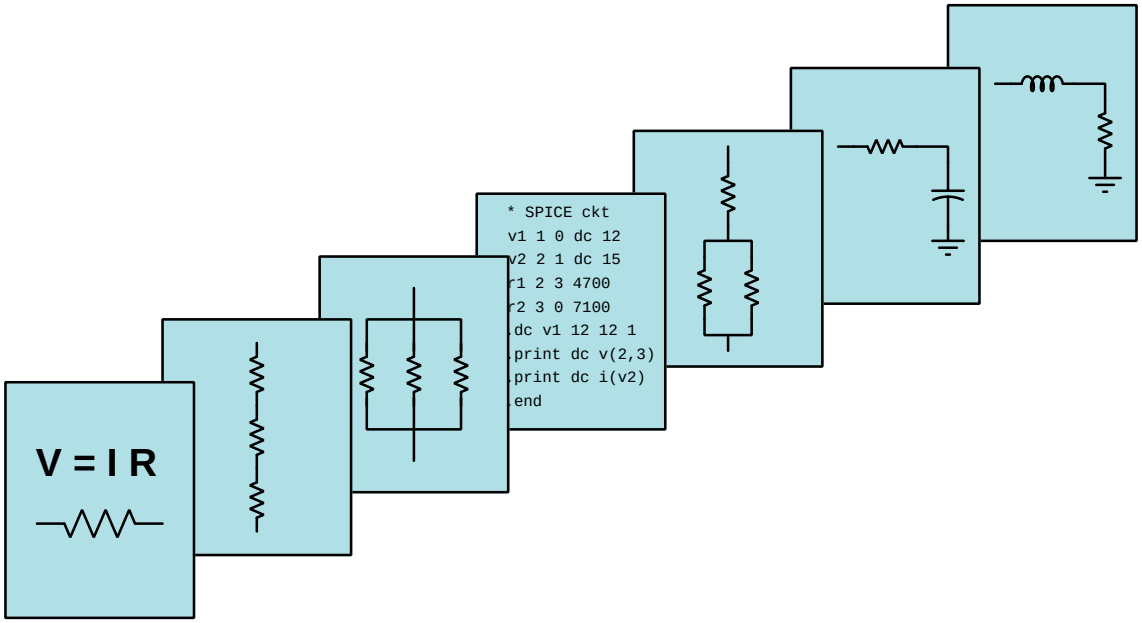
Modular Electronics Learning (ModEL) project



Troubleshooting and Prototyping Tips

Last update = 5 October 2025

Contents

Chapter 1

Introduction

Developing new systems is a process often fraught with challenges. This is especially true if certain components or sub-systems in your design are poorly documented or have known design flaws of their own. This document is a repository for general troubleshooting in electronic circuit development as well as a collection of tips and useful information on specific pieces of software and hardware. Expect this document to grow substantially over time!

Chapter 2

General circuit prototyping

- **Build and test complex systems in stages!** – Building the entirety of a complex system and expecting it to function properly on the first try is folly, due to the high likelihood of multiple problems. Instead, identify portions of your circuit or system that may be constructed and tested individually, then build and test them one-by-one before connecting them together to form a larger system. This strategy keeps the "problem space" as small as possible so it's easier to locate and remedy problems, whether they be faults or design flaws. Breaking apart a malfunctioning complex system and testing the separated sections works well for the same reason.

- **When in doubt, collect more data!** – If you find yourself confused on why a circuit is not doing what you think it should, *take more measurements!* Test equipment will show you what your eyes cannot see, and tests done with different types of instruments (e.g. oscilloscope instead of multimeter) will show you things those other instruments might not reveal.

- **Ensure stable source voltages** – Most electronic circuits absolutely require stable DC power supply voltages to function properly. The DC power supply "rails" should ideally exhibit unchanging voltage values well within the high and low allowable values for the circuit(s) being powered, sagging negligibly when loaded, and having little or no "noise" (e.g. ripple, etc.). Checking for proper power supply voltages using a voltmeter is always a good first step when troubleshooting a misbehaving circuit. Checking those same voltages using an *oscilloscope* will show transients that a multimeter will miss.

- **Always decouple your supply rails** – Capacitors connected in parallel with the DC voltage source(s) act to stabilize voltage (see above) during moments of transient current demand. It's difficult to have too much of this "decoupling" capacitance, but it's also important that this capacitance have minimal equivalent series resistance (ESR) so as to not impede current when it needs to quickly source or sink it. Minimum decoupling capacitance will be based on the magnitude of expected transient current (I), the maximum tolerable voltage sag (dV), and the expected duration of the transient current (dt) in accordance with $I = C\frac{dV}{dt}$. NP0 ceramic capacitors are excellent for low ESR, while aluminum electrolytic and tantalum capacitors are terrible.

- **Never let CMOS logic inputs float** – CMOS-based digital logic IC inputs must always have a definite connection to "high" (+V) or "low" (Ground). If left unconnected (i.e. "floating"), inputs will be susceptible to stray electric fields and may assume *any* logic state at random.

- **Never let comparator or opamp inputs float** – Comparators and operational amplifier ICs also have high-resistance inputs and should not be "floated" for the same reason.

- **Wire routing and placement matters at high frequency** – Parasitic capacitance and inductance values are negligible in DC and low-frequency AC circuits, but at high frequencies they can become problematic. This is how signals "couple" from one conductor to another. Keep "aggressor" conductors away from "victim" conductors, minimize wire lengths, etc.

- **Pulse integrity** – A well-formed digital pulse signal must have steep rising and falling edges, with valid logic voltage levels between those edge events. Many circuits using flip-flops will behave strangely if clock pulses rise or fall too slowly, for example binary counter ICs generating incorrect count sequences!

- **Pulse timing** – "Synchronous" digital circuits using clock pulses to coordinate actions between components require input signal voltages to be in stable states both before and after each clock pulse arrives in order to reliably read those input signals. This is known as *set-up time* and *hold time*, respectively.

Chapter 3

Solderless breadboard caveats

Solderless breadboards are useful tools when prototyping circuits using through-hole components, but they have several important limitations every student of electronics needs to know.

- **Voltage and current limitations** – Breadboards are not intended for high-power circuits. As such, both their voltage and current ratings are quite modest. A high-quality breaboard model at the time of this writing is the model BB830 by BusBoard Prototype Systems, and its datasheet states a maximum voltage of 36 Volts and a maximum current of 2 Amperes.

- **Connection resistance** – Not only does each wire-to-board connection have substantial resistance (often many tenths of an Ohm), but this resistance varies considerably if the wire or component lead happens to move at all. This is a major source of trouble when your circuit design demands precision resistance values, and/or low resistance (e.g. less than 10 Ohms) values! In such cases it is better to use a terminal block or even solder components together rather than make those connections on a solderless breadboard.

- **Power rails** – Many breadboards offer "power rail" connections spanning the length of the board, making it convenient to connect DC voltage source terminals at one end of the board and accessing those rails at any point along the length using short jumper wires. *However, not all breadboard power rails work the same!!* Some models, notably the legacy "Radio Shack" and "Archer" breadboards manufactured by Tandy, have *divided* power rails which only run half the length of the board, and are not clearly marked as such.

- **Use the right wire** – Solid wire only, not stranded, of an appropriate AWG gauge number (22 AWG is standard). Wires that are too thin won't made good contact with the board's internal spring clips, and wires that are too thick may not fit in and may even damage the spring clip if forced!

- **Backing surface** – Most breadboards require a solid backing surface when used, to provide physical support for the spring clips when wires are pushed through the connection holes. A tabletop works well, as does the metal backing plate usually provided with a new breadboard.

Holding a breadboard in mid-air when inserting wires into it is a bad idea, as is adhering it to a soft surface with no hard sheet or plate in between the board and that soft surface.

- **Not all breadboards are made the same!** – Quality varies widely in breadboard design and construction. For example, some breadboards have unreasonably high insertion forces, others will not accept square post terminals, etc.

Chapter 4

Multimeter tips

4.1 General multimeter advice

- **Meters are loads** – Voltmeters have high input resistance, but they are not perfect "opens". Ammeters have low input resistance, but they are not perfect "shorts". All meters, to some extent, place an energy burden on the circuits they monitor.

- **Ammeter fusing** – Quality multimeters always provide a fuse in-line with the red test lead which blows if ever excessive current passes. These fuses have no effect on voltage measurement, and cannot protect against excessive voltage!

- **Sign indicates polarity** – Whenever a meter indicates a positive quantity it means the red test lead is at a higher electrical potential than the black test lead. When measuring voltage this means red = + and black = −; when measuring current it means conventional flow into the red and out of the black.

- **Resistance versus diode-check modes** – Most digital multimeters offer different modes for sensing continuity, and these usually include *resistance* and *diode check*. Both modes generally work by sourcing a current (conventional flow exiting the red lead and entering the black) and sensing voltage. In the case of resistance-measuring mode the meter outputs a constant current and infers resistance by the amount of voltage dropped, the amount of current sourced depending on the range of the resistance measurement. In the case of diode-check mode the meter outputs a constant current and directly registers the voltage dropped by the PN junction. One important distinction between these two modes is compliance voltage (i.e. the maximum voltage output by the meter as it attempts to drive a constant current): in resistance-measuring mode the meter limits its compliance voltage to a level low enough that a PN junction should not be forward-biased, in order to avoid false measurements if a PN junction happens to be connected in parallel with the resistance you intend to measure.

- **AC/DC discrimination** – Modern digital multimeters generally do an excellent job of discriminating between AC and DC quantities in those modes. For example, a digital voltmeter set to DC mode will register a DC power supply's voltage while ignoring ripple, while the same multimeter set to AC mode will register the ripple voltage while ignoring the DC voltage level. This is an excellent feature to use when one does not have an oscilloscope to check for ripple on DC power supply rails.

- **Min/Max mode** – Arguably one of the most important features of a digital multimeter, the ability to record the minimum and maximum quantities since engaging the Min/Max feature is extremely helpful for troubleshooting intermittent problems. Note that Min/Max mode should be engaged only *after* the signal is acquired by the meter, or else the lack of measurement (zero) will be recorded as Minimum. Also, Min/Max mode usually locks in the meter's range, if the meter is auto-ranging.

