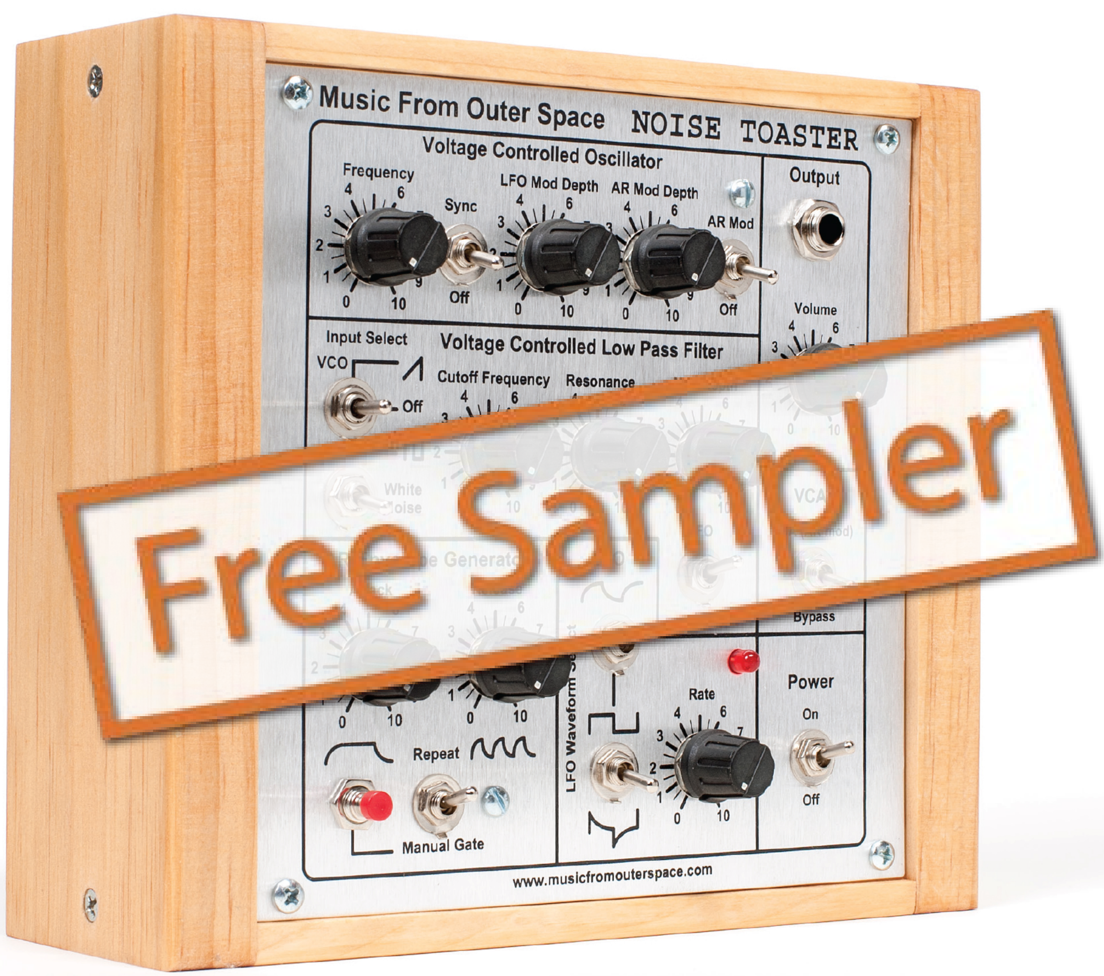
Make: Analog Synthesizers



A modern approach to old-school sound synthesis

Ray Wilson

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Make: Analog Synthesizers

by Ray Wilson

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Table of Contents

1 What Is Synth-DIY?

In the mid-1960s an electronics engineer with a Ph.D. from Cornell University in engineering physics was starting a musical revolution, and he didn't even know it. That engineer was Robert Moog. In a small factory in bucolic Trumansburg, New York, he was developing a series of unique electronic analog sound synthesizers that would take the musical world by storm.

At the same time, the muse of invention was striking a West Coast engineer named Don Buchla. Buchla was developing his own unique series of electronic analog sound synthesizers. Both Moog and Buchla's remarkable inventions were *voltage-controlled*; they both used a varying voltage to control the sound-shaping functions of the synthesizers' modules.

It wasn't long before analog synthesizer sounds and music were being heard everywhere all the time. They made their way into music studios, records, commercials, jingles, company sound logos, movies, every genre of music, video games: everything. Analog synthesizer sounds and music had become so widespread that scores of companies saw the potential market and dove headlong into the analog synthesizer business. Some popular manufacturers were Moog, ARP, Oberheim, Yamaha, Korg, Fairlight, E-mu Systems, Roland, and many others.

Although extremely popular for many years, the analog synthesizer's sales numbers eventually began to dip with the advent of less expensive, easier-to-manufacture, *and pretty darn snazzy* digital synthesizers. Instead of creating sounds using analog sound-producing circuitry, digital synthesizers use microprocessors to do the heavy lifting. Binary representations of various sound and instrument waveforms are stored in read-only memory (ROM). The microprocessor coordinates the synthesizer's real-time user interface activity, scans the polyphonic keyboard, and finally processes and streams the digital audio data to the synthesizer's output.

This was one of the digital synth's weaknesses. Instead of the completely continuous, organic, full sound of the analog synthesizer, the digital units often included digital conversion artifacts and lacked sonic character. Figure 1-1 highlights the difference between a waveform generated digitally and a continuous waveform generated by analog circuitry. The early digital units borrowed from analog synthesis for filtering and sound envelope shaping for a time, but the lower cost, manufacturing advantages, and technical advances of the digital units soon ended the analog synthesizer's dominant reign of many years.

Sadly, history also shows that while it takes an electronics genius to invent amazingly cool synthesizers, it also takes a great deal of business sense to keep a company in the black. Just about all of the major players in the synthesizer industry had an electronic genius or two on board, but only a few remembered to hire a chief financial officer (CFO). Many of the major players in the synthesizer business are now only a memory, a distant electronic wail in the breeze.

However, analog synthesizers were just too cool to stay gone forever. There has always been a small analog synth priesthood keeping the faith alive, but today, people all over the planet are rediscovering the warm, inimitable analog synthesizer sound. They're finding that turning *real* knobs, flicking *real* switches, plugging in *real* patch cords to produce *real analog* sounds is way more interesting and engaging than scrolling through an LED parameter display or clicking virtual switches with a mouse. Today many musicians and hobbyists with an interest in electronics are discovering that with the right schematics, tools, printed circuit boards (PCBs) and ingenuity, making their own analog synthesizer is well within reach. The book you're holding in your hands right now has the information you need to put you squarely onto the road to *doing it yourself* when it comes to building your very own analog synthesizer.

A Bit of Analog Synthesizer Etymology

Before we move on, let's take a moment to consider what the term *analog synthesizer* really means. The word *analog* puts me in mind of *organic*, *living*, *real*, and *continuously variable*. A good definition of the word *analog* would be "of, relating to, or being a mechanism in which data is represented by continuously variable physical quantities." The key point we're interested in as far as describing an analog synthesizer is "continuously variable." An analog synthesizer creates sound by means of electronic circuit elements: resistors, capacitors, transistors, and integrated circuits. If you observed the output of an analog synthesizer with an oscilloscope, you would see that the waveform voltage is continuous, as opposed to the characteristic stepped appearance of a digital signal source (Figure 1-1). This is one of the characteristics that give analog synthesizers their warm, fat, and much-sought-after sound.

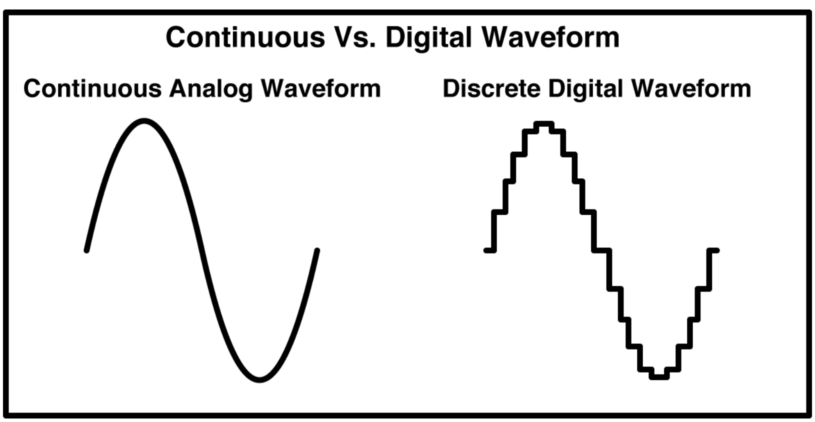

Figure 1-1. *Continuous waveform versus discretely stepped digital waveform*

Additionally, much of the circuitry found in an analog synthesizer has roots in the early analog computers. These were very early computers built from operational amplifiers and passive electronic components (resistors, capacitors, coils, etc.) that performed mathematical operations such as logarithms, multiplication, division, addition, subtraction, and even root finding. Analog computers were used by scientists and engineers to solve all manner of mathematical problems before modern digital computers were developed. Variables were entered using potentiometers (informally known as *pots*) to set voltages, which the analog computer would process in real time. Interestingly, the circuit used in an analog synthesizer to regulate the response of the voltage-controlled oscillator (VCO) to control voltage is a linear voltage to exponential current converter that might well have been found in an electronic analog computer.

Now we turn to the term *synthesizer*. To synthesize is to take existing elements and combine them to produce something new. Anyone who has heard the incredible range and variety of sounds that come from an analog synthesizer would have to agree that its combination of unique electronic circuitry produces incredible sounds not heard before on this planet. Analog synthesizers are also perfect for producing convincing reproductions of just about any acoustic or electronic instrument.

How do I define analog synthesizer-DIY, or synth-DIY, as I call it? It's people making their own electronic sound boxes, noise makers, and synthesizers; and modifying Speak & Spells and other vintage electronic sound toys to get weird and unusual sounds from them. It's conventions where from a few to as many as hundreds of people who share the synth-DIY passion get together to compare notes and see and hear one another's latest projects. It's learning about electronics and components, reading schematics, soldering PC boards, and wiring front panels. It's learning where to find the best prices and selection for electronic components. It's learning what tools and equipment you'll need to succeed and how to troubleshoot the projects you make. It's being creative, including learning how to set up a recording studio right on your computer so you can make multi-track recordings of your sound creations. And finally, its actually making your own analog synthesizer, from something as small as a lo-fi noise box to as huge as a modular monster that would have cost tens of thousands in the analog heydays.

What Can I Build?

What you can successfully build depends on the level of electronics knowledge you possess, the effort you put forth to learn and become proficient, and the passion you have to build your own analog synthesizer. Please rest assured that even if you are just getting started, the analog modular *sky* is the limit—if you really want to get there. I always suggest that newbies cut their teeth on solderless breadboard experimentation or one of those electronic experimenter kits. After you've gone through the experiments and know a bit more about resistors, capacitors, transistors, and ICs, step up to a kit with a PCB that requires soldering—because wielding a soldering iron is a fundamental skill you just can't do without. I'll go over the tools you'll need and how to set up your workbench in Chapter 2. But now, let's take a look into your possible DIY future and feast our eyes on some photos of analog synthesizer DIY projects people have contributed over the years. Many graphic artists are drawn to synth-DIY and express themselves not only audibly but visually as well.

