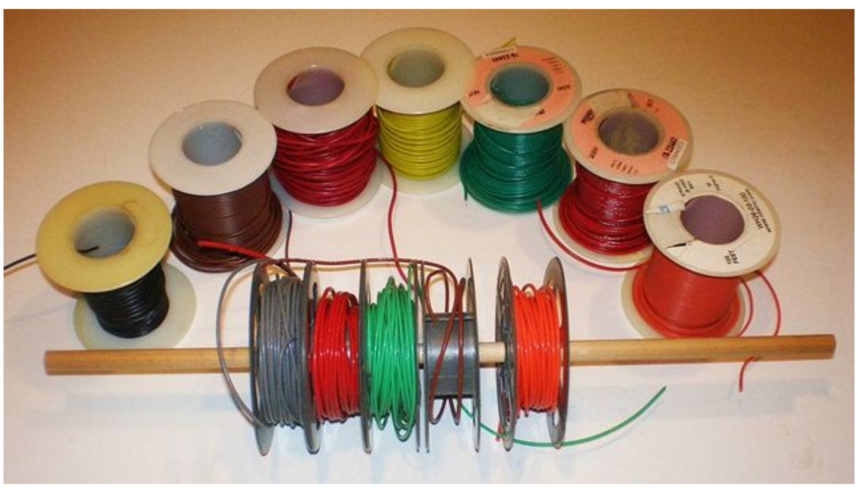


Once the oscillator seems to work as well as needed, you're ready to build the real circuit. Even with the "final" version of a circuit on a circuit board, don't add the shielding and precision power supply until the circuit is operating correctly with the other circuit modules that it must work with. The PC board version of your circuit can be *MUCH* smaller and more compact than the bread board version and will be hard to modify. A quality circuit board will have different stray capacitances and inductances which will alter the performance slightly. At each stage of the development, adjust the part values and adjustments until the entire project works together, like a symphony orchestra. Here is the circuit board version of the same circuit:



Hook-up wire

"Hook-up" wire is a common name for the insulated wires used to connect circuit modules or to connect a switch or potentiometer to the rest of the circuit. There are two basic types, ***multi-strand*** and ***solid conductor***. Multi-strand is a single "wire" composed of multiple tiny wires, much like a rope or a flexible steel cable. Typical wiring in tube and transistor ham gear uses size 20 to 24 gauge wire. Thicker wires are stiff and awkward to use. Thinner wires tend to break off at the solder joints. Multi-strand wire is flexible and doesn't break even when the wire is bent repeatedly. However, if you use too much solder connecting a multi-strand wire, the solder will often flow up among the wire strands and convert the bundle of thin wires into a single, solid wire. Again, if there's too much solder, the multi-strand wire may break when flexed.



Electrons don't care about the color of a wire's insulation. However, wiring a circuit and trouble-shooting it is ***much*** easier if we use different colors for different functions of the circuit. Establish your own color codes for positive voltage lines, negative voltage wires, ground wires, active signal wires, etc. For example, I use green or black wires for ground. I connect the positive pole of the power supply with red wire. Define insulation colors any way you like, just be consistent!

For homebrew work, the most convenient sizes are 20 to 24 gauge wires with colored,

vinyl insulation. **Teflon** insulated wires, like the wire spools on the wooden dowel, withstand abrasion, heat and voltage much better than vinyl. Unfortunately, Teflon insulation is hard to strip and I usually have to carve if off with a pocket knife. In my opinion, wires thicker than 20 gauge are usually awkward for our kind of equipment. Reserve thick wires for high currents, say over 5 amperes.

Solid conductor wire is usually sold on spools and insulated with plastic. The most common use I have for bare copper wire is making little "test loops" or test locations that stick up from a circuit board. Oscilloscope probes can be clipped onto these test loops. I also use loops of solid wire to clip on a variable power supply for testing.

Magnet wire

Some solid conductor wire is insulated with a tough, colored enamel. This type of solid wire is called ***magnet wire.*** It's designed for winding coils in which each turn of the coil is pressed against its neighboring turn. Coils are supposed to generate inductance. Without the coating, the turns would all short together and become a copper cylinder with no inductance. The enamel coating is impervious to soldering and is difficult to scrape off. Hold the end of the wire against a hard surface then scrape off the enamel with a pocket knife.

Wire connections and soldering

This is a big subject. I suppose the simplest wire-connection method is simply to twist bare wires together. As explained Chapter 3A, I have learned and re-learned that *CONNECTIONS THAT AREN'T SOLDERED CAN'T BE TRUSTED!* Crimped connections often work in the short term, but fail after weeks or years. Once I bought an old car that had been rewired by its previous owner. The wiring was connected with lugs and eyelets which were fastened mechanically to the wires using the appropriate special crimping pliers. Apparently it worked well for several years before I owned it. After I bought it, it developed so many intermittents, I eventually soldered every connection.

Unless the circuit you're building is a small, temporary experiment, it really needs soldered connections. Simple, inexpensive soldering irons with a fine point work well for ordinary, easy connections. But for tiny solder joints on small, fragile transistors, a fine-pointed soldering iron with a variable temperature control is needed. Without the temperature control, it's easy to damage semiconductors. Eventually you'll need one.

Electronic circuits are nearly always soldered with 60% tin/40% lead or silver. The flux is contained in the center of wire-like solder. A common flux material is rosin, pine tree sap. The flux makes the solder melt easily and helps it merge with copper wires. Similar, heavier wire solder is sold in hardware stores for soldering copper pipes. This "acid flux" solder works better on old, corroded pipes. But when used on delicate wiring, the acid continues to react with the copper and may eventually cause the connection to become intermittent. However, if you ever need to connect copper wire to steel, acid core will work, while rosin core won't.

Tinning connections before soldering

"Tinning" refers to melting a bit of solder onto a terminal or wire end before you try to make the connection. If you generously tin both the wire and its destination, the solder will already be in place for the solder joint. Then all you have to do is bring the two pieces together and heat them. If neither the wire nor the joint are tinned, extra time will be needed to heat all three metal components - the destination, the wire lead and the solder.

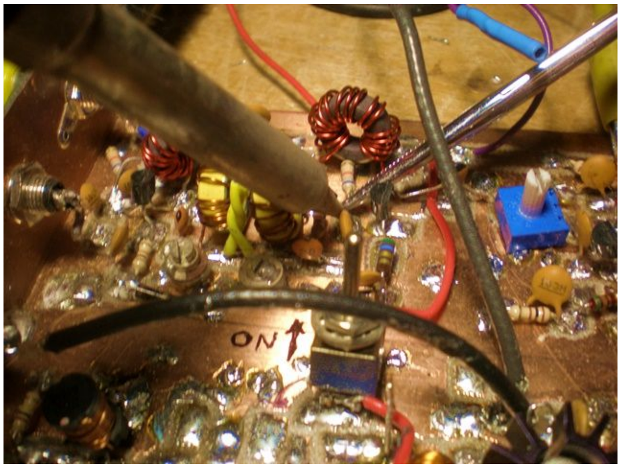
Instructions on "how to solder" often tell us that, before we solder, we first need to make a mechanical connection between the wire and its destination node. If you're wiring something big, like an electric lawn mower, that's good advice. Unfortunately, with tiny electronic circuit boards there simply isn't room for that. Back in 1965 printed circuits were always designed for through hole components. Small holes were drilled through the board. The components were mounted on the opposite side of the board from the traces. The component leads were fed through the holes and bent in place, making a reasonably solid mechanical connection.