- **Auto-ranging** – Speaking of auto-ranging, this feature is where the meter chooses its own range value in acquiring a new signal, in order to give the user the best resolution. However, this feature can also become annoying if the signal in question rises and falls enough to

provoke repeated "range-changes" on the meter's part, much like an automobile's automatic transmission refusing to remain in one gear despite a constant load. Auto-ranging may always be overridden by the user!

- **Sample rate** – Every digital measuring device works by periodically sampling the signal rather than continuously reporting it as an analog instrument does, and the rate at which this sampling occurs is important to know when the signal in question varies rapidly. Learn the sample rate of your meter, knowing that the bare-minimum rate must be *twice the frequency of the signal of interest* in order for any aspect of that signal to be reliably captured. Some digital meters offer a "Fast Min/Max" mode where the sample rate is higher than normal in order to better capture transients, usually gaining speed by sacrificing resolution.

- **Resolution** – Speaking of resolution, some digital multimeters offer a "precision" resolution mode displaying extra digit(s) for the user. This high-resolution mode works by sacrificing sample rate, displaying the sampled quantity at greater intervals.

4.2 A gallery of multimeter "tricks"

The digital multimeter (DMM) is quite possibly the most useful tool in the electronic technician's collection[1]. This one piece of test equipment, properly wielded, yields valuable insight into the status and operation of many electrical and electronic systems. Not only is a good-quality multimeter capable of precisely indicating electrical voltage, current, and resistance, but it is also useful for more advanced tests. The subject of this section is how to use a digital multimeter for some of these advanced tests[2].

For all these tests, I suggest the use of a top-quality field multimeter. I am personally a great fan of *Fluke* brand meters, having used this particular brand for nearly my whole professional career. The ability of these multimeters to accurately measure true RMS amplitude, discriminate between AC and DC signals, measure AC signals over a wide frequency range, and survive abuse both mechanical and electrical, is outstanding.

[1] As a child, I often watched episodes of the American science-fiction television show *Star Trek*, in which the characters made frequent use of a diagnostic tool called a *tricorder*. Week after week the protagonists of this show would avoid trouble and solve problems using this nifty device. The *sonic screwdriver* was a similar tool in the British science-fiction television show *Doctor Who*. Little did I realize while growing up that my career would make just as frequent use of another diagnostic tool: the electrical multimeter.

[2] I honestly considered naming this section "Stupid Multimeter Tricks," but changed my mind when I realized how confusing this could be for some of my readers not familiar with colloquial American English.

4.2.1 Recording unattended measurements

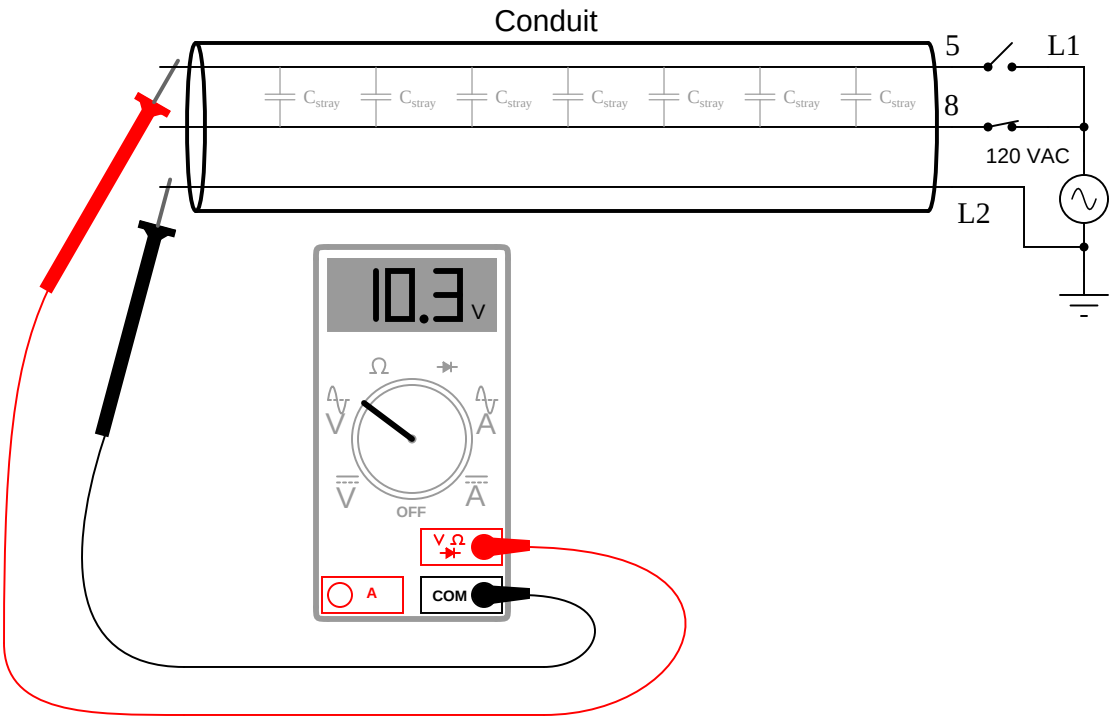
Many modern multimeters have a feature that records the highest and lowest measurements sensed during the duration of a test. On Fluke brand multimeters, this is called the *Min/Max* function. This feature is extremely useful when diagnosing intermittent problems, where the relevant voltages or currents indicating or causing the problem are not persistent, but rather come and go. Many times I have used this feature to monitor a signal with an intermittent "glitch," while I attended to other tasks.

The most basic high-low capture function on a multimeter only tells you what the highest and lowest measured readings were during the test interval (and that only within the meter's scan time – it is possible for a very brief transient signal to go undetected by the meter if its duration is less than the meter's scan time). More advanced multimeters actually log the *time* when an event occurs, which is obviously a more useful feature. If your tool budget can support a digital multimeter with "logging" capability, spend the extra money and take the time to learn how this feature works!

4.2.2 Avoiding "phantom" voltage readings

My first "trick" is not a feature of a high-quality DMM so much as it is a solution to a common problem *caused* by the use of a high-quality DMM. Most digital multimeters exhibit very high input impedance in their voltage-measuring modes. This is commendable, as an ideal voltmeter should have infinite input impedance (so as to not "load" the voltage signal it measures). However, in industrial applications, this high input impedance may cause the meter to register the presence of voltage where none should rightfully appear.

Consider the case of testing for the absence of AC voltage on an isolated power conductor that happens to lie near other (energized) AC power conductors within a long run of conduit:

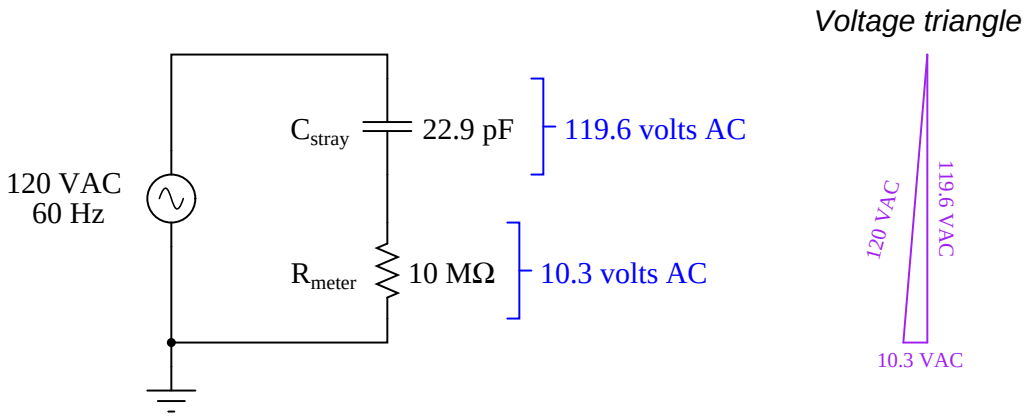


With the power switch feeding wire 5 in the open state, there should be no AC voltage measured between wire 5 and neutral (L2), yet the voltmeter registers slightly over 10 volts AC. This "phantom voltage" is due to capacitive coupling between wire 5 and wire 8 (still energized) throughout the length of their mutual paths within the conduit.

Such phantom voltages may be very misleading if the technician encounters them while troubleshooting a faulty electrical system. Phantom voltages give the impression of connection (or at least high-resistance connection) where no continuity actually exists. The example shown, where the phantom voltage is 10.3 volts compared to the source voltage value of 120 volts, is actually quite modest. With increased stray capacitance between the conductors (longer wire runs in close proximity, and/or more than one energized "neighboring" wire), phantom voltage magnitude begins

to approach that of the source voltage[3].

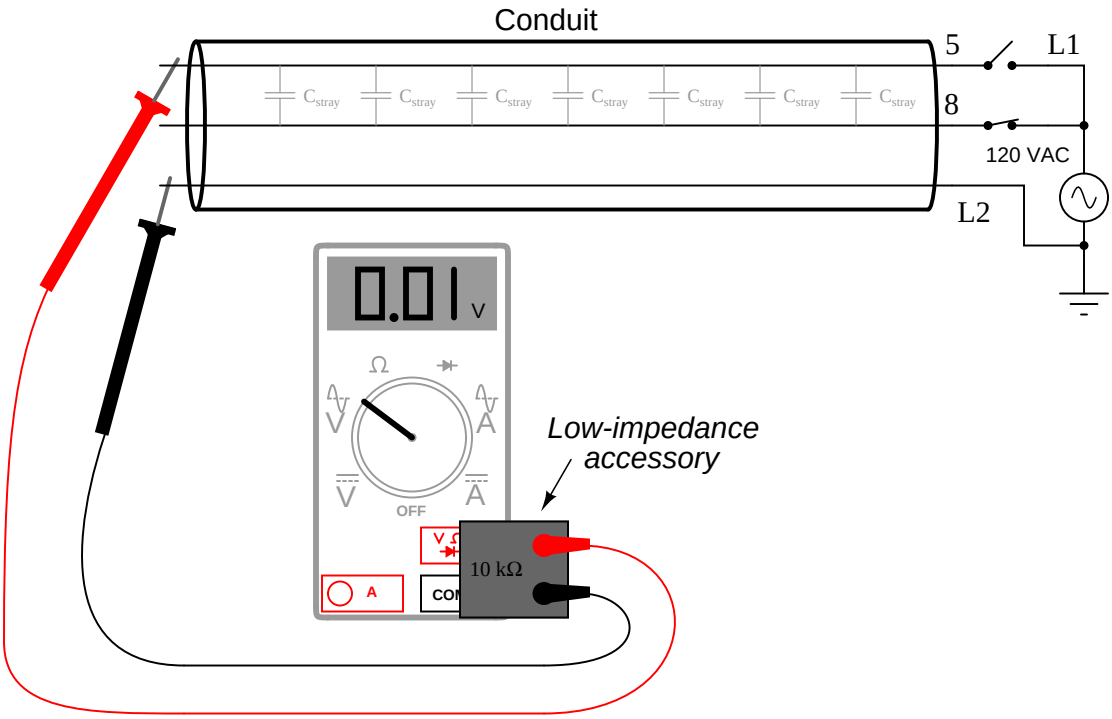
The equivalent circuit is shown here, with the DMM modeled as a 10 MΩ resistance:



An analog voltmeter would never have registered 10.3 volts under the same conditions, due to its substantially lower input impedance. Thus, "phantom voltage" readings are a product of modern test equipment more than anything else.