Figure 1-2 shows the popular MFOS *Alien Screamer* built by DIYer Bernard Magnaval, of France. DIYers build their own cases and make their own faceplates. I love the creativity shown in this build: the bright colors and cool-looking knobs. The Alien Screamer has a VCO and a low-frequency oscillator (LFO) that can be used to both modulate and sync the VCO. The LFO provides a variety of waveforms with which to modulate the VCO's frequency. For its size and simplicity, this little guy makes some totally cool sounds.

Figure 1-2. *Music From Outer Space Alien Screamer*

This DIYer etched the circuit board for this eight-step sequencer in Figure 1-3 from a layout published on the MFOS website and then built up the entire project. Sequencers are used for repeating patterns of notes and creating arpeggiation effects.

Figure 1-3. *Music From Outer Space eight-step sequencer*

The Sound Lab Mini-Synth (Figure 1-4) is a favorite among DIYers, with its two VCOs and warm-state variable voltage-controller filter (VCF), as well as a normalized switching scheme that permits a *ton* of sonic variety. This is the project that put MFOS on the synth-DIY map and has been built by hundreds of people around the world.

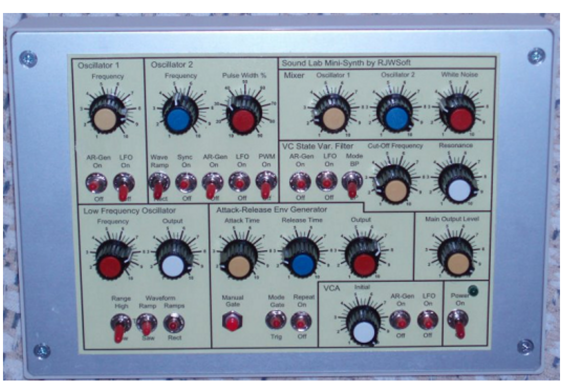

Figure 1-4. *Music From Outer Space Sound Lab Mini-Synth*

Some people go to great lengths to express themselves through synth-DIY. Figures 1-5 through 1-7 show some of the more unusual examples. If you plan to gut your Stradivarius for a synth case, I suggest you think it over calmly for a bit, but in the end, the decision is yours. Using parts of a human body is also up to you, but as you can see, it has been done. And finally, some folks like to wear their synthesizer and march through their neighborhood. Doing so is entirely up to you and perhaps your homeowners association.

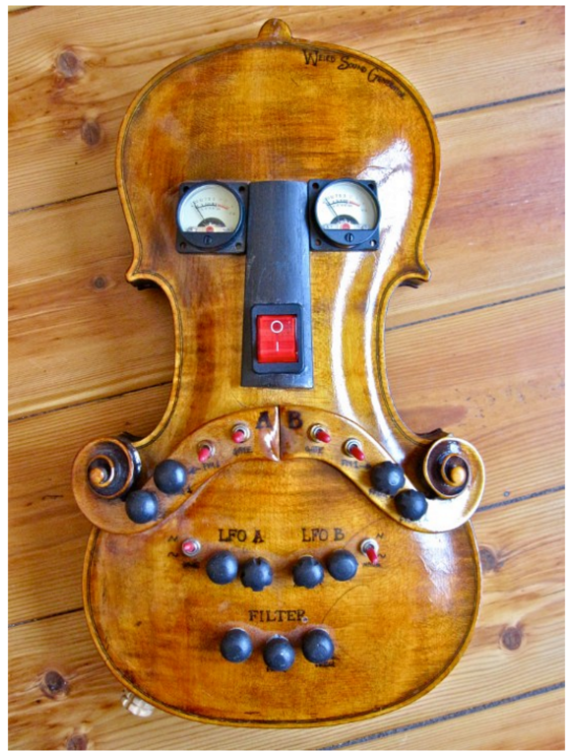

Figure 1-5. *A Stradivarius made into a Weird Sound Generator*

Figure 1-6. *A skull with a WSG built into it; this controversial implant technique is still in clinical trials*

Figure 1-7. *A wearable synth designed for a synth marching band (I would start going to high school football games if the band included WSGs like this one)*

How Far Can I Go?

As I've stated above, and depending on your effort, the sky really is the limit. While not expensive, the practice does require a bit of expendable income. But then, so does just about any hobby. When you start to get serious about analog synthesizer projects, you will be surprised at the cool things you can build. Let's look at some more advanced projects built by some serious DIYers.

The Sound Lab ULTIMATE is a challenging MFOS project, but the attention to detail and effort expended are rewarded with a fully featured analog synthesizer. This project goes farther than the Sound Lab Mini-Synth and adds a third oscillator, a sample and hold module, a second LFO, and several attenuators used for general signal attenuation and control. The normalized switching scheme permits wide sound variability, and patch points permit synthesists to route signals in unique ways. The project in Figure 1-8 (which includes the keyboard) was built by Magnaval.

Figure 1-8. *Music From Outer Space Sound Lab ULTIMATE*

You can create a monster modular synthesizer that has as many modules as you care to build, like the one in Figure 1-9, built by DIYer Michael Thurm of Germany. This synthesizer has capabilities comparable to units costing tens of thousands of dollars back in the analog synth's heyday. The sound possibilities of something like this are virtually limitless.

So now you know where this road can take you. You can dip your toe into the water and build a simple sound generation box, or you can dive into the deep end and build a giant modular analog synthesizer or, of course, anything in between. I can say from experience that synth-DIY is one of the coolest hobbies going. Not only does it provide interesting and engaging building experiences, but the resulting noise boxes and/or musical instruments you make will also provide endless hours of imaginative and creative fun.

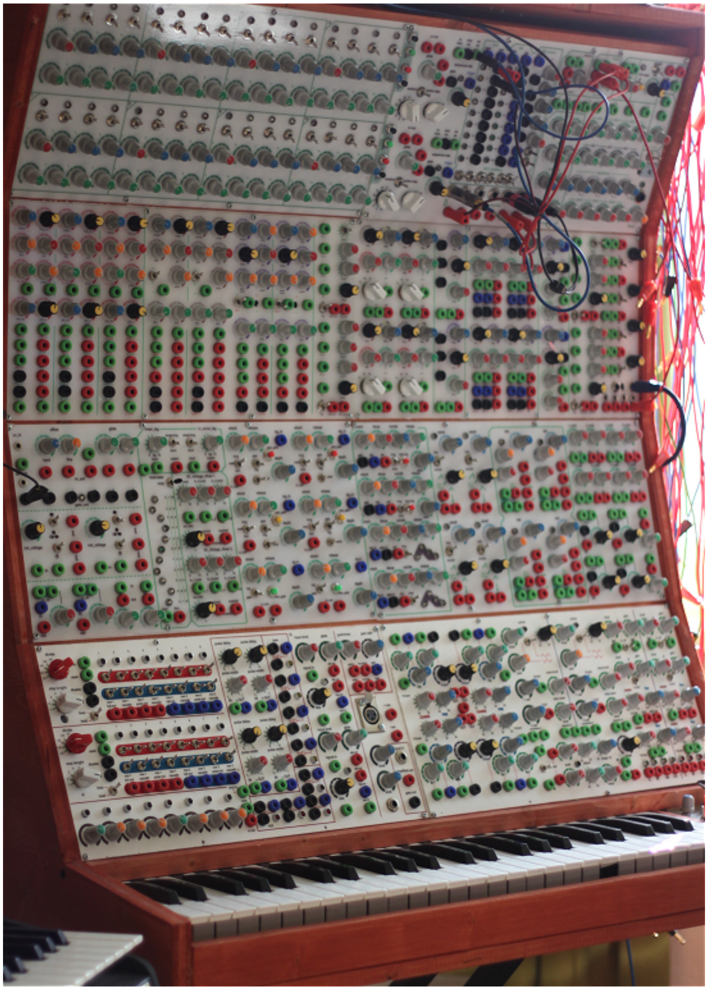

Figure 1-9. *Michael Thurm's huge modular analog synthesizer*

Tooling Up for Building Analog Synths

2

This chapter describes all the electronic instruments you'll need on your workbench to succeed with your synth-DIY projects.

I attended NASA soldering certification classes back in my days at Intec Systems and learned to solder and desolder through-hole and surface mount components under a stereo microscope. I'll share some insights that will help you improve your soldering and, just as important, your desoldering technique.

I'll also share some of the experience I've gained in getting the right price and making the right selections for electronic components. I'll conclude this chapter with some troubleshooting techniques and tips that may save you time once you're done building and have run into problems.

Instrumenting Your Workbench

Trying to work on an electronic project without the proper test instruments is like trying to work on a car without a set of wrenches. It's tough to get the lug nuts off with your fingers. Without a multimeter, you won't be able to read voltages, currents, or resistances. Without an oscilloscope, you won't be able to verify whether a waveform is properly trimmed, a frequency is what it should be, or whether two or more logic signals are coordinated in time.

In some cases, you can get by with a subset if you choose the right tools. For example, a frequency counter is definitely nice to have, but I suggest you save some money by buying a multimeter with frequency counting capability built right in. I bought a decent frequency counter but soon discovered that the frequency counting function in my 50,000-count multimeter captures and displays the frequency using a faster frequency determining algorithm.

As I go over each piece of test equipment, I'm not going to recommend a particular brand or model; instead I'll give you all the features each piece of test equipment should have before you buy it.

The Oscilloscope

There are two types of oscilloscope: analog and digital (Figure 2-1). Both are very useful, but digital scopes have a lot of features that put them ahead of their analog counterparts. *Analog* oscilloscopes display a continuous waveform on their cathode-ray tubes (CRTs), whereas *digital* scopes display their sampled and digitized waveforms on what is essentially a small color computer display. We'll go over the vital specifications for both types and then explore some of the useful functions that only the digital units provide.

Figure 2-1. *An analog (left) and digital (right) oscilloscope*

Frequency Response (or Bandwidth)

All oscilloscopes have a high limit to the frequency they can accurately display without distortion. You'll see scopes advertised as 20 MHz, 40 MHz, 100 MHz, or higher. The higher a scope's bandwidth, the more expensive it is, since they use specialized analog components to attain the higher frequency response. When you try to look at a waveform whose frequency is beyond a scope's bandwidth, it will appear attenuated and distorted such that you just can't trust what you're looking at.

On the low end of the frequency bandwidth, your scope should have DC measurement capability. This is the only way you will be able to look at really slowly changing waveforms or DC voltage levels. A faster scope's Time/Div selector will have smaller time per division settings at the upper end of its range than a slower (lower bandwidth) one. In DC-capable scopes, there is a selector switch for each input channel to set the input mode to AC or DC. In AC input mode, the DC component of the input signal is blocked, allowing you to observe just the AC component of the input signal. This is helpful when trying to observe a low-level signal riding on a relatively high DC level.

The good news is that for analog synth work, you can get away with a relatively low bandwidth analog scope. As a matter of fact, 20 MHz will do just fine. However, if you want to be able to look closely at the edges of digital signals, which do come up even in analog synth work, you may want to go with a 40 MHz, 50 MHz, or even a 100 MHz bandwidth scope. And don't forget to ensure that the scope has DC measurement capability.

The bottom line is this: buy the highest bandwidth DC-capable scope you can afford.