Modern boards are almost entirely surface mount. The components are on the same side as the circuit traces and there's no practical way to secure them mechanically before soldering.

Soldering instructions often warn that, "It's bad practice to bring solder to the connection by first generously tinning the soldering iron." If you are blessed with three hands, I agree with that. Occasionally I have held the roll of solder in my teeth while holding the component in one hand and a screwdriver in the other. The flat screwdriver tip holds the tips of the wires in place on the PC board while I bring in the tip of the soldering iron. There are dedicated tools called "soldering aids" which serve the same purpose as my little screwdriver. Buy one if you want!

Using a hemostat

A hemostat clamp is an under-appreciated tool. They were originally designed to clamp small, bleeding blood vessels during surgery and stop the blood loss. They work the same as needle nose pliers. They differ in that they are longer and thinner and can penetrate down between tall components. Another virtue is that they can securely clamp onto the lead of a resistor or other component and they will remain attached until you release them. Unlike needle nose pliers, you don't need to apply pressure continually to maintain your grip on the hemostat. If you need to replace a resistor or other part, they're frequently located deep between tall parts on a circuit board. There is often barely enough room for the soldering iron, let alone stubby pliers or fat fingers.

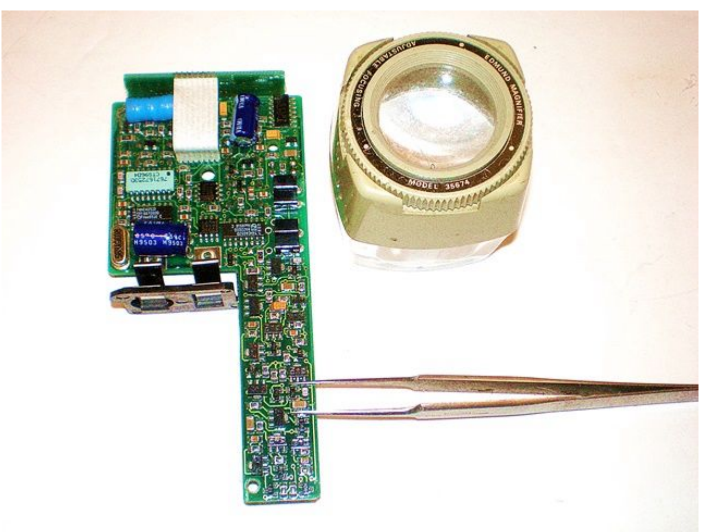


In the photo above, a hemostat coming in from the right is clamped onto 1/4 watt resistor lead. The soldering iron is held in the left hand. As always, holding the solder with your teeth or un-used fingers is a contortion act. At least with the hemostat, you don't have to maintain pressure on needle nose pliers to keep a grip on the wire. Best of all, you won't burn your fingers.

In the old days, I often positioned parts on a circuit board by simply holding them with my fingers while I applied the solder iron with the other hand. Once the solder ran freely and formed a shiny bead on the junction, I removed the iron. After the solder melted, I couldn't remove my hand until the shiny bead of solder cooled to a slightly dull or gray color. The color change always happened just after the heat had passed through the component and was burning my fingers! I learned that the molten solder was not solidified until just ***after*** the pain in my fingers became almost unbearable. That is a terrible way to solder!

Tweezers for surface mount components

Modern electronic components have progressed to becoming tiny, sand-like granules designed to be mounted on P.C. boards by robots, not humans. Humans are limited by our eyesight and fat fingers. As shown below, fine pointed tweezers are used to handle the chips. A microscope of some sort is needed to examine the solder connections. To make matters worse, we old guys often have a bit of tremor.



The circuit surface mount circuit board shown above was up-to-date technology in 1995. Now, in 2022, those surface mount parts are "big" and old-fashioned. Modern boards aren't 2-layer, like this 1995 board. The latest boards have ***many*** different levels, like a tall office building. The chips themselves have as many as 100 contact points ***under*** the chip. The contacts are no longer located at the edges. It was barely practical to build boards like the one shown above in a basement workshop. In my opinion, home-building with the latest boards and components is no longer practical. Some gung-ho guys still manage to build 2010 technology boards. They lay out the board traces using their computers, e-mail the drawings to China, then wait for Fedex to deliver the boards. Tiny syringes, tweezers and microscopes are used to apply the solder paste and lay down the chips. They use a precise, temperature-controlled oven to heat the boards and melt the solder. The next step up in technology would be to install an entire, modern, "pick-and-place" robot assembly line in your basement.

Printed circuit boards are essential

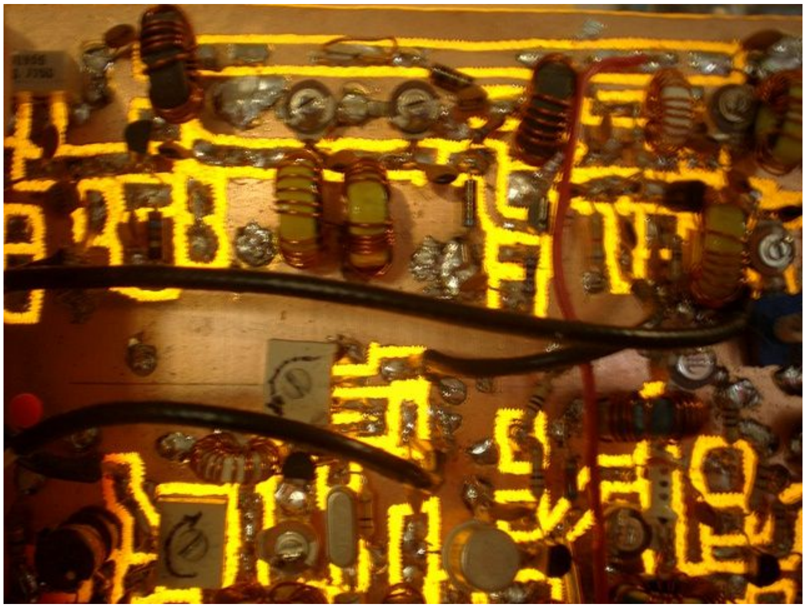
Transistors operate at low voltage and relatively high currents. High currents make the tiny amount of inductance in a wire or circuit board trace become important at radio frequencies. It is essential to build transistor circuits on printed circuit boards so that the connections between parts are as short as possible. Interconnecting transistors and LC circuits* with long, skinny wires rarely works well at radio frequencies. Techniques for building circuit boards are described in detail in Chapter 6A. There are several ways of making printed circuit boards. A printed circuit board usually begins with a sheet of non-conductive material, usually fiberglass. A layer of copper metal is plated onto one side of the board or on both sides.