[3] I have personally measured "phantom" voltages in excess of 100 volts AC, in systems where the source voltage was 120 volts AC.

The obvious solution to this problem is to use a different voltmeter – one with a much lesser input impedance. But what is a technician to do if their only voltmeter is a high-impedance DMM? Connect a modest resistance in parallel with the meter input terminals, of course! Fluke happens to market just this type of accessory[4], the SV225 "Stray Voltage Adapter" for the purpose of eliminating stray voltage readings on a high-impedance DMM:



With the voltmeter's input impedance artificially decreased by the application of this accessory, the capacitive coupling is insufficient to produce any substantial voltage dropped across the voltmeter's input terminals, thus eliminating. The technician may now proceed to test for the presence of AC control signal (or power) voltages with confidence.

[4]Before there was such an accessory available, I used a 20 kΩ high-power resistor network connected in parallel with my DMM's input terminals, which I fabricated myself. It was ugly and cumbersome, but it worked well. When I made this, I took great care in selecting resistors with power ratings high enough that accidental contact with a truly "live" AC power source (up to 600 volts) would not cause damage to them. A pre-manufactured device such as the Fluke SV225, however, is a much better option.

4.2.3 Non-contact AC voltage detection

While the last multimeter "trick" was the elimination of a parasitic effect, this trick is the exploitation of that same effect: "phantom voltage" readings obtained through capacitive coupling of a high-impedance voltmeter to a conductor energized with AC voltage (with respect to ground). You may use a high-impedance AC voltmeter to perform qualitative measurements of ground-referenced AC power voltage by setting the meter to the most sensitive AC range possible, grounding one test lead, and simply touching the other test lead to the insulation of the conductor under test. The presence of voltage (usually in the range of millivolts AC) upon close proximity to the energized conductor will indicate the energization of that conductor.

This trick is useful for determining whether or not particular AC power or control wires are energized in a location where the only access you have to those wires is their insulating sheaths. An example of where you might encounter this situation is where you have removed the cover from a conduit elbow or other fitting to gain access to a wire bundle, and you find those wires labeled for easy identification, but the wires do not terminate to any exposed metal terminals for you to contact with your multimeter's probe tips. In this case, you may firmly connect one probe to the metal conduit fitting body, while individually touching the other probe tip to the desired conductors (one at a time), watching the meter's indication in AC millivolts.

Several significant caveats limit the utility of this "trick:"

- The impossibility of quantitative measurement
- The potential for "false negative" readings (failure to detect a voltage that is present)
- The potential for "false positive" readings (detection of a "phantom voltage" from an adjacent conductor)
- The exclusive applicability to AC voltages of significant magnitude ($\geq$ 100 VAC)

Being a qualitative test only, the millivoltage indication displayed by the high-impedance voltmeter tells you nothing about the actual magnitude of AC voltage between the conductor and ground. Although the meter's input impedance is quite constant, the parasitic capacitance formed by the surface area of the test probe tip and the thickness (and dielectric constant) of the conductor insulation is quite variable. However, in conditions where the validity of the measurement may be established (e.g. cases where you can touch the probe tip to a conductor known to be energized in order to establish a "baseline" millivoltage signal), the technique is useful for quickly checking the energization status of conductors where ohmic (metal-to-metal) contact is impossible.

For the same reason of wildly variable parasitic capacitance, this technique should *never* be used to establish the de-energization of a conductor for safety purposes. The only time you should trust a voltmeter's non-indication of line voltage is when that same meter is validated against a known source of similar voltage in close proximity, and when the test is performed with direct metal-to-metal (probe tip to wire) contact. A non-indicating voltmeter *may* indicate the absence of dangerous voltage, or it may indicate an insensitive meter.

4.2.4 Detecting AC power harmonics

The presence of *harmonic* voltages[5] in an AC power system may cause many elusive problems. Power-quality instruments exist for the purpose of measuring harmonic content in a power system, but a surprisingly good qualitative check for harmonics may be performed using a multimeter with a frequency-measuring function.

Setting a multimeter to read AC voltage (or AC current, if that is the quantity of interest) and then activating the "frequency" measurement function should produce a measurement of exactly 60.0 Hz in a properly functioning power system (50.0 Hz in Europe and some other parts of the world). The only way the meter should ever read anything significantly different from the base frequency is if there is significant harmonic content in the circuit. For example, if you set your multimeter to read frequency of AC voltage, then obtained a measurement of 60 Hz that intermittently jumped up to some higher value (say 78 Hz) and then back down to 60 Hz, it would suggest your meter was detecting harmonic voltages of sufficient amplitude to make it difficult for your meter to "lock on" to the fundamental frequency.

It is very important to note that this is a crude test of power system harmonics, and that measurements of "solid" base frequency do not guarantee the absence of harmonics. Certainly, if your multimeter produces unstable readings when set to measure frequency, it suggests the presence of strong harmonics in the circuit. However, the absence of such instability does not necessarily mean the circuit is free of harmonics. In other words, a stable reading for frequency is *inconclusive*: the circuit might be harmonic-free, or the harmonics may be weak enough that your multimeter ignores them and only displays the fundamental circuit frequency.

[5] These are AC voltages having frequencies that are integer-multiples of the fundamental powerline frequency. In the United States, where 60 Hz is standard, harmonic frequencies would be whole-number multiples of 60: 120 Hz, 180 Hz, 240 Hz, 300 Hz, etc.

4.2.5 Identifying noise in DC signal paths

An aggravating source of trouble in analog electronic circuits is the presence of AC "noise" voltage superimposed on DC signals. Such "noise" is immediately evident when the signal is displayed on an oscilloscope screen, but how many technicians carry a portable oscilloscope with them for troubleshooting?

A high-quality multimeter exhibiting good discrimination between AC and DC voltage measurement is very useful as a qualitative noise-detection instrument. Setting the multimeter to read AC voltage, and connecting it to an signal source where pure (unchanging) DC voltage is expected, should yield a reading of nearly zero millivolts. If noise is superimposed on this DC signal, it will reveal itself as an AC voltage, which your meter will display.

Not only is the AC voltage capability of a high-quality (discriminating) multimeter useful in detecting the presence of "noise" voltage superimposed on analog DC signals, it may also give clues as to the source of the noise. By activating the frequency-measuring function of the multimeter while measuring AC voltage (or AC millivoltage), you will be able to track the frequency of the noise to see its value and stability.

Once on a job I was diagnosing a problem in an analog power control system, where the control device was acting strangely. Suspecting that noise on the measurement signal line might be causing the problem, I set my Fluke multimeter to measure AC volts, and read a noise voltage of several tenths of a volt (superimposed on a DC signal a few volts in magnitude). This told me the noise *was* indeed a significant problem. Pressing the "Hz" button on my multimeter, I measured a noise frequency of 360 Hz, which happens to be the "ripple" frequency of a six-pulse (three-phase) AC-to-DC rectifier operating on a base frequency of 60 Hz. This told me where the likely source of the noise was, which led me to the physical location of the problem (a bad shield on a cable run near the rectified power output wiring).

4.2.6 Generating test signals

Modern digital multimeters are fantastically capable measurement tools, but did you know they are also capable of *generating* simple test signals? Although this is not the design purpose of the resistance and diode-check functions of a multimeter, the meter does output a low DC voltage in each of these settings.

This is useful when qualitatively testing certain measurement instruments such as data acquisition modules and other meters designed to input a low-voltage or low-current DC signal. By setting a multimeter to either the resistance (Ω) or diode check function and then connecting the test leads to the input terminals of the signal-sensing device, that device's response may be noted.

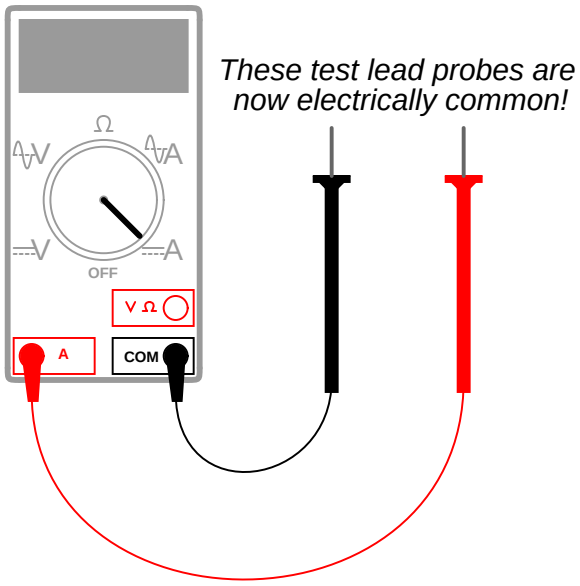
Of course, this is a *qualitative* test only, since multimeters are not designed to output any precise amount of voltage in either the resistance or diode-check modes. However, for testing the basic response of a process indicator, recorder, controller, data acquisition channel, DCS input, or any other DC-signal-receiving devices, it is convenient and useful. In every multimeter I have ever tried this with, the diode-check function outputs *more* voltage than the resistance measurement function[6]. This gives you two levels of "test signal" generation: a low level (resistance) and a high level (diode check). If you are interested in using your multimeter to generate test voltages, I recommend you take the time to connect your multimeter to a high-impedance voltmeter (such as another digital multimeter set to measure DC volts) and note just how much voltage your meter outputs in each mode. Knowing this will allow you to perform tests that are more quantitative than qualitative.