Input Channels

I cut my teeth on a single channel EICO brand oscilloscope that didn't even feature DC measurement capability. Going from no scope to any scope was a great thing. My next step up was a single-channel Hewlett Packard I got for $20 from a friend that at least had DC measurement capability (the scope, not the friend). Single channel will work for you if that's all you can lay your hands on. However, as soon as opportunity knocks, go to a multichannel scope. There are many, many times when you need to see the time difference, voltage difference, and shape difference of two waveforms, and a two-channel scope is just the ticket. Scopes go up to four channels, but those tend to get pretty darn pricey.

I recommend at least two channels for serious analog synth work, but if you happen to own a diamond mine, go for four.

Sensitivity

The vertical sensitivity of an oscilloscope is very important. The better the scope is, the *lower* the sensitivity will be able to go. Again, it takes specialized circuitry to allow a scope to display parts of 1mV per division with any kind of accuracy. That's considered the *noise level* to a lot of people. A decent scope is going to start at about 2mV to 5mV per division but may include a multiplier function that adds a bit more gain and can get you down to a 1mV or better minimum level. The scope's Volts per Division knob is what you use to select the sensitivity, which ranges from about 5mV to 5V, 10V, or higher.

The oscilloscope's probe is an important part of the input circuit (Figure 2-2 shows a typical oscilloscope probe). Scope inputs generally have an impedance of one megaohm. The X1 ("times 1") probe mode is the *what you see is what you're measuring* mode. In addition, most scope probes have a switch that allows them to be set to X10 ("times 10") attenuation. When in X10 attenuation mode, you need to remember to multiply the scope's Volts per Division setting by 10. This is because the probe puts a resistor in series with the scope's input, which causes the voltage measurements to be attenuated by a factor of 10.

This is useful for measuring higher amplitude signals than the scope's Volts per Division setting permits, but just as usefully in this mode, the probe's impedance goes up by a factor of 10 (to 10 megaohms). The higher the impedance of the probe, the less effect it has on the circuit you're observing.

Figure 2-2. *The oscilloscope probe becomes part of the circuit you're measuring, so it is important that it is a quality part*

Oscilloscope inputs have capacitance associated with them as well. This may vary from scope to scope, but it is generally in the range of about 10 to 30 picofarads in X1 mode and one-tenth that in X10 mode (another X10 advantage). When measuring low level signals, it is best to use X1 mode if possible; otherwise, you're putting a X10 attenuator in front of the scope designer's quiet little input amplifier, and you may need the added resolution the X1 mode provides.

Last but not least, remember to *compensate* the probe in X10 mode to ensure that the impedance between the probe and scope input are matched; otherwise, you'll be observing a distorted waveform. Scopes generally have a square wave generator with a connection point on the face that provides a convenient compensation waveform. Just connect the probe (set to X10 mode) and adjust the variable capacitor on the probe until the wave looks square and not differentiated (front edge of square wave higher than normal) or integrated (front edge of square wave lower than normal). Use the plastic adjustment tool that comes with the probe, as a metal one could affect the adjustment.

If you get a scope capable of at least 5mV per division on the low end, at least 5V per division on the high end, and X10 probe capability, you'll be in great shape. Higher priced scopes will have more sensitive input circuits and may permit higher voltage measurements as well.

What Else Should I Look for in a Scope?

When looking at an analog scope — either new or used — check for these additional features:

- Beam Intensity and Focus controls
- Vertical Magnification Factor button on Input Channels
- Sweep Magnification Factor button in Time/Div control area
- Position controls for Input Channels and Sweep Start
- Automatic Triggering and Trigger Level, Mode, and Source selection
- Variable adjustment controls for Input Level and Sweep Time
- Ability to invert one or both input signals
- Ability to do X/Y waveform display

Buying a scope with some of these features missing is not the end of the world, but the more of them you get, the happier you'll be with it. I heartily recommend that you try out a used scope before buying it, although that may be impossible if you're at a yard sale or flea market. The older an analog scope is, the dimmer the display becomes, and the more out of calibration it may be. As you progress in electronics, try to find a way to get access to a better scope if the first one you buy lacks essential features.

The Digital Multimeter (DM)

I'm only going to go over digital multimeters because they have become so inexpensive and ubiquitous (Figure 2-3 shows a typical digital multimeter). If you already have an old analog multimeter with a precision movement that provides you with enough accuracy, stick with it. However if you're just getting started, go for the digital multimeter. You can get a decent starter unit for the price of lunch at a fast food restaurant.

As the number of display digits or resolution goes up, multimeters get more and more expensive. Another factor in multimeter cost is whether the unit is battery powered (lower cost) or includes a power supply (higher cost), as many bench models do.

One thing to keep in mind when reading multimeter specs is that in addition to the accuracy percentage, you will see an additional +/- least significant digit(s) count. This just means that the reading may bobble around a little in the least significant (or two least significant) digits, so the lower this range, is the better.

Always use the most appropriate range (if the multimeter does not auto-range) for your meas-

What's Special About Digital Scopes?

I have both a 40 MHz analog scope and a 50 MHz digital scope on my bench, and I use them both all the time. The features that set digital scopes apart from their analog couterparts are legion. The scope's control panel has many of the same controls as the analog scope for convenience. If you had to enter a special settings mode and scroll through a software menu just to set a channel's volts per division or the scope's sweep speed you would get *real* tired of it *real* fast.

However there are a *lot* of functions that *are* hidden behind menus that you access via general purpose *assignable* buttons typically located on the front panel next to the main display. In menu mode, the scope will show you a menu of functions on the screen next to these buttons and you use them in conjunction with a digital pot or two to select and adjust the parameter of interest. Basically a digital scope is an analog scope with really fast A to D converters for the input channels and a *powerful computer* to process the data streaming from the A to D converters. I'm not going to go over *every* function a digital scope provides, but here are some of the cooler features:

- High-contrast multicolor LED or LCD display
- Cursor measurements of both time and amplitude for the displayed waveforms
- Auto-measurements of rise time, fall time, frequency, duty cycle, etc. of the displayed waveforms
- Math functions such as fast Fourier transform (FFT)
- Pass/fail testing of waveforms
- Waveform image acquisition
- Scope "set up" memory and storage
- USB output for storing scope data and waveform images on flash drive
- Auto-calibration
- Capture and hold transient signals for display and measurment

There are times when, even with all these cool features available on my digital scope, I still find my analog scope very helpful. When you start working with a digital scope you'll see what I mean. Sometimes the digital scope picks up *too much* data and you find yourself looking at a lot of noise and digital artifacts that a typical analog scope CRT smooths over for you. In their defense digital scopes provide a variety of filtering functions to deal with this but digging through menus to find these functions is not always conducive to productivity in my opinion.

The bottom line when buying a digital scope is to go for the largest display, highest sample rate (for example 1G samples/sec), largest memory (for example 1M points), and most bits of resolution (8 at least) you can afford. Take care of your scope and it will serve you for years and years.

Figure 2-3. *A typical digital multimeter*

urement to ensure you're getting the most accurate reading. Setting your meter to the 2V range and trying to read 20mV is asking for inaccuracy. A more appropriate range would be the 200mV range. Set the meter so that the expected measurement is near the top of or at least well within the selected range. When measuring an unknown voltage set the meter to the correct mode (AC or DC) and highest voltage setting before adjusting the range down as appropriate.

What should the multimeter you buy be able to do? Here is what I consider to be the basic functionality and accuracy required for getting started in analog electronics work:

- Minimum three and one-half digits
- Minimum 2000 count precision
- 200mV or lower minimum DC voltage scale
- High-contrast readable display
- Measures voltage (AC and DC), current, and resistance
- DC voltage measurement accuracy should be at least +/–0.5% of full scale reading
- AC voltage, DC *current*, and resistance measurements should be accurate to at least +/–1.0% of full scale reading

The more precise and accurate a multimeter is, the more expensive it's going to be. Low noise parts must be used, temperature compensation must be designed in, and the circuitry has to be reliable for years. The rather logical law of test equipment prices is this: *premium parts equal premium price*.

Multimeter Advanced Features

If you can afford to step up to a meter with these additional features, you'll be glad you did:

- Higher accuracy than listed above (.05%, .03%, etc.)
- Auto-ranging
- AC current measuring function
- Frequency counting function
- Capacitance measuring function
- Diode and transistor test capability
- Data hold function
- Delta measurement mode
- USB, GPIB, and/or RS232 computer interface

Logic Probe

A logic probe is a very simple piece of test equipment used to verify the state of a logic gate's output (Figure 2-4). Essentially, it is a pen-like device with two (red and green) or three (red, green, and yellow) LEDs that glow individually, depending on what logic level the probe's tip is contacting.

Figure 2-4. *A typical logic probe*

The logic probe must be powered from the circuit under test, and so it has two leads (typically red and black) that come out of one end and connect to the positive and ground of your circuit. When you probe the output of a logic gate, the logic probe typically lights the red LED for a high logic level, the green LED for a low logic level, and the yellow LED for an indeterminate logic level.

Another feature some logic probes have is pulse detection, which stretches out narrow logic pulses (both high going and low going), giving you a visual indication that a logic pulse was detected at the tip, even if it would normally be too narrow to detect visually. You can build a simple logic probe yourself or buy one with more features to save the trouble. Logic probes come in very handy for troubleshooting complementary metal-oxide semiconductor (CMOS) logic circuits in which levels do not change very rapidly. For observing rapidly changing logic signals, an oscilloscope is required.

The Bench Power Supply

When you are just getting started in electronics, you can work entirely with batteries. Eventually, however, you may want to expand your projects until batteries are no longer practical and a line-powered supply becomes necessary (Figure 2-5). When you're working on the bench, it's not always convenient to go tear down a patch you may have in progress, disconnect your synth-cabinet, bring it into your shop, and run jumper cables from its power supply to test something you're developing or troubleshooting. After you go through that rigmarole a few times, I'll bet buying a bench power supply moves higher up on your priority list. What should you look for in a bench supply?

Figure 2-5. *A typical bench power supply*

Most synth-DIY projects use a bipolar (or dual) DC power supply. Op amps, for instance, one of the most commonly used synth-DIY components, require a positive voltage, a negative voltage, and a ground. In synthesizers, the dual or bipolar power supply voltage is usually between 9V and 15V. Thus, the synthesizer's power supply might provide +9V, –9V, and ground; or +12V, –12V, and ground; or +15V, –15V, and ground, depending on the designer's choice. Occasionally you'll find a synth that has a bipolar supply as well as an additional +5V supply that is used to power logic chips or microprocessors.

What Is a Dual Power Supply?

It may not be obvious to people just getting started in synth-DIY, but most analog synth circuits require positive voltage, negative voltage, and a ground. The op amps in the synth's modules require this type of power to work properly. You can power op amps with a single voltage supply if you create a "virtual ground." To do this, use a resistor divider to create a voltage level that is halfway between the negative and positive poles of the single voltage supply. A capacitor is often added between the "virtual ground" potential and the supply's negative pole for stabilization (as seen in Figure 2-6). This "virtual ground" potential is then used as the circuit's signal ground. It should be noted, however, that a virtual ground is nowhere near as solid or low impedance as a "real" ground provided by a line-powered dual power supply.

The upshot of all this is that you'll need at least a dual output power supply. A dual output power supply is a box with two independent power supplies whose output voltages can be adjusted individually. Often they include built-in voltage and current meters to display both the voltage setting and the current being drawn from the supply. More expensive units include a current limit setting that protects the circuit being powered from being destroyed by excessive current.