* (An LC circuit consists of an inductor resonating with a capacitor.)

Single-sided printed circuit boards

Single-sided boards are the most common type found in old equipment. The classic board consists of a 1/16 inch F4 fiberglass sheet with 1 ounce copper plating on one side. Two-sided circuit boards are the same except the opposite side is also copper plated. Circuits are carved or etched onto the board by removing the copper metal in a pattern. The result is a web of metal lines, "***traces***," which serve as wires connecting the resistors, transistors and other discrete components.

A common difficulty with printed circuits is that stray bits of solder or fine wire end up lodged against traces making a short circuit between one trace and another trace or ground. The easiest way to spot these shorts is to hold the single-sided board up to the light and let the light shine through the fiberglass. This is like an "X-ray" and allows you to inspect nearly all the board at once. If there is a short, it is usually obvious and a microscope isn't needed.



Another advantage of single-sided boards is that the unwanted capacitance between the traces and ground can be very low. This makes single-sided boards practical at VHF frequencies, such as 6 meters (50 MHz) and above.

Double-sided circuit boards

For me, the advantage of 2-sided boards is that the unused back side has no components on it and is a perfect electromagnetic shield of grounded metal. This means that the ground sheet prevents radio signals coming from the outside, like AM radio stations, from coupling directly into your circuit. Similarly, RF currents on your board won't be coupled out the back of the board and effect other circuits. For example, quality ham receivers are equipped with a precision crystal filter for isolating radio signals. It is vital to keep the many signals on the input of the crystal filter from coupling to the desired signals on the output. Without shielding, the crystal filter accomplishes nothing.

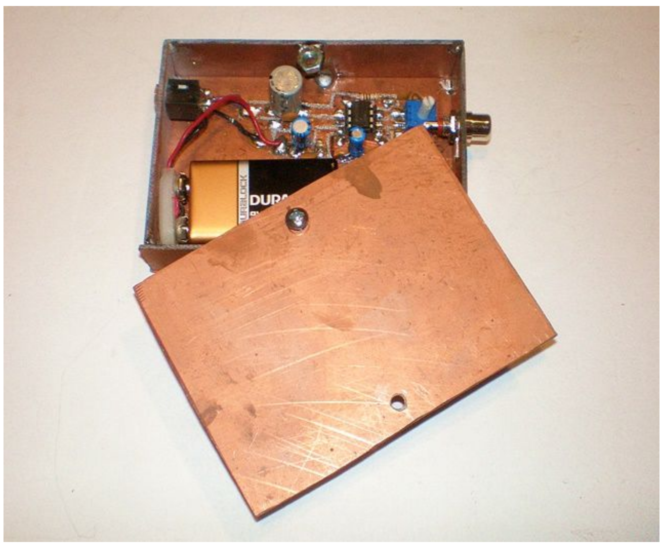
The resistance across the un-etched copper sheet on the back of a double-sided board is always (virtually) zero, even at very high frequencies and high currents. In contrast, the skinny copper traces on the component side frequently have significant impedance,* or resistance, at high frequencies and high currents. To keep your "grounded circuit nodes" truly grounded, you can connect the grounded traces on the front of the board to the back side using feed-through wires. Drill a tiny hole through the grounded pad then pass a small bare wire through to the back side. Solder both sides. Assuming you intend the back side to be grounded, be sure the front and back grounds are connected in multiple locations.

*"Impedance" is the total resistance to alternating current flow at a specific frequency that is produced by the sum of all the capacitors, resistors and inductors in a circuit.

Double-sided boards have high stray capacitance to ground and are difficult to use above 30 MHz, 10 meters. Also, double-sided boards are harder to troubleshoot than single-sided. Since light doesn't pass through them, you need to inspect them with a magnifying glass to spot the tiny shorts. Another common fault is that solder-coated wire ends, that are supposed to be soldered to a connection node, are above the node, but not actually touching it. With the jeweler's loupe or microscope you can see that the wire end is suspended above the node, but not in contact. Whether my circuit boards are single or double-sided, I mount my parts on just one side.

Two-sided boards can become shielded enclosures

Another advantage of 2-sided boards is that you can solder side walls onto the board and turn it into a grounded, shielded box. This results in a 5-sided box which can be covered with an aluminum or PC board lid. This completes a grounded shield around your entire circuit. For example, if you are plagued by a local, high-power AM radio station, the shield can keep that signal out of your ham radio band filters and amplifiers. Without a shield, you might find uninvited rap music riding on top of your ham friends.



The photo above shows a totally shielded audio amplifier. I built it in a desperate attempt to keep 60 Hz AC hum out of the audio modulation in my 2 meter FM transmitter. It didn't work. It's a nice box, though.

Metal shielded boxes keep out unwanted radio waves

Radio waves can exist at any frequency above zero Hz. That includes the 60 Hz (or 50 Hz) sinewaves used in our household power. In the 60 Hz example of a line noise hum penetrating my shielded box, it was a very difficult application, so I'm not surprised that it failed. 60 Hz "hum" in my audio circuits is a common difficulty with any electronics plugged into the AC power. Because 60 Hz is such a low frequency, it is approaching the zero frequency and is almost a static magnetic field.

Usually, when I add really large filter capacitors to my power supply, like 6000 µF, the hum is silenced. I had already done that to my transmitter, but a small hum persisted. My 2 meter transmitter runs at 146 MHz. However the FM modulation was generated at 18.4 MHz add FM modulation must be applied to the oscillator where the signal originates. The basic sinewave needs to vary its frequency up and down in accordance with the speech frequencies and amplitudes. All circuits powered by AC will have some slight 60 Hz hum riding on them, even if it is only a microvolt RMS. In the case of my audio signal its hum was about 10 millivolts. This was undectable to the ear. But to move the 18 MHz signal up to 146 MHz, the basic signal had to be multiplied 8 times, so 8 times 10 mv RMS became 80 mV RMS. At 80 mv it became audible. Still another factor is that FM modulation is not just frequency modulation of the original audio frequencies, it is also FM modulation of the original audio amplitude variation. Both AM and FM are varying in such a way to exaggerate the hum.

Double-sided PC boards for VHF and UHF

The capacitance between all the traces on the circuit side and the sheet of grounded copper on the back provides a capacitive pathway to ground for very high frequency (VHF) oscillations. The downside of double-sided boards is that, if you wish to use them for VHF circuits, they will have poor gain or won't work at all. I concluded that, usually, double-sided boards were impractical above 30 MHz. Higher frequencies are easier to build with single-sided boards.