[6] There is a design reason for this. Most digital multimeters are designed to be used on semiconductor circuits, where the minimum "turn-on" voltage of a silicon PN junction is approximately 500 to 700 millivolts. The diode-check function must output more than that, in order to force a PN junction into forward conduction. However, it is useful to be able to check ohmic resistance in a circuit *without* activating any PN junctions, and so the resistance measurement function typically uses test voltages *less than 500 millivolts*.

4.2.7 Using the meter as a temporary jumper

Often in the course of diagnosing problems in electrical and electronic systems, there is a need to temporarily connect two or more points in a circuit together to force a response. This is called "jumpering," and the wires used to make these temporary connections are called *jumper wires*.

More than once I have found myself in a position where I needed to make a temporary "jumper" connection between two points in a circuit, but I did not have any wires with me to make that connection. In such cases, I learned that I could use my multimeter test leads while plugged into the *current-sensing* jacks of the meter. Most digital multimeters have a separate jack for the red test lead, internally connected to a low-resistance *shunt* leading to the common (black) test lead jack. With the red test lead plugged into this jack, the two test leads are effectively common to one another, and act as a single length of wire.



Touching the meter's test leads to two points in a circuit will now "jumper" those two points together, any current flowing through the shunt resistance of the multimeter. If desired, the meter may be turned on to monitor how much current goes through the "jumper" if this is diagnostically relevant.

An additional benefit to using a multimeter in the current-measuring mode as a test jumper is that this setting is usually current-protected by a fuse inside the meter. Applying jumper wires to a live circuit may harbor some danger if significant potential and current-sourcing capability exist between those two points: the moment a jumper wire bridges those points, a dangerous current may develop within the wire. Using the multimeter in this manner gives you a *fused* jumper wire: an added degree of safety in your diagnostic procedure.

Chapter 5

Linux computer operating system

Linux is a powerful and open-source Unix work-alike operating system for a wide range of computing platforms. One of the appeals of Linux is its extensive array of "utility" programs that do useful tasks. This chapter outlines some of them.

5.1 Linux utilities for command-line navigation

The command-line user environment is crude in appearance compared to a point-and-click "graphical window" interface, but much more powerful in many respects.

To list the contents of whatever directory (folder) you happen to be "in" at any given time, simply use the "listing" command `ls`. To see a listing of all files and subdirectories in full detail showing such things as date, size, etc. simply use the "long" option for `ls` like this:

```
ls -l
```

To navigate downn one level into a sub-directory (sub-folder) with a given name, use the *change directory* command `cd` followed immediately by the name of the desired directory. For example, if there is a sub-directory named `src` you would like to descend into, type:

```
cd src
```

To navigate one level up in the directory (folder) structure, use the *change directory* command `cd` like this:

```
cd ../
```

Creating a new copy of a file is done using the "file copy" command `cp`. For example, taking a file named `data.csv` and copying it to the new name `testresults.csv` may be done as follows:

```
cp -vi data.csv testresults.csv
```

The `-vi` options invoked here for the `cp` command instruct it to be *verbose* (telling you what it's doing as it's doing it) and also to *interactively* prompt you in case the command might overwrite existing files.

The "file move" command (`mv`) works similarly to `cp`, the major difference being the original filename will cease to exist and only the new one will remain after this command executes. For example, to *rename* the file `data.csv` to `testresults.csv`, use the "move" command as follows, again the use of the options `-vi` being highly recommended so you can know and confirm what will happen:

```
mv -vi data.csv testresults.csv
```

Failing to include the `-vi` options for either command will result in it executing without notice and without asking your permission if a file is to be over-written.

To create a new sub-directory called `My_new_directory`, use the "make directory" command:

```
mkdir My_new_directory
```

To destroy the same, use the "remove directory" command:

```
rmdir My_new_directory
```

5.2 Linux utilities for general file viewing and editing

5.2.1 Linux text editors

At some point you will need to use a *text editor* to view and/or edit text-based files, as much of the Linux operating system is controlled by these files. An easy-to-use text editor is `nano`, using Control-key sequences to do things like save files and exit. A much harder-to-use editor is `vim` which despite its idiosyncratic behavior is quite popular and found on virtually every Linux system.

Example: using `nano` and then `vim` to view a file named `myfile.txt`:

```
nano myfile.txt
vim myfile.txt
```

5.2.2 Linux text-viewing utilities

A useful utility for read-only viewing of text files is `cat`, which simply prints the contents of a text file to the screen. For larger text files containing multiple pages' worth of text, a useful utility is `less` which gives you up- and down-control of the screen.

Examples:

```
cat myfile.txt
less myfile.txt
```

If the file you wish to view isn't plain-text but contains "binary" data, a better tool is `hexdump` which will output a hexadecimal listing of every byte contained in that file. For example, to view the bytes contained within a graphic JPEG image file named *photo.jpg*, do the following (using the `-C` option to show it in "canonical" form complete with ASCII interpretation of the bytes):

```
hexdump -C photo.jpg
```

A very powerful utility used to scan text files for instances of specific text strings is `grep`. For example, to scan for lines of text containing the word "computer" inside the file `myfile.txt`, type:

```
grep computer myfile.txt
```

To scan for text strings containing space characters, the string must be enclosed in quotation marks:

```
grep "computer virus" myfile.txt
```

To report any lines *not* containing a specific text string, use the `-v` option:

```
grep -v computer myfile.txt
```

5.3 Linux command-line plumbing

One of the powerful features of the command-line environment within Linux is the ability to chain multiple utilities together by means of additional characters. This is referred to as "plumbing" by Linux enthusiasts because it is analogous to piping the discharge of one process into the intake of another.

Sometimes we might wish to take the screen-output of one command and "plumb" it as the input to another command. For example, suppose we wish to scan all running processes on the computer using the `ps -e` command but only display those lines of text containing the word "server", such as in a case where we want to know how many server programs are currently running. To do this we may plumb together the `ps -e` and `grep` commands using the "pipe" symbol (`|`) like this:

```
ps -e | grep server
```

Similarly, if we wish to record the output of any command-line utility to a text file rather than print it to the screen, we may use the "redirection" (`>`) symbol between the command and the name of the new text file. For example, taking a detailed listing of all files in the present directory and saving that list to a file named `file_log.txt`:

```
ls -l > file_log.txt
```

If we later wish to append the contents of the file `listing.txt` to our log file, we may do so using the append redirection symbol (`>>`) as follows:

```
cat listing.txt >> file_log.txt
```

If a particular utility requires text data to be sent to it upon invocation, we may do so using another redirection command (`<`). Legacy versions of SPICE required this to read netlists, as shown in the example below:

```
spice < netlist.cir
```

5.4 Linux utilities for text file manipulation

`sed` stands for *stream editor*, which is a form of non-interactive text editor, and it is an extremely important utility for bulk editing of text-based files. It is run either with arguments presented in the command line, or alternatively with arguments presented in a separate file (usually named with a `.sed` extension) referenced in the command-line invocation. The arguments passed to `sed` take the form of so-called *regular expressions* which are Unix-standardized text strings instructing operations such as search-and-replace, deletions, etc.

A common application for `sed` is searching-and-replacing words or sets of words within a text file. Consider a plain-text file named `moveable.txt` containing a passage from Ernest Hemingway's memoir *A Moveable Feast*:

```
She had no confidence in books written in English, paid almost nothing for them,
and sold them for a small and quick profit.
"Are they any good?" she asked me after we had become friends.
"Sometimes one is."
"How can anyone tell?"
"I can tell when I read them."
"But still it is a form of gambling.  And how many people can read English?"
"Save them for me and let me look them over."
```

The following command entered at the computer console's command line will de-capitalize the word "English":

```
sed -e s/English/english/ moveable.txt
```

```
She had no confidence in books written in english, paid almost nothing for them,
and sold them for a small and quick profit.
"Are they any good?" she asked me after we had become friends.
"Sometimes one is."
"How can anyone tell?"
"I can tell when I read them."
"But still it is a form of gambling.  And how many people can read english?"
"Save them for me and let me look them over."
```

The argument `s/English/english/` instructs `sed` to search (`s`) the scanned text for any instances of the text string `English` and replace it with `english`. The `-e` option instructs `sed` to send the edited text to standard output where it will be displayed on the computer's command-line console immediately following the entered command. Had we used the `sed` option `-i` rather than `-e`, it would have actually edited the `moveable.txt` file itself and not output anything to the console:

```
sed -i s/English/english/ moveable.txt
```

If the intention is to actually modify a saved text file, a safer usage of `sed` would be to use the `-e` (output to console) option and then use redirection to create a new text file so that the original is left unedited:

```
sed -e s/English/english/ moveable.txt > moveable2.txt
```

Another common usage for `sed` is deletion of lines within text data. Consider the following example where we intentionally delete any lines read from the `moveable.txt` file containing the string `it`:

```
sed -e /it/d moveable.txt
```

```
"Are they any good?" she asked me after we had become friends.
"Sometimes one is."
"How can anyone tell?"
"I can tell when I read them."
"Save them for me and let me look them over."
```

Note how this not only deleted the line containing the *word* `it`, but it also deleted all lines with words containing the letter combination `it`!

Next, we will use a `sed` command to delete all lines beginning with the word `and`:

```
sed -e /^and/d moveable.txt
```

```
She had no confidence in books written in English, paid almost nothing for them,
"Are they any good?" she asked me after we had become friends.
"Sometimes one is."
"How can anyone tell?"
"I can tell when I read them."
"But still it is a form of gambling.  And how many people can read English?"
"Save them for me and let me look them over."
```

Note how only the second line was eliminated from the output, while the last line containing `and` in the middle rather than at the beginning remains.