If you're just getting started, I recommend using batteries to power your electronic experiments. It's better to make your mistakes using batteries because they are less likely to damage a miswired experiment than a high current output bench supply. Figure 2-6 shows two ways to make a bipolar supply using 9V batteries and a few components.

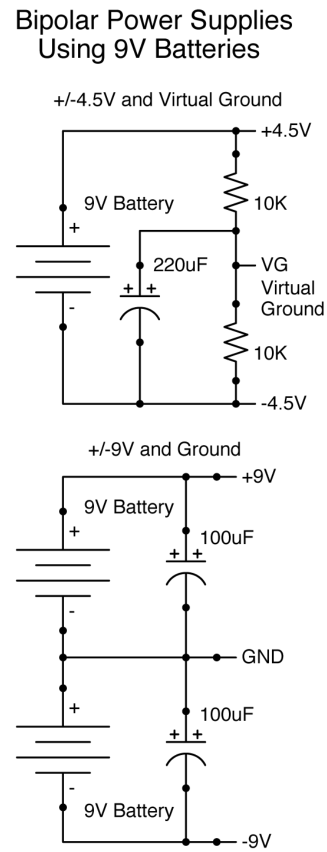

Figure 2-6. *A dual power supply can also be made from a single 9V battery by creating a virtual ground, or by using two 9V batteries wired as shown here.*

About ATX Supplies as Bench Power Supplies

Be careful if you decide to harvest a power supply out of an old computer. Not only do they supply enough current to weld with (don't short the output without goggles on) but often the power is noisy, since they are switching power supplies. A full-wave rectified dual-analog supply delivering a couple of amps of clean power is a better choice.

The plus and minus connection points of both supplies are normally isolated electrically from the unit's case, which is connected to earth ground. Don't connect the positive or negative connection points to the unit's earth ground terminals when using the supply to provide plus and minus voltage to a circuit under test. First set the voltages on both supplies to the desired voltage level. For our explanation, we'll work with +12V. Connect the negative connection of one supply to the positive connection of the other supply. This will become the neutral (or signal ground) connection output point of the dual DC supply. The remaining unconnected positive terminal becomes the positive output of the dual DC supply (+12V), and the remaining unconnected negative terminal of the other supply becomes the negative output of the dual DC supply (–12V).

If you place the black lead of your DM on the junction of the connected positive and negative terminals and the red lead on the remaining positive supply output, you will measure +12V. Leave the DM's black lead where it is and place the red lead on the remaining negative supply output, and you will measure –12V. The dual bench supply you buy should have, at least, these basic features:

- Two independent power supplies, both adjustable between 0V and 30V
- Both outputs minimum 2A capacity
- Voltage and current meters
- Low output ripple voltage

If you can afford to step up to these additional features, you'll be glad you did:

- Current limit setting on both supplies
- Tracking capability (one supply's controls affects both supplies)
- Third output (5V at 2 or 3 amps)

Look around the major Internet shopping sites for *dual power supply*, and buy one with the features and price point you want. Use your favorite search engine to look for *electronic instrument suppliers* to find even more distributors to check out.

Some Nice-to-Haves

Here are some instruments that, as this section's name implies, are *nice to have*. However, before you go out and buy them, look for a multimeter with more accuracy and functionality. I say this because you can save money by getting a multimeter that also measures capacitance and frequency. A multimeter of this kind will give you the ability to match capacitors or read frequencies when you need to, and you don't have to crowd up your bench with a bunch of instruments you only use once in a while. Often you'll want (or need) to measure more than one thing at a time, which is why I list a second multimeter in the *nice-to-haves*.

Second Multimeter

Making more than one measurement at a time comes up so often in electronics work that it just makes sense to splurge for another multimeter as soon as you can.

Capacitance Meter

A dedicated capacitance meter is nice to have when you need to match capacitors or check the value of a cap removed from equipment whose value may be marred or gone (Figure 2-7). They are generally auto-ranging, can measure a wide range of capacitance (example .1pF to 199.99 mF), have data hold, and include multiple measurement modes. As with multimeters, look for a high "count" unit, since the higher the count, the more accurate the readings will be.

Figure 2-7. *A typical capacitance meter*

However, unless you *really* need extreme measurement range and accuracy, go for a more functional multimeter with capacitance measuring capability.

Frequency Counter

Before I even get started, I repeat: *buy a multimeter with frequency-counting functionality for your first instrument*. If you know you're going to be making simultaneous voltage and frequency measurements, then buy a second multimeter with frequency measuring capability. Frequency counters are cool, but many of them take more time to "count" the frequency than you may think, which can be irritating when you need to make quick measurements in real time.

Many frequency counters have precise settable gate times, during which the number of transitions that take place on the input are counted (Figure 2-8). So if the meter reports that 10 transitions took place during a 1-second gate time, we know that the frequency is about 10 Hz. If the meter reports that 10 transitions took place during a 10-millisecond gate time, then we know the frequency is about 1 kHz. So if you want to look at a frequency that is below 1 Hz, get ready to wait while the counter counts the transitions during the successive *10-second* gate times. The prize for your patience is 100mS accuracy (if you can call that accurate). Most dedicated frequency counters are mainly for counting high frequencies in the MHz and GHz region and give short shrift to the audio and lower-frequency range.

Figure 2-8. *A typical frequency counter*

The dedicated frequency counter certainly has its place, but a much faster algorithm for determining the frequency of a regular non-modulated signal is to measure its period accurately and then display the period's reciprocal value (1/(cycle period) = frequency in cycles per second). The more accurately you measure the period, the more precise the frequency measurement. Many multimeters do this, and in my lab it's the only way I measure frequency anymore. My dedicated frequency counter sits and collects dust. As Marley said to Scrooge: "Mark me… buy a multimeter with frequency counting functionality"—or something along those lines.

Function Generator

A function generator comes in handy all the time when working on analog synthesizers (Figure 2-9). I still list it as a nice-to-have because a hobbyist can make a simple but useful function generator for bench use. Since the waveform, amplitude, DC offset, and frequency of the output of the function generator can be adjusted, you can create whatever type of signal you need to exercise a module or circuit you're working on. Many function generators have CMOS and TTL (transistor–transistor logic) level signal outputs in addition to the normal waveform outputs, which also come in handy on occasion.

Figure 2-9. *A typical function generator*

Function generator output waveforms typically include sine, square, and triangle waves. Make sure the function generator you buy has adjustable waveform skew (or duty cycle), which gives it the ability to produce pulse, ramp, and sawtooth waves as well. Another cool feature is *frequency sweep* capability. This is the ability to repeatedly sweep the function generator's frequency using either a log or linear curve from a low frequency to a high frequency, with both sweep width and sweep rate being adjustable. This function is often useful when looking at the response of a filter or an amplifier to determine its bandwidth. As you feed the sweeping frequency into the circuit under test input, you observe the amplitude of the output of the circuit under test using an oscilloscope. The frequency at which the observed output signal's amplitude is 3dB lower (approximately 71% of the value being applied to the circuit under test input) is considered the top end of the circuit under test's *bandwidth*. Better (more expensive) function generators go higher in frequency, have more waveforms, and allow more precise sweep settings. If you can manage to add one to your instrument ensemble, then by all means do so, as you will find it useful.

Tips for Reliable Soldering

People often write to me regarding problems they're experiencing while getting a synth module to work properly. I usually encourage them to find a friend or relative with electronics experience but also suggest they try this or that, depending on the situation. Nine times out of ten, the problem was a *bad solder joint*.

Reliable solder joints are the cornerstone of a reliable circuit. Improper solder joints can lead to all kinds of problems: intermittent behavior, noise, crackling, and even circuit failure. A host of factors affect the quality of solder joints. Here is a list of some of the important factors affecting solder joint quality:

- The temperature of the soldering iron
- The condition of the solder iron's tip
- The type of solder and flux used
- The cleanliness of the surfaces to be soldered
- The skill of the person soldering

Temperature-Controlled Solder Station

I must have gone through 12 dozen cheap pencil soldering irons before I finally broke down and bought a temperature-controlled soldering station (Figure 2-10). While the cheap pencil solder irons are an inexpensive way to get started, I heartily recommend that you save up and get an adjustable temperature-controlled solder station ASAP. I have seen units on Amazon selling for between $20 and $100, so it's not a major investment. I have a couple of soldering stations: one by a "name brand" company, and one by a "never heard of them" company. I use both of them all of the time and they both do the job just fine. So what exactly should you look for in a temperature-controlled solder station?

- Adjustable temperature range from 250 degrees C (500 degrees F) to 450 degrees C (850 degrees F)
- Working temperature attained within a minute
- Solder pencil holder included

- Tip cleaner sponge or brass coils included
- Soldering pencil that's comfortable to hold

Figure 2-10. *Typical temperature-controlled soldering station*

Alright, now that we have a decent solder station, how do we put it to the best use?

Soldering Tips

I recommend 1/32-inch thick, rosin-cored, 60/40 (tin-lead) solder. When wiring panel components, you might want to use a thicker solder (1/16 inch) of the same type. Buying solder in bulk is less expensive than buying small rolls or tubes. The one-pound spool of solder, while a bit of an investment, is actually the most cost-effective way to go and will last a long time.

Set the temperature of your solder station to between 320 degrees C (608 degrees F) and 380 degrees C (716 degrees F). The 60/40 (tin-lead) solder melts at a lower temperature than that (215 degrees C or 419 degrees F), but when you apply the soldering iron's tip to whatever you're soldering, it rapidly loses heat. This necessitates the higher temperature setting to ensure that the solder becomes molten quickly and good eutectic bonding takes place.

The rosin flux in the solder has several important benefits. It prevents surface oxidation during heating, cleans the surfaces to be soldered, and lowers the surface tension of the molten solder, helping it to flow readily and form a reliable eutectic bond between itself and the items being soldered. Always remove rosin flux residue after soldering with an appropriate solvent for the rosin type. Choose an environmentally friendly type of flux remover (no chlorinated fluorocarbons) to keep the ozone layer and your karma in good shape. Don't apply power to the PC board until you have removed all of the cleaning solvents and the board is dry.

Get yourself a chemical pump bottle and keep it full of a mixture of 75% isopropyl alcohol and 25% acetone, and you'll have a great solvent for cleaning rosin flux. If you can get the 99.9% pure isopropyl alcohol (drugstore variety is 91% pure), the mixture will contain less water, which can be absorbed by PC boards and components, but don't obsess, since the 91% variety seems to work just fine. Use solvent-soaked plastic or horse hair bristle brushes to scrub areas in need of flux removal. I like to cut the bristles short on a few brushes for when more scrubbing power is needed. Cotton swabs can be used for cleaning but can leave fibers behind. Canned air is good for blowing the excess solvent and suspended flux off of the board as well as drying it after cleaning. When the solder joints are shiny and the PC board material looks clean, not dull and streaky, you're good to go. Figure 2-11 shows the basic tools necessary for reliable soldering and desoldering.

Figure 2-11. *Tools you'll need for soldering*

Setting the tip temperature too high (not far above 380 degrees C) is just bad all over. You will evaporate the solder's rosin core, preventing it from doing its important work. You will melt plastic elements of components that adjoin terminals. You will delaminate pads from your PC board. You may cause value changes or worse, destroy temperature-sensitive components. Stay within the safe temperature range (320 to 380 degrees C), and don't linger on a soldered joint once the solder flows.