There is one type of double-sided board construction technique for very high frequency (VHF) and ultra high frequency (UHF) called "microstrip" in which designers use special (expensive) double-sided PC boards with exotic fiber-glass insulation. They exploit the trace capacitance to ground making coax-like pipes from one component to the next. Schematic diagrams for VHF and UHF circuits often show little labeled rectangles on the wires between parts. These describe the precise measurements of the traces between components. I've tried to do "microstriping" by trial and error using ordinary (cheap) two sided boards. The microstrip traces are supposed to convey VHF signals from one node to the next without attenuation. Sadly, my attempts using cheap board material didn't work. For VHF circuits I use single-sided boards but leave large expanses of intact copper for the ground and power traces.

Trouble-shooting a receiver

Suppose you build a receiver using any of the several receiver designs: Before you try to listen for signals on your new creation, it's desirable to know if there really are signals on the air for you to hear. As you probably know, the ham bands rarely have ham signals 24/7. If you're a beginner, I assume you don't have a signal generator or a transmitter you could use to generate your own test signal.

Do you have access to a commercial ham band receiver? if so, you can find out whether there are signals on the air. Even better, you should be able to hear your local oscillator tone "whistling" on the desired band. If the receiver is designed for lower frequencies, such as 80 or 40 meters, listen in the evening when you're likely to hear the most signals. A simple long wire, 10 feet long should be a large enough antenna to pick up lots of stations. Ideally, it should have access to the sky and not be indoors. Some houses, like mine, have aluminum foil-coated insulation in the walls to maintain humidity in our dry climate. Unfortunately, the metal also shields the house from radio signals. Cell phones work poorly inside my house.

Another test you might try is to bypass the input filter and connect the antenna directly to the mixer input. That will detect signals much like a crude crystal set, even if the local oscillator isn't working. You should be able hear lots of signals - in fact, way too many! However, it will tell you whether your audio amplifier and headphone are working. Always try to test circuits one piece at a time. Does your headphone actually work? Plug it into a working radio and see.

Does your audio amplifier work? One crude method is to apply a flashlight battery to the input of the amplifier. Connect wires onto the battery voltage terminals - Scotch tape will work. One wire goes the receiver ground, the other wire is loose. Scratch the loose wire onto the mixer input terminal and the audio amplifier input. The 1.5 volt, intermittent "signal" should make a scratching noise audible in the headphone. You can also use this method to test the headphone directly.

"Shooting a board"

When I was working as an engineer in the R & D department, it occurred to me that the technicians down in the production and customer repair departments must have trouble-shooting tricks I had never thought of. The method that was new to me was the idea of "shooting" a circuit board. Our company's products were made from tiny surface mount components on crowded little circuit boards. When "shooting a board," the technician set up the malfunctioning board next to a known good board. He applied power to both boards, then measured the voltage with respect to ground on circuit nodes throughout the circuit. A bad component will have incorrect voltages at its connecting nodes.

Although not as sensitive, a similar method can be performed with a multi-meter. Connect one pole to ground and measure the resistance to ground at each node. Because turned-OFF transistors look like open circuits, this resistance method will not be as informative as the node voltage method.

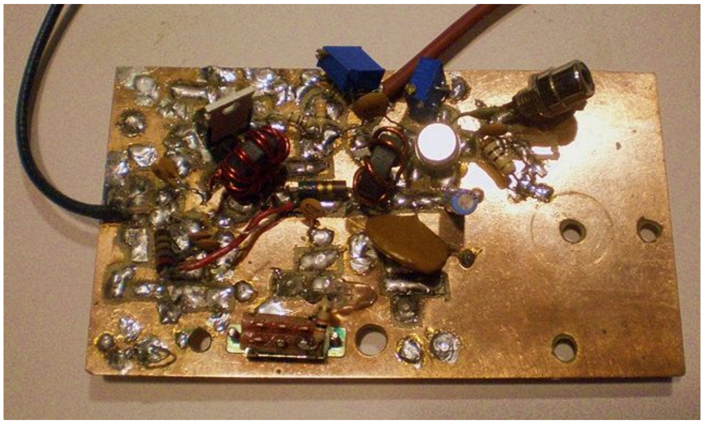
If you are constructing an entire ham station, you won't be mass producing any one type of PC board. The exceptions are the QRP boards described in Chapters 6, 11 and 15. Although not identical, the different ham band boards are close enough that the voltage readings will be similar between one band and another. This will be true even if the transistor types are different.

If your hobby is progressing the way mine has, you will build several audio amplifiers and will settle on one or two favorite circuits. Every receiver and every phone transmitter needs one of these amplifiers. Because they're the same circuit, audio amplifiers are another opportunity for "shooting boards" when trouble-shooting.

Trouble-shooting a transmitter

Like a receiver, we need to build and test one transistor stage at a time. Start with the crystal oscillator or Variable Frequency Oscillator (VFO). Listen for the signal on your HF receiver. Then add the buffer amplifier stage and so on. The buffer amplifier will probably make the same signal noticeably louder. If you have doubts about a circuit, first make a crude prototype that will be easy to modify.

I often start with an old scrap PC board that has had all the components salvaged. After parts have been stripped off, the scrap board has lots of random solder-coated copper islands and traces with no remaining wires or components. Lay out the new circuit using your proposed parts. Tack the ends of the component leads down to the existing solder bumps. Cut the old traces wherever they interfere with your new circuit.



The scrap board shown above was used to make an experimental 5 watt CW QRP final amplifier. Notice that the parts were simply soldered onto the existing solder bumps. Where a trace was needed to connect one node to another, I used the red wire. Pil Joo, VA3GPJ, designed a 40 meter output stage and driver based on an IRF510 MOSFET transistor. These inexpensive MOSFETs work on 12 volts and are much cheaper than the high-priced bipolar output transistors I was using. I didn't have an IRF510, so I used a similar IRF530. My version of his circuit worked, but wasn't as efficient as Pil's output stage and wasn't worth repeating. Obviously I should try it again using an IRF510.

As with trouble-shooting the receiver, you can use the working transistor stages to drive and confirm that later stages are working properly. The crystal oscillator or VFO module generates a signal for the following amplifiers. An oscilloscope is best for looking at the output of each stage. However, we can also learn from the current drawn by each stage. The emitter (or source) resistor and the isolation resistor on the collector (or drain) circuit are convenient ways to do this. Measure the DC voltage across these resistors, divide the voltage by the resistance and you will determine the DC current passing through the transistor. You already know the power supply voltage. Once you know the DC current passing through a transistor, you can calculate the power drawn in watts. Voltage x Current = Power in Watts.

How much DC current does the whole chain of RF amplifiers draw? It is helpful if your power supply has a built-in ammeter to measure the total current drawn by the transmitter. As a rule of thumb, a 5 watt CW QRP should draw about 500 milliamps (1/2 ampere) from a 12 volt supply. In other words, the QRP is roughly 50% efficient. Half the power becomes the desired RF output, the other half becomes waste heat - hot transistors and resistors.