`sed` is also able to make block deletions in a text stream. Consider this example, where we delete all lines from the one containing `Sometimes` to the one containing `But`:

```
sed -e /Sometimes/,/But/d moveable.txt
```

```
She had no confidence in books written in English, paid almost nothing for them,
and sold them for a small and quick profit.
"Are they any good?" she asked me after we had become friends.
"Save them for me and let me look them over."
```

When multiple `sed` edits need to be applied to a particular file, there is the option of writing each of the `sed` arguments to a separate text file and then using the `-f` option to instruct `sed` to read its arguments from that file. For example, the following is a listing of the contents of a text file named `script.sed`:

```
s/English/english/
/Sometimes/,/But/d
```

Now we are ready to tell `sed` to get its instructions from this file when processing the contents of `moveable.txt`:

```
sed -e -f script.sed moveable.txt
```

```
She had no confidence in books written in english, paid almost nothing for them,
and sold them for a small and quick profit.
"Are they any good?" she asked me after we had become friends.
"Save them for me and let me look them over."
```

5.5 Linux utilities for networking

Several powerful networking and network-diagnostic utilities exist within most distributions of Linux. This section highlights some of those.

5.5.1 SSH secure remote login utility

To remotely log into a computer running Linux, you may use the "secure shell" utility (`ssh`). The Linux target machine must be running an instance of `ssh` server in order for a remote client to connect. On modern Windows operating systems `ssh` is a built-in utility, but you may also use third-party apps such as `Bitvise`.

Invoke `ssh` as follows, assuming a login name of "Tony" on the target Linux computer having an IP address of 169.254.10.1:

```
ssh -l Tony 169.254.10.1
```

You will be prompted by a request for the correct password. Once logged in, you have the same access and level of control as any user typing on a keyboard directly connected to that target Linux machine! This includes the ability to run `curses`-based character-graphic applications residing on the remote host.

`ssh` makes use of public key cryptography, where both publicly-accessible as well as private keys are used to encrypt and decrypt data, respectively. The very first time you invoke `ssh`, you will be prompted to create a public/private key pair for the transaction. Simply answer "yes" (Y) to the prompt and the rest is done automatically.

An `ssh` session is terminated by issuing the `logout` command at the remote console prompt.

5.5.2 SFTP secure file transfer utility

A file-transfer utility based on `ssh` is called `sftp`, which stands for *secure file transfer protocol*. Like `ssh`, `sftp` utilizes public key cryptography and is invoked at the command line as follows to access the account of `tony` on a computer having an IP address of 169.254.10.1:

```
sftp tony@169.254.10.1
```

This results in a new prompt appearing on the console, in which you may issue any one of several standardized `sftp` commands including `get` (to retrieve a file from the remote host), `put` (to send a file to the remote host), `ls` to print a listing of files in the current directory, `cd` (to change directories), `quit` to leave the session, etc. Some examples are shown below:

```
sftp> cd ~/Downloads
sftp> get data.csv
sftp> put smileyface_image.jpg
sftp> quit
```

5.5.3 NETCAT TCP/UDP/sockets utility

A very powerful networking utility useful for sending messages and other text-based data across TCP/IP connections is "netcat" or `nc`. This is a client/server toolset which means someone must start up a `netcat` server on one end and a client on another end of the network. Typically a server session is invoked on one computer to "listen" for incoming messages like this, specifying a TCP port number in the last argument:

```
nc -lv 1234
```

Then a client session is started on another computer, and directed to the first computer's IP address (e.g. `169.254.10.3`) and TCP port number (e.g. `1234`) like this:

```
nc -v 169.254.10.3 1234
```

Once this connection is established, people at both computers will be able to type messages back and forth to each other! If we wish to send text-content files from one computer to the other, we may use the "zero" option for the client end and redirection operators as follows:

Server end

```
nc -lv 1234 < source_file.txt
```

Client end

```
nc -zv 169.254.10.3 1234 > dest_file.txt
```

5.6 Linux utilities for programming

5.7 Linux utilities for PostScript document files

Chapter 6

Digital radio modules and software

6.1 Software-defined radio receiver recommendations

Of all the software-defined radio (SDR) hardware units I've tested, the *RTL-SDR* unit sold by RTL-SDR Blog is by far the best financial value. Other SDRs may have better resolution or have capabilities such as transmission, but the extremely low cost and wide frequency range of the RTL-SDR receiver makes it an outstanding value for students. It receives all frequencies between 500 kHz and 1766 MHz, and also offers 4.5 Volt DC "bias tee" capability for powering such devices as Low-Noise Amplifier (LNA) modules with DC power impressed on the same coaxial connection as the RF signal:

The single most important piece of advice I have for using the RTL-SDR module is to utilize a USB extension cable when connecting it to your computer's USB port, as the device itself is rather long and heavy and will place mechanical strain on that connector if directly plugged in.

If you don't mind a narrower frequency range, the *Airspy HF+ Discovery* receiver unit is an outstanding performer with greater signal sensitivity than the less expensive RTL-SDR receiver. It receives lower-frequency signals between 0.5 kHz and 31 MHz, and higher-frequency signals between 64 MHz and 260 MHz. Note how low the frequency range goes (down to 500 Hz!) but that there is a "dead" zone between 31 MHz and 64 MHz, and it tops out at only 260 MHz compared to the RTL-SDR's maximum frequency of nearly 1.8 GHz:

Airspy provides a simple-to-use server for sending the receiver's I-Q data stream over a TCP/IP network, which makes it particularly useful for distributed applications with a remote-mounted receiver.

All SDR receivers have substantial power requirements, the RTL-SDR drawing nearly 300 mA from its USB (5 Volt) cable and from whatever computer it's plugged into. This is important to note especially if you are powering the SDR receiver from a battery-powered computer, and/or one with limited USB power-sourcing capability such as a single-board PC.

6.2 Airspy spyserver software tips

Airspy manufactures easy-to-use and powerful software defined radio (SDR) receiver units. A software application called `spyserver` may be used to stream data from one of these SDR receivers onto a network so that multiple client applications can seek RF signals from the receiver. The following instructions are for building the `libairspy` USB driver from source code on a Raspberry Pi computer running Debian-based Linux. This building-from-source is likely necessary in order for spyserver to actually connect with the AirspyHF+ radio unit via USB. I am indebted to *John's Tech Blog* (`https://hagensieker.com/2019/03/16/airspyhf-spyserver-on-raspberry-pi/`) for details on how to build and install the driver from source code, the Linux command-line instructions for this task being John's words verbatim.

First, use the `apt` utility in Debian Linux to install all the necessary software packages for this purpose, running as root ("`sudo`") for super-user privileges:

```
sudo apt-get install build-essential cmake libusb-1.0-0-dev pkg-config
```

Next, it is advisable to install some more dependencies in order to avoid having spyserver just connect and then disconnect upon invocation:

```
sudo apt-get install airspy libairspy0 libairspy-dev
```

Having these dependencies allows you to easily check your serial number for the conf file below by issuing the `airspy_info` command:

```
airspyhf_info
```

Issue the following commands in order to build and install the driver on the Raspberry Pi computer:

```
mkdir airspy
cd airspy
wget https://github.com/airspy/airspyhf/archive/master.zip
unzip master.zip
cd airspyhf-master
mkdir build
cd build
cmake ../ -DINSTALL_UDEV_RULES=ON
make
sudo make install
sudo ldconfig
```

Once the driver has been built from source code and installed, here is how to run the `spyserver` software on the Raspberry Pi computer. The spyserver file is an executable ready-to-run, but must be run as root:

```
sudo ./spyserver &
```

Leave the plain-text `spyserver.config` file as downloaded, unless you want to change some of the details. The `bind_host` parameter should be left at `0.0.0.0` and if the `bind_port` is left at the 5555-6666 range it means the `spyserver` program will randomly grab one TCP port from within this range when invoked.

When running an SDR client application such as `SDR#` on a computer remote to the Raspberry Pi, you set the "Source" to "AIRSPY Server Network" and then simply specify the Raspberry Pi's IP address and whatever TCP port number the spyserver grabs when started. For example, `sdr://169.254.173.16:5555` if spyserver happened to use TCP port 5555 on a Raspberry Pi with 169.254.173.16 as its IP address.

If you run spyserver in the background (i.e. `./spyserver &`) then it is possible you may eventually end up with multiple instances running simultaneous which is no good. To check the running process list on the Raspberry Pi, run the ps command with the `-e` ("show everything") option and the pipe that to grep to display only those lines containing the word "spy" like this:

```
ps -e | grep spy
```

6.3 GNU Radio Companion software tips

`GNU Radio` is a free and open-source software package for performing digital signal processing of the type often necessary for software-defined radio systems. `GNU Radio Companion` is a graphical user interface to `GNU Radio` allowing one to build digitial signal processing chains using drag-and-drop function blocks connected together with arrows rather than writing Python or C++ code as is necessary with `GNU Radio` by itself.

In making a graphical function-block diagram (called a *flowgraph*), every function block inserting a stream of data into `GNU Radio` from an external device is called a *source*, while every function block sending a data stream to some external device is called a *sink*. For example, a software-defined radio (SDR) receiver sending I-Q data to `GNU Radio` would do so via a source function block. Conversely, an SDR transmitter would need a sink block to get data to it from `GNU Radio`. Visual displays to the computer's monitor such as spectrum displays and oscilloscopes also use sink blocks.

Unfortunately, the folder organization for all the function blocks within `GNU Radio Companion` leaves something to be desired. While a "magnifying glass" search tool exists in the software, it is a literal text search which means it doesn't work unless your text string is 100% correct. The following is a list of function blocks I've found useful for creating flowgraphs:

- `Core/Soapy/Source/` – this folder contains source blocks for commonly available software-defined radio (SDR) receiver hardware including RTL-SDR, AirspyHF, HackRF, PLUTO, and others!

- `Core/Soapy/Sink/` – this folder contains source blocks for commonly available software-defined radio (SDR) transmitter hardware including HackRF, PLUTO, and others!

- `Core/Waveform Generators/` – this folder contains waveform source blocks such as `Signal Source` useful for digitally synthesizing waveform signals such as cosine waves.