Be careful when soldering switches, jacks, or any components that have plastic parts. Applying the solder pencil's tip to a component's terminals for too long or with too much pressure or heat can transfer heat to any surrounding plastic, melting it and damaging or destroying the component. Turn the heat down a bit when you're about to solder components with plastic parts. Experiment on a spare part so you know how it will react when exposed to soldering temperatures.

Rosin Paste Flux

I've mentioned that excessive heat can damage plastic parts of panel components. To minimize the solder iron application time, I apply a tiny amount of Qualitek 50-4002B PF400 Rosin Paste Flux with a toothpick to terminals prior to soldering. The additional rosin flux makes the solder wet to the panel component terminals more quickly, reducing their exposure to high temperature.

Let the soldering iron heat up before beginning. Dampen the solder station's cleaning sponge by first wetting it and then squeezing the excess water (and any solder balls) out of it over the trash can. Damp is good but soaking wet is…not so good. You want the sponge to be able to clean the tip, but you don't want to cause the tip's temperature to fall excessively by dipping it into a soaked sponge. After a few wipes on the damp sponge to remove any lingering old solder or oxidation, apply some fresh rosin core solder to the tip and wipe it on the sponge again. Keeping the tip coated with fresh solder will help it to transfer heat quickly to the items being soldered.

You don't have to clean every pad/lead combination with solvent prior to soldering because the rosin flux core in the solder does an admirable job of cleaning the surfaces. I can't remember the last time I was plagued with a cold solder joint, so history bears me out on this. Of course, if there is obvious oxidation on a component lead or pad, you should take the time to clean it before soldering.

When soldering a joint, you want to contact all of the surfaces to be soldered with the tip in order for heat to transfer to them evenly. Figure 2-12 illustrates the recommended application of the soldering iron tip to all surfaces for best heat transfer. After you apply the solder iron, immediately apply the solder so that it contacts both the tip and the heated surfaces. Once the solder flows, remove the tip and let the joint cool undisturbed. Don't linger after the solder has flowed, or the bad things discussed above will happen, possibly ruining a perfectly good day. Don't apply too much solder. The soldered joints should not look like bumps but should have concave fillets. Practice on a scrap PC board until you feel comfortable and your solder joints look shiny and have nice fillets.

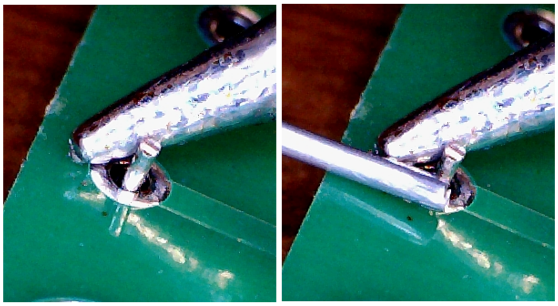

Figure 2-12. *Proper solder tip and solder application*

I generally solder about 10 to 16 component leads and then repeat the tip cleaning process. During soldering, if you apply the solder so that it contacts the tip and the materials being joined, you will ensure the tip has fresh solder and rosin on it, which will keep it from oxidizing. However, after you solder a number of joints, the tip will start to accumulate crud, and you'll need to clean it. With experience, you'll find the optimum number of solder joints you can make between tip cleanings.

Double-sided PC boards have what are known as *plated through-holes*. During the manufacturing of PC boards, the holes for mounting components are drilled through the copper-clad material first, and then those holes are plated through with copper (Figure 2-13 shows a cross-sectional view of a plated through-hole). This is a process that causes copper to be plated onto the walls of the component mounting holes drilled through the PC board material. These plated through connections give PCB pads extra strength and resistance to delamination and are used to route electrical signals between the two sides of the PC board. AAfter plating the insides of the through-holes with copper, the etching, solder coating, and solder masking processes are completed.

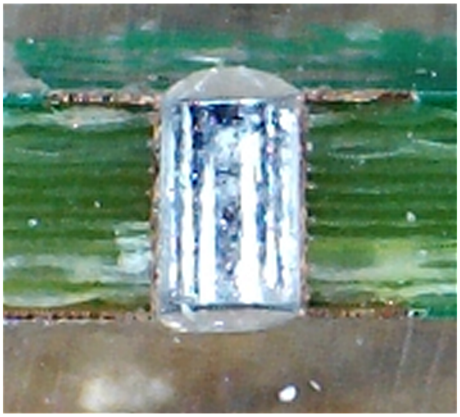

Figure 2-13. *Plated through-hole*

When soldering a double-sided PC board, the solder flows onto the donut pad surface and component lead, through the cavity between the component lead and the sides of the plated through-hole, and all the way up onto the top side's anular ring (Figure 2-14). This is exactly what you want, and you'll see solder fillets (metallic concave surface surrounding the component lead) formed on both the bottom and the top of the PC board.

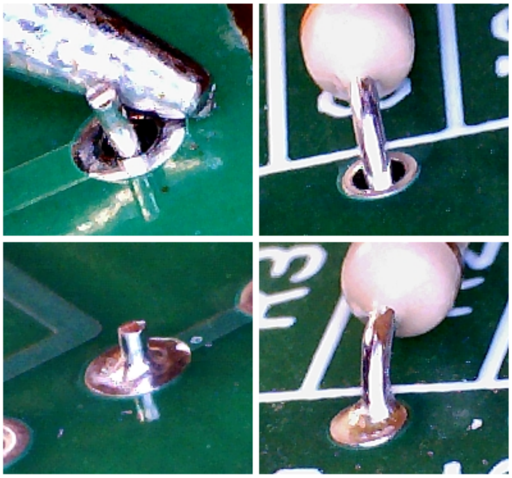

Figure 2-14. *Solder flow through plated through-hole*

If too much heat is applied by the tip and the rosin boils away, you may get poor wetting, the solder may appear bumpy and gray, and no top fillet will be seen. STOP! Turn the heat down a bit and apply some fresh solder (with rosin in it) to *reflow* the joint. A good solder joint should appear bright and shiny, especially after cleaning (Figure 2-15). Too much solder applied to a joint or that accidentally bridged two pads may need to be removed using desoldering braid (discussed below).

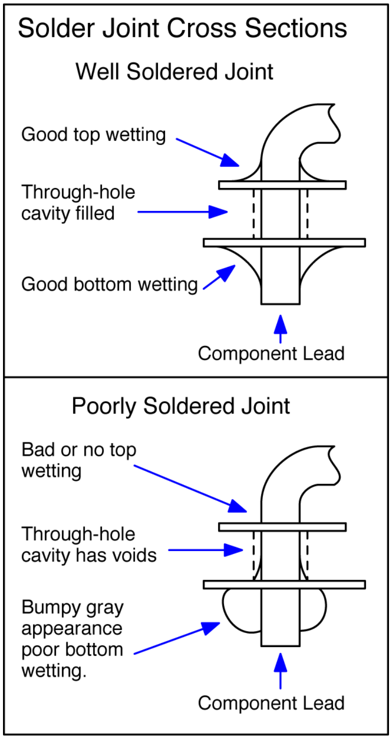

Figure 2-15. *A well-soldered joint versus a poorly soldered joint*

Companies make special vises that can hold a PC board during soldering. They are very convenient to use but in no way required. When populating a PC board for soldering, your best bet is to install a few components at a time onto the board. Bend the leads protruding through the bottom of the PC board so the components don't fall out of the board when you invert it to trim them. In higher density areas, bend the leads away from any nearby pads to avoid accidental solder bridges from forming.

The reason I suggest trimming component leads prior to soldering is that the physics of trimming the leads post-soldering can apply a significant shock to the solder joint that can break the joint's eutectic bond. Something like that has the potential to haunt your circuit's future reliability, so before soldering, always trim the leads using a lead trimmer designed to reduce mechanical shock to the component.

Desoldering Is Important, Too

You've been troubleshooting a circuit, and lo and behold, you find a component you need to remove. Here is what to do. On the top side of the PC board, cut the component's leads and discard it. Turn the board over. Using aluminum or stainless steel tweezers with a fine point, grasp the remaining lead with one hand and apply the soldering iron tip so that it contacts the PCB pad and the lead simultaneously. When the solder becomes molten, *gently* pull the lead with the tweezers and remove it. If the solder solidifies, apply a bit more solder (we want its rosin flux) and try again. The lead should come out with little effort. Once you've gotten the leads out, it's time to clear the holes of solder so you can install the replacement component.

I find solder braid extremely useful, so that's what I'm going to discuss. I think spring-loaded vacuum solder suckers have too much capacity to do harm to circuit board pads, so I very rarely use them. I will occasionally use a solder sucker for desoldering jack or pot terminals (things I can't suck pads off of), but thicker braid works fine for that, too.

Desoldering braid is made of very light gauge copper wires that are braided and impregnated with rosin flux. It comes in a variety of widths, and the wider it is, the more capacity to *absorb* or *wick* solder it has. Desoldering braid is not very expensive, so buy a few rolls of varying widths to have on hand. Figure 2-16 shows some typical solder wick dispensers.

Figure 2-16. *Two widths of desoldering wick*

To use desoldering braid, expose a couple of inches of new braid and then use the plastic case as a handle. Don't hold the copper braid itself, as it can get quite hot. We're going to apply the braid to the pad whose hole we want to clear and then apply the soldering iron's tip to the braid. If possible, apply the braid so that an eighth of an inch or so extends beyond the pad. Always clean and re-tin your soldering iron's tip immediately prior to applying it to the braid. Apply the cleaned, newly tinned tip to the braid right over the pad to desolder with light force so that the heat from the tip transfers to the braid, which in turn transfers to the solder on the pad and melts it. You should see the copper-colored braid turn silver as the solder flows into it. In Figure 2-17, I have removed the soldering iron but left the braid for you to see the silver color that forms as the solder flows into the braid. In practice, as soon as you see the braid become silver, remove it and the soldering iron tip simultaneously. Nine times out of ten, the hole will be clear but if it's not, don't panic; here's what to do.

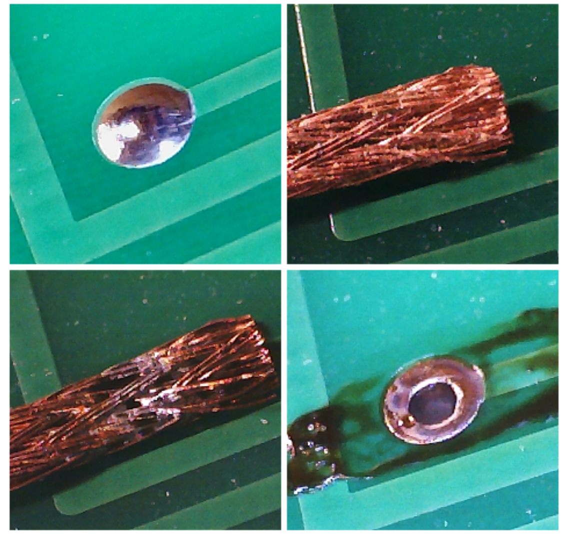

Figure 2-17. *Clearing a pad's hole with desoldering braid*

Apply a bit of fresh rosin core solder to the pad's hole and try again. Sometimes you need to *prime* the braid with a tiny bit of solder to get the heat to transfer properly. Don't use too much, or the braid will become saturated, rendering it incapable of wicking additional solder. With practice, you'll hit the nine-times-out-of-ten mark and only have to fuss with a pad once in a while.