There are 3 "classes" of RF amplifier designs which will be discussed in later chapters. Class A is about 30% power efficient, Class B is about 50% and Class C is about 70% efficient. The whole transmitter is generally about 50%. The power consumed by the transmitter is the DC power supply voltage times the DC current drawn = the DC Power consumed. The efficiency is the Radio Frequency (RF) power output divided by the DC power consumed.

If the transmitter is drawing the correct amount of power and the output waveform is a sinewave, the CW signal should sound OK on the ham bands. While testing a transmitter, instead of an antenna we should use a dummy antenna. Dummy loads are usually a physically large power resistor, typically 50 ohms. Virtually all stations on the ham bands are using commercial transmitters. Stay off the air until you are sure you are locked on the desired frequency and your signal sounds just like the other guys.

"Tuning" a transmitter

Any voltage source, whether it's a 9 volt transistor battery or a 100 watt ham transmitter, has an internal "voltage source impedance." Impedance, the effective internal resistance of the voltage source, limits how much current your source can deliver. You can't commute to work in your electric car when it is powered by a tiny 9 volt battery. The 9V battery source impedance is way too high to supply hundreds of amperes. The best it can do is tens of milliamperes.* The internal impedance of an electric car battery is super low and delivers hundreds of amperes to the car motor.

* A milliampere is 1/1000 ampere.

It turns out that the power (energy per second) transferred from a voltage source to the load is maximum when the load - a light bulb, motor, or antenna - has the same apparent impedance as the voltage source. ***Source impedance should equal load impedance.*** The internal impedance of a transmitter is determined by its DC power supply internal impedance and the design of the transistor or tube output stage. In turn, the transmitter "drives" its load which is the antenna. The antenna literally transfers the energy out into the space surrounding the antenna. Free space also has a load impedance, but it varies with frequency and the antenna dimensions.

For the transmitter impedance to match the antenna impedance, it is nearly always necessary to have an LC resonating coupling circuit between the transmitter and the antenna. Modern commercial ham transmitters have fully-automatic "antenna tuners" built into the output circuits. Tuners make the antenna load impedance "look the same" as the transmitter source impedance. Provided that the ham uses a commercial ham antenna designed for the same frequency band, he will be blissfully unaware that the impedances are being automatically matched for him. Home-built, *manually operated*, antenna tuners are described in Chapter 9.

Light bulbs are simple antenna substitutes

An old-fashioned filament light bulb with the same wattage as the transmitter output makes a useful "dummy load" antenna. Old-fashioned 7 watt Christmas tree bulbs make good loads for a 5 watt QRP transmitter. They glow brightly in pretty colors when 7 watts is delivered to them. Light bulbs do not have the "standard" 50 ohm antenna impedance and need an antenna tuner. Save those old filament bulbs! They can be used as mild heating elements to prevent water pipes from freezing, incubating bird eggs, etc. Once I opened a rarely used closet in my grandmother's house and discovered an ancient Edison light bulb that still worked. It even appeared to have a carbon filament. That would be valuable to a museum!

Once your light bulb is as brightly lit as you expected, try listening to your signal in your ham receiver. I like to short out the antenna input jack so that the receiver can barely hear the transmitter. That way the signal will sound the same as if someone were listening to your transmitter from hundreds of miles away, not 3 feet away. Hopefully your signal will be as stable and have as pure a CW tone as the ham signals transmitted with commercial equipment. In summary, use whatever equipment you may have to confirm that all aspects of the transmitter are working.

Even if you are listening to your dummy load signal with a crude homebuilt receiver, you can tell if it is operating in the ham band. If there are ham signals both above and below your signal, you're almost certainly transmitting inside the ham band where you belong.

Mismatched antennas may cause the transmitter to overheat.

If you built your own antenna or you are using an antenna designed for a different ham band, your automatic antenna tuner may not be able to make the match. The result will be hot output transistors. Once a circuit handles more than about 10 watts, it is usually important to be sure components aren't overheating due to misalignment or inadequate heat dissipation. A beginner's first home-made transmitter will probably only work on a single ham band and deliver 5 watts or less. If it is working properly, it probably won't be necessary to worry about overheating and temperature ratings. Is a transistor or integrated circuit becoming hot? How hot? ***If you touch it with a wet finger and it hisses into steam, that is way too hot.*** That component will soon die, if it hasn't already.

Building high power transmitters and power supplies are not usually attempted by beginners. Transistors and integrated circuits have temperature ratings which are found in the fine print on the data sheet for the part. Expensive versions of the same component will often tolerate much higher temperatures. Component temperature ratings are important for the high power amplifiers and power supplies found in transmitters. If you routinely overheat a transistor or integrated circuit, it may fail after months of use. Some high-priced multi-meters, such as the Fluke model 87, have a built-in thermometer. It comes with a thermocouple probe to measure component temperature.

Heat sinks

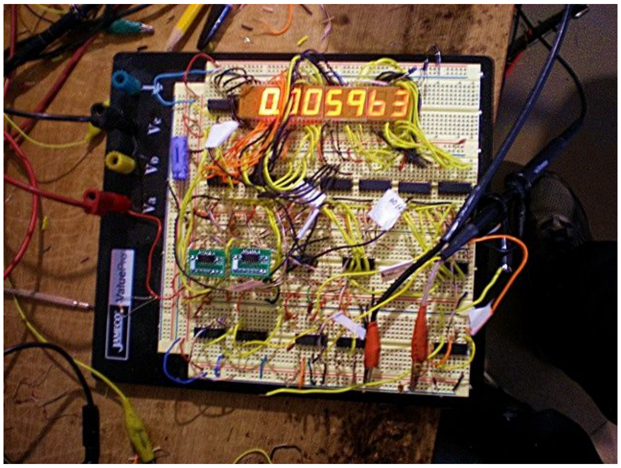
Once the output stage is operating at the expected efficiency, 50% or better, it may still be running too hot. The primary method of reducing the operating temperature of a transistor or integrated circuit is a ***heat sink***. These can be as simple as a little aluminum "hat" that clips onto a transistor. At the other extreme, the transistor can be bolted down to a large, finned aluminum heat sink. The heat sink may even be cooled by a fan that directs a jet of cool air against the comb-like metal fins.

The limits of plug-in boards

Plug-in boards are great for trying out new transistor circuits which have few parts. Examples might be circuit modules you've never tried before, such as an oscillator, an amplifier, or a single integrated circuit that's new to you. A limitation of plug-in boards is that complex circuits, especially ones with lots of integrated circuits, are hard to trouble-shoot. They are especially difficult if you don't fully understand what each wire is supposed to do. Plug-in boards tend to have intermittent connections. New plug-in boards that haven't been abused are much more reliable than old ones. But even so, after perhaps plugging in 20 wires, the probability of a loose contact begins to become significant.

I knew an engineer who had his own private plug-in boards hidden in his desk. That way he could be sure that no one borrowed his boards. Careless technicians often stuff large diameter wires into the holes and warp the spring contacts. Loose contact springs makes them intermittent.