- `Core/Math Operators/` – this folder contains a wide range of mathematical function blocks. Some, like `Multiply` take in multiple inputs and perform the stated function on those inputs to generate an output. Others like `Multiply Const` take in a single signal and perform the stated function with a variable which may be sourced by a `Variable` block.

- `Core/Variables/` – this folder contains multiple function blocks useful for establishing values of variables used in a flowgraph.

- `Core/GUI Widgets/QT/` – this folder contains a wide range of function blocks for user-interface functions such as dials, sliders, etc.

- `Core/Instrumentation/QT/` – this folder contains a set of "sink" function blocks useful for user-interface indicators such as spectrum displays (`QT GUI Frequency Sink`) and oscilloscopes (`QT GUI Time Sink`) and I-Q constellation diagrams (`QT GUI Constellation Sink`).

- `Core/Modulators/` – this folder contains a wide range of function blocks useful for modulating

and demodulating different types of signals, including AM, FM (narrow- and wide-band), GFSK, etc.

- `Core/Resamplers/` – this folder contains resampling function blocks useful for interpolation and/or decimation. The `Rational Resampler` does both as a ratio of interpolation to decimation, hence the name.

- `Core/Audio/` – this folder contains function blocks for encoding, decoding, sourcing, and sinking audio signals. The `Audio Sink` function block is needed to send audio signals to the computer's sound card so you can hear the output of radio receiver flowgraphs. The `Audio Source` block takes data in from the computer's microphone input which makes `GNU Radio` capable of doing audio signal processing!

- `OsmoSDR/` – this folder contains some SDR source and sink function blocks that I've found less useful than the `Soapy` blocks mentioned previously.

6.4 Linx 433 MHz on/off-keying radio transmitter and receiver module tips

These tips refer to the TE Connectivity Linx model TXM-433-LR radio transmitter (left) and TE Connectivity Linx model RXM-433-LR radio receiver (right) modules:

- **Pin spacing** – these are sold as small soldered PCB assemblies with copper pads spaced at 0.1 inch intervals along each of two sides. 100 mil header pins fit nicely against the sides and may be soldered to the pads. Beware, though, that the side-to-side spacing is *not* any multiple of 0.1 inch, and so you will end up having to bend those header pins slightly if you wish to fit them into a 0.1 inch grid perfboard or solderless breadboard!

- **Pinout** – holding the PCB assembly so that the "Linx" brand name is right-side-up to your view, pin 1 is in the upper-left corner. If in doubt, use an ohmmeter to check for continuity between the multiple GND pins on both sides of the PCB and use those results to confirm pin numbers.

- **DC power** – maximum DC voltage for these units is 3.6 Volts, so a 3.3 VDC regulator is strongly recommended especially if operating these from battery power.

- **DC current draw** – about 6.5 mA for the receiver unit and about 16.5 mA for the transmitter when transmitting at full power.

- **RF output** – although these are rated to function at 433 MHz, expect the actual frequency to vary about ± 1 MHz from the spec. The signal peak is rather wide, too, with AM modulation sidebands extending at least 50 kHz from either side of the carrier!

- **Modulation** – there is nothing sophisticated about the modulation offered by these RF modules. Digital logic levels in on the transmitter directly translates to digital logic levels out at the receiver, 3.3 Volt CMOS digital compatible.

- **RSSI output signal** – a very useful feature of the model RXM-433-LR is a Received Signal Strength Indicator (RSSI) signal in the form of a DC voltage output at pin 7. This has a range of about 1.2 Volts to 2.2 Volts, with more voltage representing stronger received RF signal. The update rate on this RSSI analog voltage signal is extremely fast – just fractions of a millisecond – making it perfectly suitable as a data signal for low-speed on/off pulses such as CW (Morse Code). An interesting caveat about this output pin is that it seems to need a weak pulldown resistance – even the insertion resistance of a digital voltmeter is enough, but

it must be there or else the receiving circuit may detect false "high" states! I've used 100 kΩ with success.

6.5 DIGI XBee PRO 900 MHz digital radio transceiver and DIGI XCTU configuration software tips

These tips refer to the XBee PRO S3B 900 MHz (unlicensed) radio transceivers, product family XBP9B-DM.

- **Network ID numbers** – all radio units must be programmed with the same Network ID in order to communicate with each other. The numerical range is 0x0000 to 0x7FFF which gives 32768 unique network identifiers! RF transmissions from other units are still received by an XBee unit even if the Network IDs are different. In other words, the modules "hear" all RF broadcasts, and differentiate modules in and out of network by analyzing the Network ID value sent in the data packets. This means the "Rx" LED of a module will blink if it "hears" data broadcast by any neighboring XBee module, even modules with different Network IDs! I strongly recommend accessing each module using XCTU software in a "radio quiet" environment.

- **Transparent Mode** – when set to Transparent Mode, the modules function as a broadcast half-duplex serial network: any serial data transmitted by one is received by all others programmed with the same Network ID value.

- **Loopback jumper** – beware of the loopback jumper on the DIGI development board, which when in place connects Tx (Pin 2) to Rx (Pin 3) and will mess up any attempt to drive the Rx pin from an external source!

- **RF module discovery** – an interesting bug is that when you are "discovering" a local RF module using XCTU software, the serial discovery process may be hampered if there is incoming communication from other RF modules on the same Network ID. A good diagnostic indicator is to check the "Rx" LED on the motherboard to see if it's blinking, which indicates incoming RF data. You'll notice that these same LEDs blink whether indicating RF data or serial (USB cable) data, which suggests a common channel where those data streams (i.e. received RF data from other modules, and "discovery" query data from the PC hosting XCTU) might collide. Another interesting bug is that the "Add a radio module" feature seems more reliable than the "Discover radio devices". If a module does have difficulty connecting and needs to be reset, this reset seems to be done automatically when the "Add a radio module" button is clicked, but not when the "Discover radio devices" button is clicked.

- **Serial console** – a related quirk is that module parameters should not be updated while the serial console is connected. Either shut down the serial console or "close" the open connection prior to making any parameter changes! You must "disconnect" the serial monitor before making any parameter changes to the radio unit, or else those parameter changes may not actually take!

- **Serial buffer overflow** – serial buffers in the DIGI modules can overflow if you send data to them too quickly! For example, when sending ASCII text data from a microcontroller to a

DIGI radio configured for Transparent Mode it is advisable to program the microcontroller to pause between successive transmissions.

- **Power consumption** – these radio units draw a significant amount of current on the 3.3 Volt power pin when starting up, more than what some microcontrollers such as the Arduino Nano can source from their regulated +3.3 V power pins! Make sure these are well-decoupled to be able to source that start-up current to the DIGI modules!

Instructions on how to update firmware in an XBee radio module connected to a PC using a USB cable:

1. Use the "Discovery" function to find the connected radio module
2. Click "could not find device" then "recovery tool"
3. Find the correct Model (Family: XBP9B-DM) (Function Set: Xbee Pro 900HP 200k)
4. Choose the desired firmware version
5. Hold reset button with Loopback pins 1,2 jumpered, leaving potentiometer jumpered as well
6. Initiate device reset in the XCTU software
7. Continue holding the reset button until the pop-up window appears initiating reset
8. Once the first pop-up window disappears a second pop-up window will tell you to release the reset switch
9. At this point the selected firmware will load onto the Xbee radio module
10. Validate that the Xbee Module can be seen by the COM port it's plugged into

Chapter 7

Programmable test equipment

7.1 Siglent SPD1305X power supply programming tips

Important tips for communicating SCPI commands to this instrument for the purpose of automated testing:

- Note that the Teledyne-LeCroy model T3PS16081P is actually a Siglent brand power supply in disguise!

- Set `my_PS.query_delay = 0.25` in order to avoid errors. By default the delay time for a SCPI "query" command is set for 0.0 seconds which causes time-out errors for this power supply. A delay of one-quarter of a second seems more than sufficient.

- Set `my_PS.write_termination = '\n'` in order to avoid errors. By default the line-terminating character sequence for all "write" SCPI commands is `\r\n` which is a "carriage-return" character followed by a "linefeed" character. To avoid this we explicitly re-initialize this attribute to simply be a linefeed character.

- The user manual is replete with typographical errors in its command summary, in the form of extra "space" characters shown between data fields of the SCPI commands. For example, the SCPI command to turn on the power supply's channel 1 output is shown as `OUTPut CH1, ON` in the manual, but the only way this command would actually work is if I omitted the "space" character between the comma and the letter "O" in "ON" like this: `OUTPut CH1,ON`.

- The Python command `dir()` is extremely useful for identifying attributes (i.e. variables) within methods (i.e. functions). For example, issuing the Python command `dir(my_PS)` lists all the attributes found within the method instantiated as `my_PS` in the working example first shown in this Case Tutorial section. This is how I was able to find the `write_termination` attribute which instructs Python how to terminate each SCPI command line, as well as the `query_delay` attribute specifying how long to wait after issuing a SCPI query before declaring a time-out error.

7.2 NanoVNA vector network analyzer tips

These notes apply to the model NanoVNA-H, hardware version 3.4 manufactured in 2007.

General set-up instructions

- Use a plastic guitar pick or the blunt end of a plastic ball-point pen or a pencil eraser head as a stylus, not your finger!
- Go to DISPLAY menu and then choose TRACE to select how many traces you wish to have displayed on the screen at any given time
- Set calibration frequency range through the STIMULUS menu, e.g. START = 50k and STOP = 900M – always calibrate the VNA using the frequency range you intend to use for your measurement!
- Go to CAL menu and then choose RESET to clear previous calibration parameters
- Go to CAL menu and then CALIBRATE sub-menu ; calibrate by pressing OPEN (the next option will color green after doing this), calibrate by connecting shorting cap and pressing SHORT, calibrate by connecting load caps and pressing LOAD, press DONE, save calibration as "SAVE 1" or higher. SAVE 0 is the power-on default calibration.
- Check calibration by connecting short/load/open and monitoring the display ; 50 Ohm load should put marker at center of Smith chart, open should put marker at right side of Smith chart, short should put marker at left side of Smith chart
- DISPLAY menu and then FORMAT sub-menu ; LOGMAG = S11 Return Loss in dB, SWR = S11 VSWR, LINEAR = same as LOGMAG but ratio instead of dB, SMITH = shows a Smith chart for complex impedance normalized to 50 Ohms, POLAR = same as SMITH but with markers shown as complex numbers
- The left-right switch on the NanoVNA may be used to position the marker on a trace to show numerical values of measurement and stimulus frequency at any point along a sweep

NanoVNASaver PC software

- First thing to do after starting software and plugging NanoVNA into the computer using a USB cable is to select the appropriate Serial port ; click on "Rescan" until it shows the NanoVNA option
- Click on "Connect to device"
- Must do the calibration procedure from the NanoVNA itself, not through the NanoVNASaver software!
- "Sweep settings" defaults to Single Sweep where you have to click "Sweep" every time to take a measurement! Switch to Continuous Sweep to do what the NanoVNA does by default when not connected to the NanoVNASaver software.