Obtaining Electronic Components

I've been buying electronic components for decades, and one thing I've seen over the years is that prices are all over the map. Always shop around when you're preparing to gather parts for a project. Potentiometers, switches, resistors, capacitors—any electronic component can be purchased online from hundreds if not thousands of vendors. I'm not saying that you should abandon your local electronics retail store, especially if it provides a wide selection of parts at competitive prices. However, if that has been the *only* place you've been buying components, it's time to find out what online electronics stores have to offer.

Surplus Parts

You'll want to stock your *lab*, be that the desk in your bedroom or a space set aside in your attic, basement, or garage. When it comes to things like resistors and capacitors, you can often find great deals by scouring the surplus sites. Use your favorite search engine to look for "surplus electronics," and you'll be visiting websites for as long as you've got time.

Capacitors

Often, surplus electronics sites will sell capacitors that they've bought from companies that have overstock or are going out of business. If you can't find the value you need there, remember that you can create capacitance values you don't have in your stock by putting caps in series or parallel with one another (see Figure 2-18).

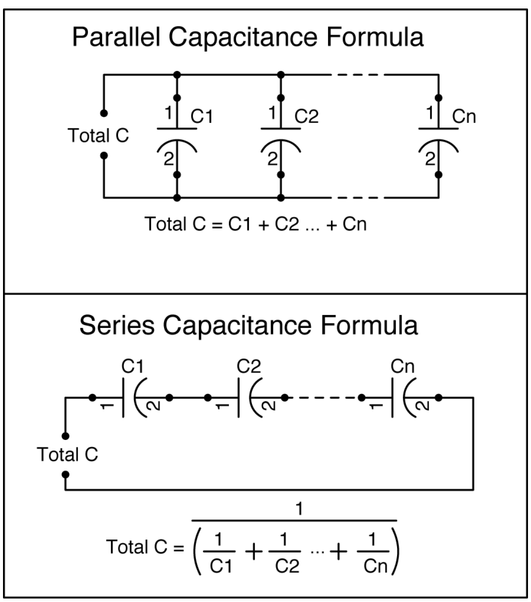

Figure 2-18. *Formulae for capacitors in parallel and series*

There are several types of capacitors commonly used in analog synths: nonpolarized ceramic and film caps, nonpolarized aluminum caps, polarized aluminum electrolytic caps, and polarized tantalum electrolytic caps. The polarized types must be connected so that the polarity of the applied voltage matches the polarity markings on the body of the cap. Applying reverse voltage to a polarized cap will damage or destroy the capacitor, rendering it leaky or otherwise physically compromised.

Ceramic caps are great for coupling AC signals within a circuit where DC blocking is important. Film capacitors have characteristics that come in handy in certain applications. For example, polycarbonate and polystyrene film capacitors have great temperature tolerance and very low leakage. They are often used in sample-and-hold circuits where the capacitor has to hold a voltage for a long time without drooping.

Tantalum electrolytic capacitors have very low leakage and are great in instances where you're putting a large resistance in front of the cap and charging it. In this circumstance, if the cap exhibited excessive leakage, it might, for example, never charge to a necessary threshold voltage. To appreciate what capacitor leakage is like, just imagine putting a 10M or lower resistor in parallel with the cap you're trying to charge. The leakage is always trying to discharge the cap whether you want it to or not.

Aluminum electrolytic capacitors come in values from submicrofarad to several farads (yep, I said farads). They are often used for localized stabilization of voltage levels on PC boards in the 10µF to 100µF range and come in values large enough (tens of thousands of µF) to be used as the main filtering caps in power supplies. They are useful in timing circuits, filters, AC coupling, power supplies, and many, many other uses. Aluminum electrolytic capacitors have higher leakage than tantalum types.

Bipolar electrolytic caps provide a high value of capacitance, without the polarization normally associated with electrolytic caps. They use a trick you can use when you need a large amount of capacitance but don't want polarization issues. If you connect the negative poles of two polarized caps, you can use the remaining two positive poles as the leads of a bipolar (or nonpolarized) cap. The value of the two caps in series can be determined from the formula shown in Figure 2-18. If the caps have the same value, 10μF for example, the value of the newly formed bipolar cap will always be one-half of the original values, in this case 5μF.

The *working voltage* of a capacitor is the voltage that can safely be applied to its plates before the dielectric material between them breaks down, resulting in destructive arcing. To avoid this, always buy capacitors for your project whose working voltage is well above the highest voltage you plan to apply to them in your application. Normally this is the power supply voltage, but a safety factor of 1.5 to 2 times the power supply voltage will keep your project's reliability up. Thus, if you are working on a project in which your caps might be exposed to a potential of 20V, then buy caps with a working voltage of 35V or more. For a 9V battery-powered project, 16V or 25V caps would fill the bill.

The physical size and lead spacing of capacitors can be important. Film and ceramic capacitors with lead spacing of 5mm (.2") are very convenient for breadboard work. Getting caps with too high a working voltage can result in caps that take up more physical space than necessary for a lower voltage project, so keep package size in mind when buying caps. Capacitor data sheets contain detailed size specifications, and you should become familiar with them.

For people who are just getting started, I suggest building projects that come as kits to ensure that you have all of the correct parts. This not only provides a more satisfying project experience, but it also teaches you what the components look like and what size and type to buy next time. Sourcing the parts yourself for projects is definitely the most cost-effective way to go. Request catalogs from the larger online electronics part distributors and look through them to familiarize yourself with what parts are out there, what sizes they come in, and what they cost.

Any time I've been in an artist's studio, I've noticed that there are normally several tubes of the colors used, as well as an easel, a palette, brushes, and canvases ready to go for when inspiration strikes. Having to stop and round everything up can be a real creativity killer. As you progress, you'll find that having a stock of commonly used electronic components on hand is practically a necessity. That way, when a circuit idea pops into your head, you'll be able to plunk it onto a solderless breadboard and experiment with it, which is one of the best ways to learn. What part values should you have on hand?

Capacitors to Keep On Hand

I suggest that you stock your lab with these values of capacitance for your experiments. Buy in bulk to save money. You'll notice that I've gone with an approximate 1, 5, 10, 50… series of values. Again, bear in mind that you can put these values together in series and parallel for additional values. When opportunity knocks, I suggest you expand your parts cabinet to contain a 1, 2, 5, 10… series of values. A series like that would go 10pF, 22pF, 47pF, 100pF, 220pF, 470pF, etc. You can generally find surplus ceramic or film caps that have these values, and for experiments, either type will work fine. Capacitor assortments are available that contain a nice range of values for breadboard experiments. You can buy tantalum or aluminum electrolytics for values at and above 1μF.

Value	Max Voltage Rating	Type
10pF	50V	Ceramic Capacitor
47pF	50V	Ceramic Capacitor
100pF	50V	Ceramic Capacitor
470pF	50V	Ceramic Capacitor
.001μF	50V	Ceramic Capacitor
.0047μF	50V	Ceramic Capacitor
.005μF	50V	Polystyrene Capacitor
.01μF	50V	Ceramic Capacitor
.047μF	50V	Ceramic Capacitor
.1μF	50V	Ceramic Capacitor
1μF	35V	Aluminum Electrolytic Capacitor

4.7µF	35V	Aluminum Electrolytic Capacitor
10µF	35V	Aluminum Electrolytic Capacitor
47µF	35V	Aluminum Electrolytic Capacitor

The .005µF polystyrene capacitor is handy for VCO and sample and hold experiments.

Resistors to Keep On Hand

Surplus houses will often offer new resistors sold in either tape and reel format or bulk. It's way cheaper to buy resistors by the hundreds (or more if you use enough of them) than to buy them one at a time, so take advantage of bulk pricing and stock your lab with the values I suggest below. As in the case of capacitors, resistor experimenter sets with 5 or 10 pieces of a wide range of common resistance values are also available. It's good to have one of those on hand as well as a good number (20 to 100 each) of each of the following values for your breadboard experimentation work.

Value	Max Power Rating	Accuracy	Type
100 ohm	1/4W	5%	Carbon Film or Composition
1K	1/4W	5%	Carbon Film or Composition
2K	1/4W	5%	Carbon Film or Composition
4.7K	1/4W	5%	Carbon Film or Composition
7.5K	1/4W	5%	Carbon Film or Composition
10K	1/4W	5%	Carbon Film or Composition
20K	1/4W	5%	Carbon Film or Composition
47K	1/4W	5%	Carbon Film or Composition
75K	1/4W	5%	Carbon Film or Composition
100K	1/4W	5%	Carbon Film or Composition
200K	1/4W	5%	Carbon Film or Composition
470K	1/4W	5%	Carbon Film or Composition
1M	1/4W	5%	Carbon Film or Composition
2M	1/4W	5%	Carbon Film or Composition
4.7M	1/4W	5%	Carbon Film or Composition
10M	1/4W	5%	Carbon Film or Composition
100K	1/4W	1%	Metal Film
200K	1/4W	1%	Metal Film

Resistors can also be arranged in series and parallel to obtain values you don't have in your parts cabinet. The formulae for determining the resistance of resistors in series and parallel are shown in Figure 2-19. The 1% resistor value parts drawer suggestions are for times when you want more accuracy, say for a D to A converter or a precision gain circuit.

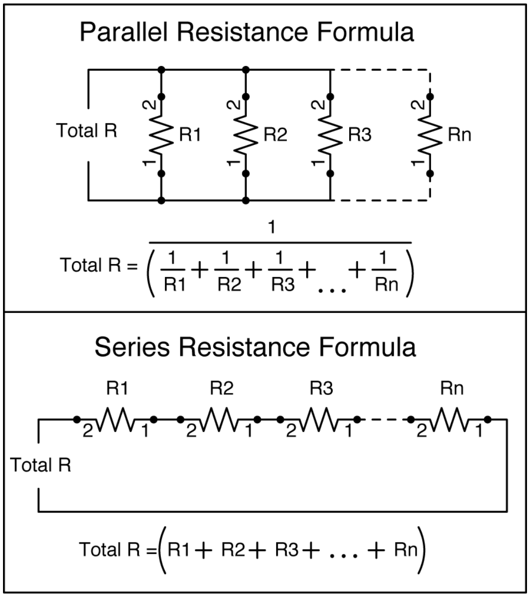

Figure 2-19. *Formulae for resistors in parallel and series*

Mechanical Components

Mechanical parts like potentiometers, battery snaps, switches, transformers, wire, etc., are often available from surplus houses, and buying them there can save you a lot of money. Revisit the same places you found when doing your Internet searches for "electronic surplus," and look for pots, switches, and transformers specifically to see what they've got. When all else fails and you can't find what you're looking for on surplus sites, you'll have to bite the bullet and go to a bona fide electronics distributor like *Mouser*, *Digi-Key*, *Jameco*, *Avnet*, etc. Compare who has the best price and buy it there. Do an Internet search for any of these distributor names to quickly find links to their websites.

Potentiometers are a common feature in most analog synths, and prices for them can vary a lot. A typical potentiometer can cost between $1 and $50, and if you don't know what you're looking for, you may spend way more than you need to. You'll typically want to buy carbon film or conductive plastic pots with a power rating between 300mW and 500mW, tolerance of 20%, panel-mounted configuration, in a 24mm or 16mm case size. Pots come with a variety of shaft lengths and types. There are knurled shafts, "D" shafts, and round shafts.