The first vacuum tube computers were fundamentally limited by how complicated they could be. When the computer complexity reached about 3,000 tubes, the probability of having a dead tube became so high, that poor reliability made it impractical to increase the computer's capability. Plug-in boards are similarly limited. Fortunately, individual transistors and ICs don't have the complexity limitation when built on proper PC boards.



I tried to prototype a 7 digit digital frequency counter using the large plug-in board shown above. The counter circuit had 18 integrated circuits and numerous additional feedback loops which used diode-logic gates. As is usual with digital ICs, I didn't fully understand all those feedback loops. That made my trouble-shooting random, rather than planned. Yes, I'm sure the wiring was "correct" and it did produce a few display digits that sometimes seemed to work like a counter. But I could never get it to read an entire, correct ham frequency, like "14.046" MHz. Eventually I concluded that my old, large plug-in board was too unreliable for such a complicated circuit. I gave up.

What I should have done is start the construction on the plug-in board with a single IC that produces a measurable output that I could understand. When I was confident that the first stage is working, I could rebuild that first circuit on a real, hard-soldered circuit board. Next, I would confirm that new permanent board circuit works OK. After that, I should use the plug-in board to build the next stage and couple it to the first stage. This is slow, tedious work, but it's highly likely that the project will eventually work. This is in sharp contrast to plugging in a mess of wires and praying for success.

Failure is the mother of success

You have probably noticed that a theme of this chapter is that homebuilding involves suffering through LOTS of failed attempts. Yes, it's frustrating. But when if finally works ... the sensations of joy, accomplishment and triumph are ***WONDERFUL!***

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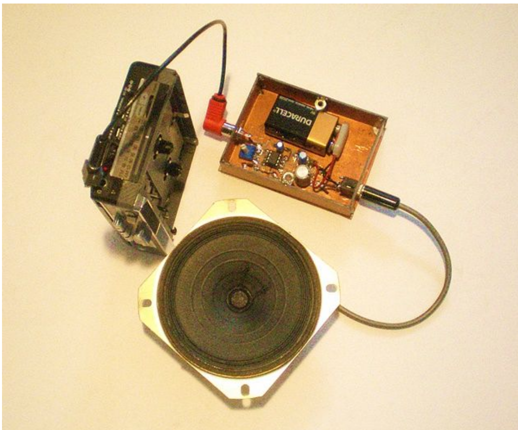
ELECTROMAGNETIC SHIELDING

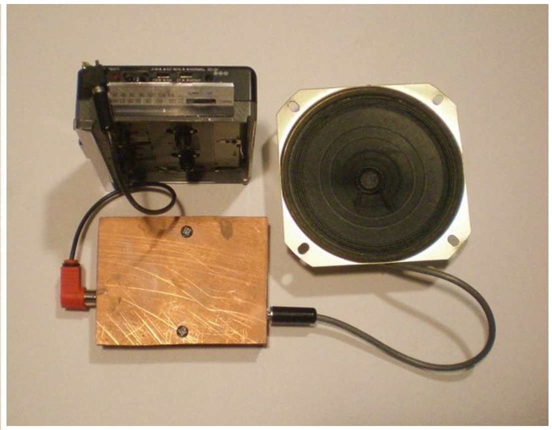
Circuit shielding experiments

Shielding is most important for building receivers and phone (voice) transmitters. This essay is somewhat off the subject of construction and trouble-shooting. Chapter 7 has the first projects that require shielded circuits. However, Chapter 3B was shorter than the other chapters, so I put it here. Better early than late!

We have all been taught that we can prevent radio waves from interfering with our circuits by surrounding them in a metal shield. When I actually ran experiments using a 2 meter handi-talkie for a radio source, I learned that shielding isn't so simple. Enclosing the circuitry in metal box keeps the radio waves out, but plugging in a microphone, a loudspeaker or other wires into the box, restores the interference. Those antenna-like wires funnel the radio waves directly inside.

Experiments





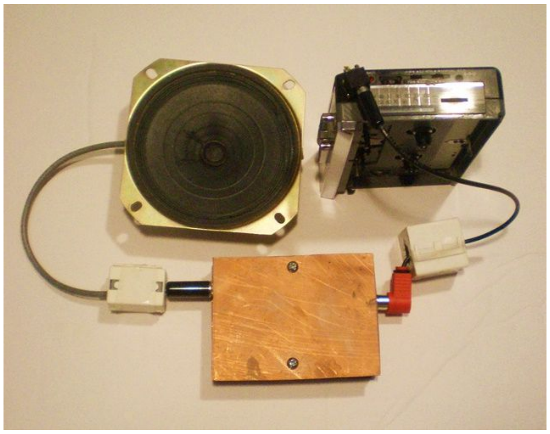
The above photo on the left is an ordinary FM radio (100 MHz) driving a small audio amplifier and loudspeaker. The cover on the shielded box has been removed. When I subjected the apparatus on the left to 5 watts of 147 MHz from a nearby, hand-held Icom handi-talkie, the radio sound was obliterated. There was just silence. When I moved 1.5 meters away from the FM radio, the sound became a sharp, rough, roar of static. At 3 meters distance, the music returned. Curiously, keying the hand-held transmitter made the music ***louder!*** That was a surprise. Perhaps it interfered with the automatic gain control circuit in the FM radio?

The above photo on the right shows the shielded audio amplifier with the shield lid screwed on. When I keyed the handi-talkie, **the interference was unchanged**. The audio amplifier and unshielded FM radio received the interference just as before.

Here is the 5 watt 147 MHz handi-talkie used to generate the radio interference.

Ferrite filter blocks

Those heavy plastic "lumps" molded around USB cables, line cords or speaker cables are high frequency filters designed to prevent radio interference. As the Radio Frequencies (RF) currents "try" to flow through the cables and into your computer or other appliance, the ferrite acts as a relatively large inductor at radio frequency and blocks the interference.



The above photo shows the same audio amplifier equipped with white, plastic-covered, ferrite filter blocks clamped onto the speaker and input leads. These filters didn't cure the interference problem, but greatly reduced it. As explained above, ***without*** **the filter blocks**, there were 3 distinct kinds of interference: Close in to the amplifier the 147 MHz signal totally suppressed the audio output. At 1.5 meters distance, the speaker made a harsh, sharp, roaring noise. 3 meters away, clear audio returned, but was louder with the 147 MHz interference than without.

In contrast, ***With*** **the ferrite blocks**, the total suppression zone was just 1/3 meter. The roaring static zone was reduced to a few centimeters distance. There was no noticeable interference beyond about 1.5 meter distance.