- Click on "Display setup" button to change screen colors (I prefer "Show lines" and "Dark mode" options turned on) ; within that pop-up window, click on the "Settings" button to choose what parameters are displayed for each of the markers
- Right-clicking on any graph gives a menu of options, including log/linear axes, saving image to a `.png` file, etc.
- The "Analysis" button opens up a pop-up window where you can select a variety of analyses to do, including minimum/maximum search for R or X, etc.

7.3 Mcumall GQ-4x4 EPROM programmer tips

A file named `devices.txt` is necessary for this program to function. You may need to manually create a directory and save this file to that directory when installing this software on your computer.

The programming software must be run as "Adminstrator" in Microsoft Windows in order to write data to a device. If run with regular user privileges, you can read data from the IC but not write to it!

This programming software offers a tab in the display called "Buffer" which shows a hex dump of the ROM device's contents. This is an editable field, into which you may type hexadecimal characters representing the binary data you wish to program into your EPROM.

Some EPROM programming applications are based on numerical values following a mathematical pattern, for example numerical values representing points along a sine wave for programming a direct-digital synthesis waveform generator. Typing all these hexadecimal values manually into the Buffer hexdump display of this software can be tedious, so an altenative strategy is to write some code outputting a list of hexadecimal numbers and then convert that list into a "binary" file which may be directly opened in the software. That binary file (name ending with a `.bin` filename extension) may be uploaded into the software by using the open file option under the File menu.

Binary files are not ASCII text files, but rather files where every one of the bits in the file directly relates to bits you intend to store in the EPROM. A binary file may be created from a plain-text ASCII file (with hexadecimal characters representing the data bits you want) and then converting that plain text into raw binary using a hex editor application, or by writing a short program in Python or C or some other language to perform the ASCII-to-binary conversion.

Chapter 8

???

8.1 ??? tips

8.2 ??? tips

8.3 ??? tips

8.4 ??? tips

Appendix A

Problem-Solving Strategies

The ability to solve complex problems is arguably one of the most valuable skills one can possess, and this skill is particularly important in any science-based discipline.

- Study principles, not procedures. Don't be satisfied with merely knowing how to compute solutions – learn *why* those solutions work.
- Identify what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any "missing pieces" to a solution. Annotate all diagrams with this data.
- Sketch a diagram to help visualize the problem. When building a real system, always devise a plan for that system and analyze its function *before* constructing it.
- Follow the units of measurement and meaning of every calculation. If you are ever performing mathematical calculations as part of a problem-solving procedure, and you find yourself unable to apply each and every intermediate result to some aspect of the problem, it means you don't understand what you are doing. Properly done, every mathematical result should have practical meaning for the problem, and not just be an abstract number. You should be able to identify the proper units of measurement for each and every calculated result, and show where that result fits into the problem.
- Perform "thought experiments" to explore the effects of different conditions for theoretical problems. When troubleshooting real systems, perform *diagnostic tests* rather than visually inspecting for faults, the best diagnostic test being the one giving you the most information about the nature and/or location of the fault with the fewest steps.
- Simplify the problem until the solution becomes obvious, and then use that obvious case as a model to follow in solving the more complex version of the problem.
- Check for exceptions to see if your solution is incorrect or incomplete. A good solution will work for *all* known conditions and criteria. A good example of this is the process of testing scientific hypotheses: the task of a scientist is not to find support for a new idea, but rather to *challenge* that new idea to see if it holds up under a battery of tests. The philosophical

principle of *reductio ad absurdum* (i.e. disproving a general idea by finding a specific case where it fails) is useful here.

- Work "backward" from a hypothetical solution to a new set of given conditions.
- Add quantities to problems that are qualitative in nature, because sometimes a little math helps illuminate the scenario.
- Sketch graphs illustrating how variables relate to each other. These may be quantitative (i.e. with realistic number values) or qualitative (i.e. simply showing increases and decreases).
- Treat quantitative problems as qualitative in order to discern the relative magnitudes and/or directions of change of the relevant variables. For example, try determining what happens if a certain variable were to increase or decrease before attempting to precisely calculate quantities: how will each of the dependent variables respond, by increasing, decreasing, or remaining the same as before?
- Consider limiting cases. This works especially well for qualitative problems where you need to determine which direction a variable will change. Take the given condition and magnify that condition to an extreme degree as a way of simplifying the direction of the system's response.
- Check your work. This means regularly testing your conclusions to see if they make sense. This does *not* mean repeating the same steps originally used to obtain the conclusion(s), but rather to use some other means to check validity. Simply repeating procedures often leads to *repeating the same errors* if any were made, which is why alternative paths are better.

Appendix B

Instructional philosophy

B.1 First principles of learning

- **Anyone can learn anything** given appropriate time, effort, resources, challenges, encouragement, and expectations. Dedicating time and investing effort are the student's responsibility; providing resources, challenges, and encouragement are the teacher's responsibility; high expectations are a responsibility shared by both student and teacher.
- **Transfer is not automatic.** The human mind has a natural tendency to compartmentalize information, which means the process of taking knowledge learned in one context and applying it to another usually does not come easy and therefore should never be taken for granted.
- **Learning is iterative.** The human mind rarely learns anything perfectly on the first attempt. Anticipate mistakes and plan for multiple tries to achieve full understanding, using the lessons of those mistakes as feedback to guide future attempts.
- **Information is absorbed, but understanding is created.** Facts and procedures may be memorized easily enough by repeated exposure, but the ability to reliably apply principles to novel scenarios only comes through intense personal effort. This effort is fundamentally creative in nature: explaining new concepts in one's own words, running experiments to test understanding, building projects, and teaching others are just a few ways to creatively apply new knowledge. These acts of making knowledge "one's own" need not be perfect in order to be effective, as the value lies in the activity and not necessarily the finished product.
- **Education trumps training.** There is no such thing as an entirely isolated subject, as all fields of knowledge are connected. Training is narrowly-focused and task-oriented. Education is broad-based and principle-oriented. When preparing for a life-long technical career, education beats training every time.
- **Character matters.** Poor habits are more destructive than deficits of knowledge or skill. This is especially true in collective endeavors, where a team's ability to function depends on trust between its members. Simply put, no one wants an untrustworthy person on their team. An essential component of education then, is character development.
- **People learn to be responsible by bearing responsibility.** An irresponsible person is someone who has never *had* to be responsible for anything that mattered enough to them. Just as anyone can learn anything, anyone can become responsible if the personal cost of irresponsibility becomes high enough.
- **What gets measured, gets done.** Accurate and relevant assessment of learning is key to ensuring all students learn. Therefore, it is imperative to measure what matters.
- **Failure is nothing to fear.** Every human being fails, and fails in multiple ways at multiple times. Eventual success only happens when we don't stop trying.

B.2 Proven strategies for instructors

- Assume every student is capable of learning anything they desire given the proper conditions. Treat them as capable adults by granting real responsibility and avoiding artificial incentives such as merit or demerit points.
- Create a consistent culture of high expectations across the entire program of study. Demonstrate and encourage patience, persistence, and a healthy sense of self-skepticism. Anticipate and de-stigmatize error. Teach respect for the capabilities of others as well as respect for one's own fallibility.
- Replace lecture with "inverted" instruction, where students first encounter new concepts through reading and then spend class time in Socratic dialogue with the instructor exploring those concepts and solving problems individually. There is a world of difference between observing someone solve a problem versus actually solving a problem yourself, and so the point of this form of instruction is to place students in a position where they *cannot* passively observe.
- Require students to read extensively, write about what they learn, and dialogue with you and their peers to sharpen their understanding. Apply Francis Bacon's advice that "reading maketh a full man; conference a ready man; and writing an exact man". These are complementary activities helping students expand their confidence and abilities.
- Use artificial intelligence (AI) to challenge student understanding rather than merely provide information. Find productive ways for AI to critique students' clarity of thought and of expression, for example by employing AI as a Socratic-style interlocutor or as a reviewer of students' journals. Properly applied, AI has the ability to expand student access to critical review well outside the bounds of their instructor's reach.
- Build frequent and rapid feedback into the learning process so that students know at all times how well they are learning, to identify problems early and fix them before they grow. Model the intellectual habit of self-assessing and self-correcting your own understanding (i.e. a cognitive *feedback loop*), encouraging students to do the same.
- Use "mastery" as the standard for every assessment, which means the exam or experiment or project must be done with 100% competence in order to pass. Provide students with multiple opportunity for re-tries (different versions of the assessment every time).
- Require students to devise their own hypotheses and procedures on all experiments, so that the process is truly a scientific one. Have students assess their proposed experimental procedures for risk and devise mitigations for those risks. Let nothing be pre-designed about students' experiments other than a stated task (i.e. what principle the experiment shall test) at the start and a set of demonstrable knowledge and skill objectives at the end.
- Have students build as much of their lab equipment as possible: building power sources, building test assemblies[1], and building complete working systems (no kits!). In order to provide

[1] In the program I teach, every student builds their own "Development Board" consisting of a metal chassis with DIN rail, terminal blocks, and an AC-DC power supply of their own making which functions as a portable lab environment they can use at school as well as take home.

this same "ground-up" experience for every new student, this means either previous students take their creations with them, or the systems get disassembled in preparation for the new students, or the systems grow and evolve with each new student group.