To avoid ending up with some goofy-looking, long-shafted pots, *always* check part numbers and specs before clicking OK. When in doubt, call the company you're buying from and ask for help selecting the correct pot/shaft/knob combination. You don't want to be up pot creek without a knob, to borrow a phrase. I buy a lot of the *Alpha Taiwan* brand potentiometers (which have a 1/4-inch-thick, round shaft and length of .335 inches) from a variety of part vendors; they work very well and are reasonably priced. Knobs for this type of pot are very common and come in a wide variety of shapes, sizes, and colors.

It's a good idea to keep some pots on hand for breadboard experimentation. I use solderless breadboards that work with 22 AWG solid wire when experimenting. For convenience, I've soldered six-inch lengths of 22 AWG solid wire to the terminals of several pots whose values I find useful and use them regularly during my experimentation. Keep five or so potentiometers of each of these values (10K Linear, 100K Linear, 1M Linear, 100K Audio, and 1M Audio) on hand for breadboarding. Other than that, I buy pots and knobs on a project-by-project basis, since it would be an expensive overkill to keep scores of pots on hand.

Switches are another part you need all the time and whose price can vary wildly. Take it from me that you can find decent-quality mini toggle switches for around a dollar each if you look hard enough. I've seen a mini toggle switch SPDT (single pole double throw) go for between $0.75 and $5.00 each. The generic mini toggle switches I buy that are in the $1.00 range are UL approved and have a current rating of 5A, which will handle any situation typically found in an analog synth. So look around, compare prices, and don't waste your money on name brands or excessively expensive components. Again, the surplus houses generally have all of the switch configurations you'll need (SPST, SPDT, DPDT, 3PDT, various push buttons, etc.). Do an Internet search for *mini toggle switch sales* or *push button sales* to find hundreds of distributors and switch styles.

For breadboarding, I've soldered six-inch lengths of solid 22 AWG wires to the terminals of a number of switches, just as I have for the potentiometers. It adds a lot of convenience to my experimentation not to have to stop and add wires to switches or pots while I'm in the heat of an experiment.

Transformers are something you run into when you start to build power supplies. You can buy power supplies prebuilt with multiple output voltages from several sources or make one yourself. If you go the *self* route, make sure you buy a transformer that has the correct primary AC voltage for your area of the world.

The most important thing after that is to get the right *secondary* AC voltage. When you rectify the output of a transformer, the rectified voltage is approximately the square root of 2 (1.414) times the VAC (Volts Alternating Current) value of the transformer's secondary (or secondary segment in the case of center-tapped transformers). Depending on the voltage regulator chip you use, you typically need to apply about three to five volts above the regulator's output voltage for proper operation of the voltage regulator. See the data sheet of the regulator you plan to use to determine what the secondary voltage of your transformer needs to be.

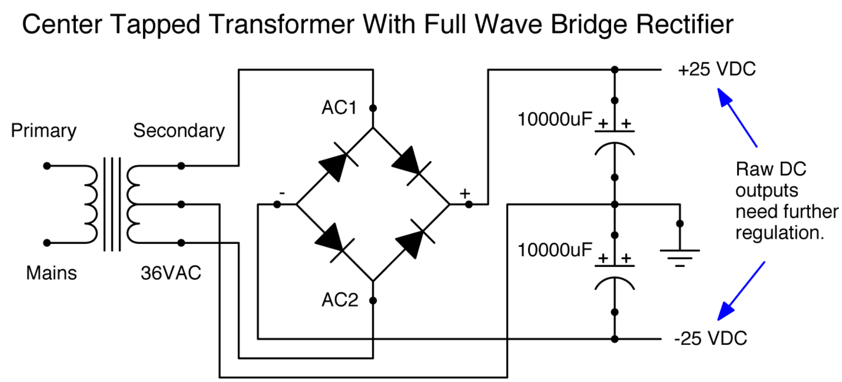

Figure 2-20. *Center-tapped transformer with full-wave bridge rectifier*

Most analog synths use a dual (also known as a bipolar) power supply, and they are most readily constructed using a *center-tapped secondary* transformer. For instance, a center-tapped 36VAC transformer has three wires on its secondary side. Two are attached to the two ends of the secondary coil, and the third is attached to the center of the secondary coil (the *center tap*). If you put the leads of your multimeter (set to measure AC voltage) across the *center tap* and either outer secondary wire, the meter will display 18VAC. If you put the multimeter's leads across the two outer secondary wires, you will read the full 36VAC. This arrangement is perfect for driving a full-wave bridge rectifier to supply a beefy dual DC supply.

Figure 2-20 shows the skeleton for making a simple but effective dual DC power supply. All you need to do is add some voltage regulators to the raw DC outputs and voila—you have a regulated power supply with 1A or more of output capacity, depending on the regulators used. The LM78XX/LM79XX series or three terminal regulators are widely used and provide up to 1A or more of regulated power to your project. They come in a variety of fixed voltages (LM7805/7905 +/–5V, LM7809/7909 +/–9V, LM7812/7912 +/–12V, LM7815/7915 +/–15V, etc.). I highly suggest that you add a switch and a fuse to the primary side of any mains powered supply.

For adjustable supplies, you can use the LM317/ LM337 adjustable positive and negative voltage regulators. You could even make your own adjustable dual DC bench supply using these regulators. By reading the data sheets for the regulator chips (a skill you should definitely develop), you'll see exactly how easy they are to put into your project.

Active Components

Active components are things like integrated circuits, transistors, and diodes. There are hundreds of thousands (if not millions) of different active devices available for electronics. You will often need to buy specialized components for projects, and you can't stock everything, but Table 2-1 lists some transistors and ICs to stock for your experimental work. Electronic parts come and go, so the specific integrated circuits I mention here may not be available in the future, which is why I will specify the function of each chip. Find the current version by searching online for the description rather than the specific part number, or try both. The *Music From Outer Space* website is a great resource for hard-to-find active and passive components.

This is my suggested list of active parts to stock in your parts cabinet. I have several of each of these devices on hand for experimentation. Look up the data sheets for the components you're not familiar with to discover the unique functions they provide. I'll cover specific uses for some of these devices in Chapters 4 and 5 as well as the appendixes.

Table 2-1. Active components parts drawers

Part Number	Function	Great For
2N3904	General Purpose NPN Transistor	Driving LEDs, discrete amplification, log converters, current sources, noise sources
2N3906	General Purpose PNP Transistor	Driving LEDs, discrete amplification, current sources
2N5457	N-Channel JFET Transistor	Source followers, sample and hold, integrator reset
PN4391	N-Channel JFET Transistor	Sample and hold, integrator reset
MPF102	N-Channel JFET Transistor	Sample and hold, integrator reset
LM13600/LM13700	Dual Transconductance Op Amp	VCF, VCA, VCO, and a million other circuits
LF444	Quad JFET Input Op Amp	Sample and hold circuits
TL074	Quad JFET Input Op Amp	Amplification, filters, comparators
TL072	Dual JFET Input Op Amp	Amplification, filters, comparators
TL071	JFET Input Op Amp	Amplification, filters, comparators
CD4066	CMOS Quad Analog Transmission Gate	Sample and hold, gating functions, effects
CD40193	CMOS 4-Bit Up/Down Counter	A to D, counting, timing and logic
CD40106	CMOS Hex Schmitt Trigger Inverter	Timing and logic
CD4094	CMOS 8-Stage Shift-and-Store Bus Register	Timing and logic
CD4013	CMOS Dual D Flip Flop	Frequency division, switch debouncing, data latching, timing and logic
CD4001	CMOS Quad NOR Gate	Logic and flip flops
CD4011	CMOS Quad NAND Gate	Logic and flip flops
CD4024	CMOS 7-Stage Ripple Carry Binary Counter	A to D, counting, timing and logic
LEDs	General Purpose LEDs (various colors)	Lighting up your project
1N914 or 1N4148	High-Speed Diodes	General rectification, timing and logic

Many online sources carry many or all of these devices. Some of the N-Channel JFET transistors are becoming harder to find but are still readily available at *Music From Outer Space* and other boutique synth-DIY sources. So what are we going to do with these components we've gathered? That's where the solderless breadboard comes in.

Solderless Breadboarding

Solderless breadboards (SBBs) are standard equipment for any aspiring synth-DIYer. They're often the place where new circuit ideas are born and honed. They're super handy for learning and/or experimenting. I can't think of an easier way to set up and tear down a circuit than using one of these guys.

Solderless breadboards are equipped with phosphor-bronze, nickel (or gold) plated wire-clips arranged on a one-tenth-inch grid. The one-tenth-inch spacing is the same as that of dual in-line package (DIP) integrated circuit leads. The clips are designed to accept component leads and solid hookup wire (22 AWG is a great size) and provide good electrical connections for low-frequency, low-current work.

Kits are available that contain a variety of wire lengths and colors with prestripped ends, prebent at 90 degrees for use with solderless breadboards. A less expensive alternative is to buy some spools of solid 22 AWG wire, cut it to length, and strip the ends as you work. Bending the ends at 90 degrees is not necessary, and you can just poke the stripped wire ends into the breadboard. Don't poke big fat leads into the breadboard or you may overbend the clips, reducing the reliability of the connection points. When I'm finished with a breadboard session, I gather up the stripped wires and keep them in a bin for next time. Figure 2-21 shows a typical solderless breadboard and two spools of 22 AWG solid hookup wire all ready to breadboard the next killer circuit.

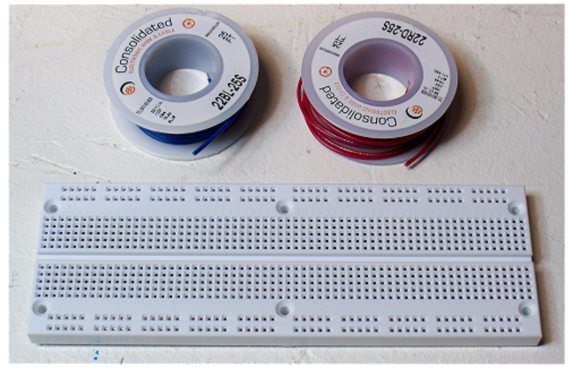

Figure 2-21. *Solderless breadboard and solid 22 gauge hookup wire*

Figure 2-22 shows the typical connection scheme used on solderless breadboards. The red lines indicate which of the clips are connected together. The power buses on the sides of the SBB are connected along the length of the SBB. Beware that often the power bus is only connected halfway down the side of the SBB. You may need to add a jumper between the two segments of the power bus if you want power all the way down the strip. The connection points that go across are connected together but do not continue through the center of the board to the other side. They are separated specifically so you can plug a DIP integrated circuit with one-tenth-inch lead spacing into the SBB and then connect its leads via the remaining socket clips on either side of the chip to additional components mounted in other areas of the SBB (Figure 2-22).

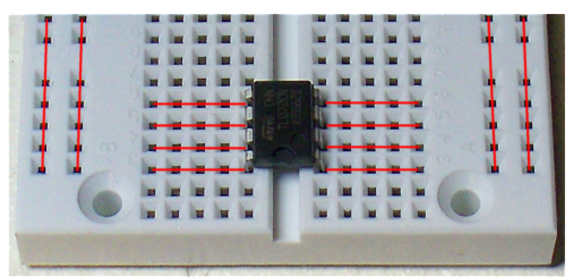

Figure 2-22. *Solderless breadboard highlighting connected clips*

Hand Tools

In Figure 2-23 we see the typical set of handtools you'll need to get started. You'll want to buy a pair or two of fine-point tweezers for use in your soldering and desoldering work. I like the stainless steel types because they're strong and they resist corrosion. Aluminum tweezers are also good but less durable. An advantage of the aluminum tweezers is that they remove less heat during desoldering when the soldering iron tip comes into contact with them.