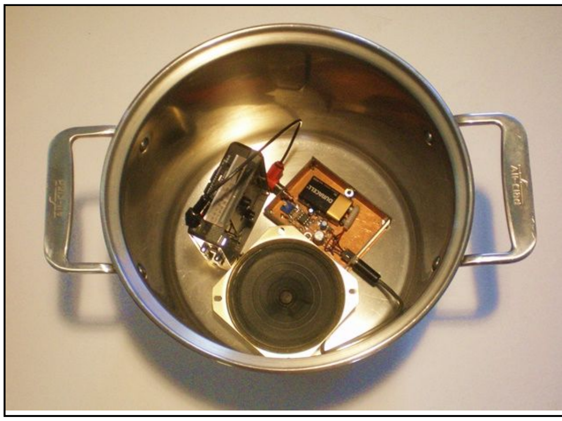
Ferrite filter frequency response

A basic engineering difficulty with simple ferrite clamp filters is that inductive filters will attenuate ALL frequencies to some degree. For example, if your coax internet connection can handle 20 Megabytes per second, filters like this on a cable would eliminate the internet quite efficiently. This problem is completely solved by replacing copper wire coax with fiber optic cable. Needless to say, a filter block clamped onto a glass fiber has no effect. Also, since fiber optic cable carries light, not electric currents, it can carry UHF frequencies, like 250 MHz. In comparison, at such a high frequency, bare copper wire becomes too high an inductance to pass UHF frequencies. The highest quality coax cable works only slightly better at 250 MHz. It works, but only with high power loss. In my experience with 434 MHz diathermy machines, the best quality, flexible coax could only transport the majority of the power over distance of about 1 meter.

As you can see, the inductance of a filter on an input wire needs to be a compromise between the two competing frequencies. We want to suppress the higher, interference frequency, while preserving the desired lower frequency signal as much as possible.

Total shielding

If we surround all the components shown earlier with a metal shield, it should completely suppress radio interference. Of course, it will also shield the FM radio from the local radio station. To demonstrate a total metal enclosure, I borrowed my wife's large, stainless steel pot. (I first had to convince her that I wasn't boiling creosote or similar application.)




When I placed the apparatus in the stainless steel pot without the lid, the music was still loud and clear but harder to tune in. When I keyed the 147 MHz transmitter, the interference was the same when the transmitter was above the pot, but it was attenuated to a degree when the transmitter was off to the side of the pot. In other words, when there is a metal wall between the antenna and the FM radio, the FM radio signal will be attenuated.

As expected, with the lid on the pot, there was no interference and no music. Next I turned up the audio gain to maximum. This produced a roar of static that was barely audible outside the pot.

Static magnetic fields

You have probably seen pictures of a bar magnet floating in mid-air over a sheet of superconductor material. Presumably the superconductor is bathed or perfused with liquid nitrogen or other liquid gas to maintain an extremely low temperature. The question is, why does the magnet seem to defy gravity? The Meissner effect is that ***a superconductor excludes any magnetic field*** - it is the perfect magnetic shield. I Googled the question and was amused to find several explanations for "The Meissner effect." The experts were just like me. I kind of understand it, but I'm missing a lot of the story. There were exotic explanations about "quantum locking" and proposed weak points in the thin superconducting sheet that produced "flux tubes." One explanation insisted that the superconductor had to be immersed in a magnetic field before it was cooled to somehow freeze the field in place. Only then would it repel a magnet. I didn't believe that one at all.

The most universal explanation is that the magnetic field cannot penetrate the superconductor and the sheet of material acts like a "magnet mirror." Whenever the magnet "tries" to fall down, the movement generates a 100% equal and opposite magnet field in the superconductor. I always wondered if a high speed camera could see the magnet dither up and down as it attempts to fall down onto the superconducting surface - probably not. In any event, it seems to me that ***superconductors should be a perfect shield for any electromagnetic field at any frequency.*** Radio waves are an oscillation between electric and magnetic fields. If magnetic fields can't exist in a superconductor, radio waves can't either.

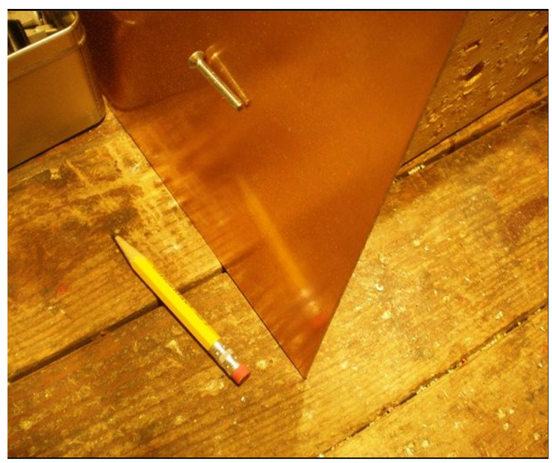
What are superconductors?

Superconductors are wondrous conductive materials with ZERO ohmic resistance. They can be made from several metals like niobium or from compounds made of copper, oxygen and other elements. Pure copper and silver are conducting metal elements that have extremely low resistance but are not superconductors. Even copper and silver have ***some*** resistance to current flow. For example, the resistance of a mile of thin, 30 gauge copper wire is 545 ohms. If you measure the resistance of a mile of 30 gauge wire made from super-conductor it would still have a resistance of ZERO ohms. When they are usable in the real world, superconductors are amazing materials! They are most often used to build extremely high force electro-magnets.

Unfortunately the best, barely practical, superconductors need to be cooled to nearly absolute zero, -273° Celsius (-459.7° Fahrenheit). The cooling is usually accomplished by cooling the superconductor in liquid helium, at a temperature of -268.93 ° Celsius or -452.2 ° F. So far, the only civilian use for superconductors I've heard of is in Nuclear Magnetic Resonant (NMR) scanners found in well-equipped hospitals. These machines resemble x-ray cat-scanners. Both machines produce detailed cross-section pictures of the human body. The NMR scanners differ because they respond to specific atoms and chemicals, not to the x-ray density of organs. They produce pictures based on the concentrations of elements or chemicals. In order to stimulate specific chemicals to resonate at radio frequencies, the body must be surrounded by a magnetic field intensity on the order of 10 Teslas. (One Tesla is 10,000 Gause. The Earth's magnetic field is 0.5 Gause!) These are INTENSE fields.

Ordinary conductors can't shield and reflect static magnetic fields.

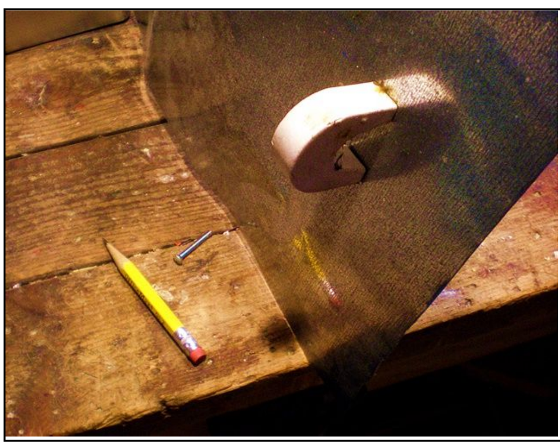
Double-sided, copper PC board material seems to be relatively transparent to ***static*** magnetic fields. It only attenuates ***changing*** magnetic fields as in radio or audio frequency waves. A unchanging magnetic field passes through a PC board as though it were plastic or paper. The photo on the left below shows a strong permanent magnet positioned against a sheet of double-sided PC board. The photo on the right shows a small steel screw stuck to the front of the copper shield. It is attracted to the magnet on the far side of the PC board.