Figure 2-23. *Hand tools for synth-DIY*

You'll also need needle-nose pliers, a good pair of diagonal cutters, a wire stripper (with small AWG stripping capability), Phillips and flat bladed screwdrivers (including small jeweler's screwdrivers), an IC remover, hobby knife, and a trimpot adjustment tool. Also important to have on hand is an assortment of multicolored test leads with alligator clips or mini-clips on the ends. They're perfect for quickly connecting things on the work bench. You'll want to get yourself a static mat and wrist band with a connecting cord to aid in combating static damage to your active components. A nice magnifying glass is invaluable when trying to read the micro-writing on small components or transistors. Lastly, a fluorescent lamp with a magnifier is invaluable for PC board inspection, soldering, desoldering, and troubleshooting.

Coming up with cases for your projects is part of the fun, and when you're just getting started, you can use available materials to save money. When I first got started, I used aluminum bake pans for making chassis and face plates. They're cheap, readily available, and can be drilled easily. When breadboarding and coming up with circuits, I'll often mount the panel controls on a piece of cardboard with HVAC aluminum tape on the back to provide a ground plane.

You can also buy premade aluminum and plastic cases from electronic suppliers to house your projects, but even then you'll need at least an electric drill to make the component mounting holes. If you plan to make your own cases for your projects, you'll need at the very least a power drill, a jigsaw, a vise, sandpaper, nails, and screws. Start small and obtain tools as you need them. You can find deals on used tools at garage sales and flea markets.

Well, you're all tooled up and you have the instruments you need to troubleshoot your projects. In the next section I'm going to cover some troubleshooting basics. Anyone building electronic equipment will tell you that troubleshooting your work is standard procedure, and the better you get at it, the faster you'll be enjoying the projects you make.

Troubleshooting Tips

You've populated your PC board with all of the components, soldered carefully, made a front panel, mounted the components on it, and wired it to your PC board. With high anticipation, you power it up, connect a cable from your project to your amp, and… nothing. To quote a famous guide often used by universal hitchhikers, "DON'T PANIC." It's not the end of the universe, you're not a failure, you're still every bit as special as your mom told you—you simply have a bug and need to do some troubleshooting.

You should put on a pair of goggles when powering up a project. There are components that will explode if they're not installed in the proper orientation. Tantalum caps, for instance, go off like firecrackers if installed backwards.

Everyone makes mistakes, especially when building an electronic project. I've been building electronic projects for decades, and I still goof from time to time. I forget a part, wire something to the wrong place, forget a wire entirely, or make some other simple mistake. The trick is knowing how to track down the problem and fix it, and that's what I'm going to try and prepare you to do.

How to Minimize Troubleshooting

You can cut way back on troubleshooting if you're ultra-careful and attentive to every detail during the construction of your project. Observe static precautions in your work area. Get yourself a static mat and a wrist band with a cord that connects to the mat. Wear it while working with active components (ICs and transistors) to ensure you don't statically damage your components while handling them. Use a magnifier light when inspecting your PC board's component values and solder joints.

I advise people to print out the PC diagram with the component legends or values on it so they can work from it. Then after the printed circuit board is populated, go back and check that you put the correct components in every location and that each of them is properly soldered. Inspect the resistor color bands carefully to be sure each is correct. For example, it's very easy to mistake a 200 ohm resistor (red/black/brown) with a 1K resistor (brown/black/red). Be certain to look carefully at the capacitor values to be sure they're all correct as well. Make sure all active components and IC sockets are oriented correctly. A transistor, diode, or IC that is oriented incorrectly will definitely cause havoc. Use IC sockets for all ICs just in case you have to go looking for a bad one. It's way easier to desocket than to desolder.

Make sure there are no component legends without a component on the PC board. Look the board over very carefully until you are certain all components have correct values and are soldered correctly. If you find a component with an incorrect value, carefully desolder and replace it. If you see a suspect solder joint, reflow it (add a tad of fresh rosin core solder) or desolder it using desoldering braid and resolder it.

I also recommend that people print out the panel wiring details for a project and then use a highlighter to mark off each wire as they install it. Do the intra-panel wiring first. These are the wires that interconnect the components on the front panel. Here again, careful inspection and attention to detail will give you the best chance of success on power-up. Go over each wire in the wiring diagram, comparing it to the wiring you just installed. Install any missing wires or reroute any that got misrouted.

When you're ready to wire the panel to the PC board, look over the schematic for the project to determine which wires will be carrying which signals. This is another reason it's important to learn to read schematics well. Keep inputs and outputs away from one another. Keep high-level signals away from low-level signals or inputs. When you put two wires next to each other, parasitic capacitance and inductance exists between them, which can cause a high-level signal in one wire to be coupled into a separate but adjacent wire.

Examples of high-level signals include VCO outputs, LFO outputs, gate signals, trigger signals, and comparator outputs. Examples of sensitive signals susceptible to reflection from high-level signal-carrying wires include mixer inputs, filter inputs, and VCA inputs. Use coax cable for sensitive inputs and only ground one end of the cable to avoid ground loops. By routing your wires properly, you'll avoid issues related to signal reflection.

What to Look For

Here are a number of things to consider when trying to find an issue with a circuit. This is where your oscilloscope, multimeter, and Sherlockian sleuthing skills (Figure 2-24) are going to get a good workout.

Figure 2-24. *A loupe is handy for close inspection of components and solder joints*

- Read over the circuit's description so that you are thoroughly familiar with what it's *supposed* to be doing.
- Make a copy of the schematic and use it to record notes and measurements made during troubleshooting.
- If you are lucky enough to have another working version of the circuit, use it to compare what you are seeing in the defective one. This is one of the easiest ways to find a problem within a circuit.
- Look very closely at changes or modifications you may have made to the circuit, even if it worked fine for a while after the change was made. Consider any degradation in circuit operation observed before the circuit stopped working. Did you connect the input or output to something you hadn't connected it to before? Considering these things can give you a leg up on where to start looking for the problem.
- Go over the component values on the PC board again to make sure every one of them is properly oriented and of the correct value.
- Go over the wiring again, as this is the most common cause of errors. Forgetting any wire is problematic, but when it's a ground or power wire that subsequently connects to other panel components, you'll see erratic behavior.
- If an IC is hot, it may not be oriented correctly. Powering an IC with reverse voltage will absolutely burn it out and destroy it. You might as well replace any chips you installed backwards because *they're dead, Jim*.
- If you etched the PC board yourself, inspect it with an illuminated magnifier to ensure that there are no shorts or opens in the copper traces. Open any shorts with a hobby knife, and close any opens with thin solid wire and solder. Look closely, as solder balls can be teeny-weeny and still short closely spaced lands or pads.
- Check that the appropriate power supply voltage is present on every IC's power pins.
- Make sure your mechanical components are wired properly. An incorrectly wired jack on the input or output of your project can stop it dead in its tracks. The terminals on phone jacks with switch legs are not always arranged the same way, so you might have the input or output wire connected to the wrong terminal on the jack.
- If you severely distorted a plastic panel component during soldering or desoldering, it may now be kaput.
- Check that all ICs are plugged into their sockets properly. If a pin gets bent under an IC instead of plugged into its socket, it will definitely be a problem.
- Swap active components (op amps, logic chips, transistors) for known good ones (IC sockets to the rescue again). Cut the pins off of and throw out bad ICs (so you don't inadvertently use them again). Some people prefer to slingshot them as far as possible from the lab.

What to Look For (continued)

- The outputs of op amps used as comparators will always be in either high or low saturation. If the output of a comparator doesn't correspond with the measurements you observe on the inputs, you either have a bad IC or an issue with the components used to set the comparator's threshold or input level. A positive feedback resistor with an incorrectly low value will cause a comparator to *stick* in high or low saturation.

- The outputs of op amps used as amplifiers or filters should *never* be saturated high or low. If you come across one that is, make sure the associated resistor values are correct. If the feedback resistor's value is incorrectly high, it could cause the op amp's output to be saturated high or low. Knowledge of op amp theory (see Appendix A) will help you to determine if the output you are observing corresponds with the signals or voltage levels on the op amp's inputs. Consider the signals or levels observed on the inputs, along with the op amp's gain and biasing, and then determine if the output is appropriate. Look at the values of resistors associated with the op amp's circuitry to verify their values. If all component values and input signals are correct, replace the op amp.

- If using an NPN transistor as a switch to drive an LED, the transistor should allow current to flow from collector to emitter when the base is biased high. If the transistor doesn't respond to changes in base voltage (and subsequently current), and the resistors in the circuit are the correct values, replace the transistor.

- When using an N-Channel JFET in a high impedance source follower application (where its drain goes to V+ and its source goes to V- through a load resistor), you should see the voltage vary on the load resistor in the same manner as observed on the JFET's gate although the DC level may be different. If the voltage on the load resistor is not varying, make sure the resistors in the circuit are the correct values—and if they are, replace the JFET for a known good one.

- Op amps with gains higher than 1 can suffer from instability and oscillate at a high frequency (usually super-audio). Sometimes this oscillation will be heard as noise on the op amp's output, but in other cases you will need an oscilloscope to observe it. Using an oscilloscope, this high-frequency oscillation can be seen superimposed on the normal signal at the op amp's output. A small value capacitor (4.7pF to 100pF) placed across the op amp's feedback resistor may quell the oscillations.

- Leaky capacitors in timing applications will reveal themselves by discharging too quickly or never charging to full voltage when being charged by a low current. Tantalum capacitors are permanently damaged by being reverse-biased and become leaky very quickly, even with short exposure to incorrect polarity.

- Shorted capacitors will show the same DC level on both sides of the cap and will show up as shorted when tested with an ohmmeter.

- Low-quality potentiometers can suffer from poor conduction between the wiper and the resistive element, resulting in crackly operation in mixers or other odd behavior associated with *dead* spots in the pot's rotation.

- You will occasionally find switches that provide intermittent contact between terminals. Replace them.

- CMOS logic chip outputs should be at supply V+ or supply ground. If you observe an intermediate level on a CMOS chip's output, it could be that the circuit it is driving is too low in resistance (check values) or that the chip is defective and needs to be replaced.

- Anytime you want to see what's going on with an IC's pin while it is disconnected from the circuit, remember you can remove the chip, gently bend the lead of interest out, reinsert the chip, and probe the now isolated lead.

- LEDs are extremely reliable, so always check the driving circuitry first if you have an LED that won't come on.

Divide and Conquer

During troubleshooting of a complex circuit that contains many ICs and modules, it's often difficult to see the forest for the trees. In a case like that, it is necessary to divide and conquer. You may need to remove all of the chips from the PC board and then reinstall them one module at a time so you can test each module in isolation.

Isolate the power supply if you think it is the problem. Disconnect it from the circuit and see if it works under a reasonable load. Keeping some 1 to 10 watt ceramic resistors in low values (10 to 100 ohms) around is good for exercising a power supply.

With patience and determination (and perhaps a wee bit o' luck), you'll find and solve the problem that's keeping your project from coming to life. And never forget that a second set of eyes is always recommended. Cultivate relationships with relatives, teachers, professors, and friends who possess electronics knowledge so you'll have a resource to bounce ideas off of when you're in a tight spot.

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