The photo below shows the same steel screw stuck to the magnet directly. Without the 1/16 inch separation caused by the PC board, the attraction is significantly stronger and the screw will stand on end. This obvious attenuation is mostly simply because of the distance. The strength of the magnetic attraction falls off as the inverse square of the distance, $1/(\text{distance})^2$.

Do steel enclosures block magnetism?

If we replace the copper PC board with a sheet of zinc galvanized steel, will it block the magnetic field? Iron is a magnetic element and will be strongly magnetized by a local magnetic field. At the same time, iron and zinc are a good electrical conductors. Steel is an iron/carbon compound. We have already observed that the magnetic field easily passes through non-ferrous metal conductors. The question is, how much will the reverse polarity magnetic field that is induced into the iron prevent the magnetic field from penetrating the steel sheet?

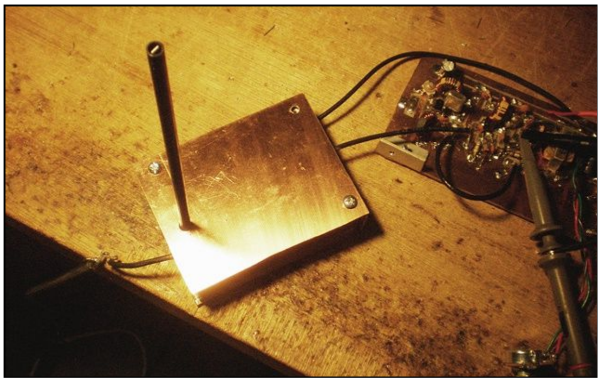


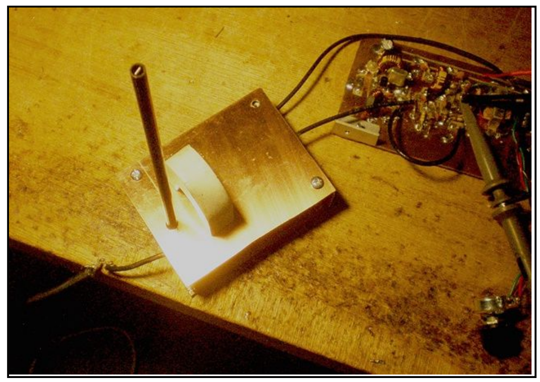
The photo on the left shows the magnet tightly clinging to a galvanized steel sheet. When the small steel screw is applied to the opposite side of the steel sheet, it sticks! At first I didn't notice any difference in the behavior of the steel screw between copper and steel barriers. The steel sheet is much thinner than the PC board and that alone will work against the attenuation by the steel material. I soon noticed that the steel screw was much more easily loosened from the steel. I could tap on the galvanized sheet and the screw would fall off. In conclusion, ***a thin steel sheet attenuates the magnetic field***, but doesn't block it entirely. Using the behavior of ferrites as an example, if a steel sheet has the same thickness as a copper sheet, the attenuation of the magnet field by iron should be roughly 100 times greater than copper.

Although I haven't tried the experiment, I'll bet that a thick steel sheet, one cm, would (virtually) eliminate the attraction of the screw to the steel sheet. The distance of separation alone is more than enough to do that.

PC board shielding for low level magnetic fields

Is shielding circuits from ordinary, low level, magnetic fields ever necessary? A copper PC board will not be able to shield circuitry from static magnetic fields. Will the static field effect the operation of circuit? The picture on the left below shows a 16 MHz tuned, LC variable oscillator of an experimental metal detector. The oscillator frequency is controlled by the variable capacitor in the shielded box. The inductor component of the LC oscillation is a loop of wire. The loop is one meter away from the circuitry at the end of a wooden probe and serves as the metal detection element. When metal approaches the loop, it changes the inductance and the oscillator frequency. The vertical plastic tube tunes the frequency.





In right hand right photo above, the magnet is placed over the oscillator capacitor and transistor, not the inductor. With no magnet on the shielded box the oscillator frequency was 16.0622 MHz. With the magnet in place there was **no frequency change!** Next I Scotch-taped the magnet onto a long wooden stick. I took the lid off the oscillator box and lowered the magnet directly onto the circuitry. Again, there was no frequency change! When the magnet actually touched the inductive choke in series with the JFET transistor source lead, the frequency plummeted several hundred KHz. In summary, ***strong magnet fields affect inductors by increasing inductance.*** The magnetic field has no obvious affect on other circuitry. In theory, a magnet on a trace or wire should increase the inductance of those conductors. In practice, ***magnets have no apparent affect on capacitors, resistors, traces and transistors***.

Would a thin sheet, steel enclosure eliminate 60 Hz radio waves?

Earlier in Chapter 3B I described trying to eliminate 60 Hz hum in an audio amplifier by shielding the amplifier with copper PC board - it didn't work. Now I'm not surprised. Whether high frequency or low, the magnetic field will not be significantly decreased by copper. The thought might briefly occur to you to use a ferrite clamp or maybe an L-C filter. But you immediately realize that 60 Hz is in the audio range of the audio amplifier. Only highly sophisticated tuned 60 Hz filters can eliminate it from both the input and output lines.

Usually, when I add really large filter capacitors to my line-operated power supply, like 6,000 µF, any 60 Hz will be silenced. I had already done that to my 2 meter transmitter, but a small hum persisted. The transmitter runs at 146 MHz. However the FM modulation was generated at 18.4 MHz. The FM modulation must be applied to the oscillator where the 18.4 MHz originates. When FM modulated, the 18 MHz sinewave varies its frequency up and down in accordance with the speech frequencies and amplitudes. The RF frequency variation will track the audio input. This produces ***narrow band FM*** modulation. However, 2 meter ham signals (usually) use ***wideband FM*** modulation. Wideband modulation is easier to detect and more likely to be high fidelity.

All circuits powered by AC will have ***some*** slight 60 Hz hum riding on them, even if it is only one millivolt RMS. In the case of my audio signal, the hum was about 10 millivolts. This was undetectable to the ear. To move the 18 MHz signal up to 146 MHz, the basic signal had to be multiplied 8 times. This method converts narrow band FM into wideband FM. Consequently, 8 times 10 mv RMS became 80 mV RMS. At 80 mv the hum became audible. Still another factor is that FM modulation is not just the ***frequency*** variations of the original audio *frequencies*. It also produces frequency variations proportional to the original audio ***amplitude*** *variations*.

In conclusion, eliminating the 60 Hz hum will require sophisticated 60 Hz R-L-C filters. In addition, the largest possible capacitor and high inductance (several Henries) DC supply filter should be stuffed into the power supply. Alternatively, you can power the transmitter with storage batteries. That's what I did!