- Incorporate external accountability for you and for your students, continuously improving the curriculum and your instructional methods based on proven results. Have students regularly network with active professionals through participation in advisory committee meetings, service projects, tours, jobshadows, internships, etc. Practical suggestions include requiring students to design and build projects for external clients (e.g. community groups, businesses, different departments within the institution), and also requiring students attend all technical advisory committee meetings and to dialogue with the industry representatives at those meetings.
- Repeatedly explore difficult-to-learn concepts across multiple courses, so that students have multiple opportunities to build their understanding.
- Relate all new concepts, whenever possible, to previous concepts and to relevant physical laws. Challenge each and every student, every day, to *reason* from concept to concept and to explain the logical connections between. Challenge students to verify their conclusions by multiple approaches (e.g. double-checking their work using different methods). Ask *"Why?"* often.
- Maintain detailed records on each student's performance and share these records privately with them. These records should include academic performance as well as professionally relevant behavioral tendencies.
- Hold mandatory "check-in" meetings between all program faculty and each new student during their first term. Offer these to all other students as an option, except for any students continuing to manifest unprofessional behaviors, poor academic performance, or who have some other need for a face-to-face meeting with faculty.
- Address problems while they are small, before they grow larger. This is equally true for tutoring technical concepts as it is for helping students build professional habits.
- Build rigorous quality control into the curriculum to ensure every student masters every important concept, and that the mastery is retained over time. This includes (1) review questions added to every exam to re-assess knowledge taught in previous terms, (2) cumulative exams at the end of every term to re-assess all important concepts back to the very beginning of the program, and (3) review assessments in practical (hands-on) coursework to ensure critically-important skills were indeed taught and are still retained. What you will find by doing this is that it actually boosts retention of students by ensuring that important knowledge gets taught and is retained over long spans of time. In the absence of such quality control, student learning and retention tends to be spotty and this contributes to drop-out and failure rates later in their education.
- Finally, *never rush learning.* Education is not a race. Give your students ample time to digest complex ideas, as you continually remind yourself of just how long it took you to achieve mastery! Long-term retention and the consistently correct application of concepts are always the result of *focused effort over long periods of time* which means there are no shortcuts to learning.

B.3 Proven strategies for students

The single most important piece of advice I have for any student of any subject is to take responsibility for your own development in all areas of life including mental development. Expecting others in your life to entirely guide your own development is a recipe for disappointment. This is just as true for students enrolled in formal learning institutions as it is for auto-didacts pursuing learning entirely on their own. Learning to think in new ways is key to being able to gainfully use information, to make informed decisions about your life, and to best serve those you care about. With this in mind, I offer the following advice to students:

- **Approach all learning as valuable**. No matter what course you take, no matter who you learn from, no matter the subject, there is something useful in every learning experience. If you don't see the value of every new experience, you are not looking closely enough!
- **Continually challenge yourself**. Let other people take shortcuts and find easy answers to easy problems. The purpose of education is to stretch your mind, in order to shape it into a more powerful tool. This doesn't come by taking the path of least resistance. An excellent analogy for an empowering education is productive physical exercise: becoming stronger, more flexible, and more persistent only comes through intense personal effort.
- **Master the use of language**. This includes reading extensively, writing every day, listening closely, and speaking articulately. To a great extent language channels and empowers thought, so the better you are at wielding language the better you will be at grasping abstract concepts and articulating them not only for your benefit but for others as well.
- **Do not limit yourself to the resources given to you**. Read books that are not on the reading list. Run experiments that aren't assigned to you. Form study groups outside of class. Take an entrepreneurial approach to your own education, as though it were a business you were building for your future benefit.
- **Express and share what you learn**. Take every opportunity to teach what you have learned to others, as this will not only help them but will also strengthen your own understanding[2].
- Realize that **no one can give you understanding**, just as no one can give you physical fitness. These both must be *built*.
- **Above all, recognize that learning is hard work, and that a certain level of frustration is unavoidable**. There are times when you will struggle to grasp some of these concepts, and that struggle is a natural thing. Take heart that it will yield with persistent and varied[3] effort, and never give up! That concepts don't immediately come to you is not a sign of something wrong, but rather of something right: that you have found a worthy challenge!

[2] On a personal note, I was surprised to learn just how much my own understanding of electronics and related subjects was strengthened by becoming a teacher. When you are tasked every day with helping other people grasp complex topics, it catalyzes your own learning by giving you powerful incentives to study, to articulate your thoughts, and to reflect deeply on the process of learning.

[3] As the old saying goes, "Insanity is trying the same thing over and over again, expecting different results." If you find yourself stumped by something in the text, you should attempt a different approach. Alter the thought experiment, change the mathematical parameters, do whatever you can to see the problem in a slightly different light, and then the solution will often present itself more readily.

B.4 Design of these learning modules

"The unexamined circuit is not worth energizing" – Socrates (if he had taught electricity)

These learning modules, although useful for self-study, were designed to be used in a formal learning environment where a subject-matter expert challenges students to digest the content and exercise their critical thinking abilities in the answering of questions and in the construction and testing of working circuits. Every effort has been made to embed the following instructional and assessment philosophies within:

- The first goal of education is to enhance clear and independent thought, in order that every student reach their fullest potential in a highly complex and inter-dependent world. Robust reasoning is *always* more important than particulars of any subject matter, because its application is universal.
- Literacy is fundamental to independent learning and thought because text continues to be the most efficient way to communicate complex ideas over space and time. Those who cannot read with ease are limited in their ability to acquire knowledge and perspective.
- Articulate communication is fundamental to work that is complex and interdisciplinary.
- Faulty assumptions and poor reasoning are best corrected through challenge, not presentation. The rhetorical technique of *reductio ad absurdum* (disproving an assertion by exposing an absurdity) works well to discipline student's minds, not only to correct the problem at hand but also to learn how to detect and correct future errors.
- Important principles should be repeatedly explored and widely applied throughout a course of study, not only to reinforce their importance and help ensure their mastery, but also to showcase the interconnectedness and utility of knowledge.

These learning modules were expressly designed to be used in an "inverted" teaching environment[4] where students first read the introductory and tutorial chapters on their own, then individually attempt to answer the questions and construct working circuits according to the experiment and project guidelines. The instructor never lectures, but instead meets regularly with each individual student to review their progress, answer questions, identify misconceptions, and challenge the student to new depths of understanding through further questioning. Regular meetings between instructor and student should resemble a Socratic[5] dialogue, where questions serve as scalpels to dissect topics and expose assumptions. The student passes each module only after consistently demonstrating their ability to logically analyze and correctly apply all major concepts in each question or project/experiment. The instructor must be vigilant in probing each student's understanding to ensure they are truly *reasoning* and not just *memorizing*. This is why "Challenge" points appear throughout, as prompts for students to think deeper about topics and as starting points for instructor queries. Sometimes these challenge points require additional knowledge that hasn't been covered in the series to answer in full. This is okay, as the major purpose of the Challenges is to stimulate analysis and synthesis on the part of each student.

The instructor must possess enough mastery of the subject matter and awareness of students' reasoning to generate their own follow-up questions to practically any student response. Even completely correct answers given by the student should be challenged by the instructor for the purpose of having students practice articulating their thoughts and defending their reasoning. Conceptual errors committed by the student should be exposed and corrected not by direct instruction, but rather by reducing the errors to an absurdity[6] through well-chosen questions and thought experiments posed by the instructor. Becoming proficient at this style of instruction requires time and dedication, but the positive effects on critical thinking for both student and instructor are spectacular.

An inspection of these learning modules reveals certain unique characteristics. One of these is a bias toward thorough explanations in the tutorial chapters. Without a live instructor to explain concepts and applications to students, the text itself must fulfill this role. This philosophy results in lengthier explanations than what you might typically find in a textbook, each step of the reasoning process fully explained, including footnotes addressing common questions and concerns students raise while learning these concepts. Each tutorial seeks to not only explain each major concept in sufficient detail, but also to explain the logic of each concept and how each may be developed

[4] In a traditional teaching environment, students first encounter new information via *lecture* from an expert, and then independently apply that information via *homework*. In an "inverted" course of study, students first encounter new information via *homework*, and then independently apply that information under the scrutiny of an expert. The expert's role in lecture is to simply *explain*, but the expert's role in an inverted session is to *challenge*, *critique*, and if necessary *explain* where gaps in understanding still exist.

[5] Socrates is a figure in ancient Greek philosophy famous for his unflinching style of questioning. Although he authored no texts, he appears as a character in Plato's many writings. The essence of Socratic philosophy is to leave no question unexamined and no point of view unchallenged. While purists may argue a topic such as electric circuits is too narrow for a true Socratic-style dialogue, I would argue that the essential thought processes involved with scientific reasoning on *any* topic are not far removed from the Socratic ideal, and that students of electricity and electronics would do very well to challenge assumptions, pose thought experiments, identify fallacies, and otherwise employ the arsenal of critical thinking skills modeled by Socrates.

[6] This rhetorical technique is known by the Latin phrase *reductio ad absurdum*. The concept is to expose errors by counter-example, since only one solid counter-example is necessary to disprove a universal claim. As an example of this, consider the common misconception among beginning students of electricity that voltage cannot exist without current. One way to apply *reductio ad absurdum* to this statement is to ask how much current passes through a fully-charged battery connected to nothing (i.e. a clear example of voltage existing without current).

from "first principles". Again, this reflects the goal of developing clear and independent thought in students' minds, by showing how clear and logical thought was used to forge each concept. Students benefit from witnessing a model of clear thinking in action, and these tutorials strive to be just that.

Another feature of these learning modules is that they do not treat topics in isolation. Rather, important concepts are introduced early in the series, and appear repeatedly as stepping-stones toward other concepts in subsequent modules. This helps to avoid the "compartmentalization" of knowledge, demonstrating the inter-connectedness of concepts and simultaneously reinforcing them. Each module is fairly complete in itself, reserving the beginning of its tutorial to a review of foundational concepts.

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

I am indebted to the developers of many open-source software applications in the creation of these learning modules. The following is a list of these applications with some commentary on each.

You will notice a theme common to many of these applications: a bias toward *code*. Although I am by no means an expert programmer in any computer language, I understand and appreciate the flexibility offered by code-based applications where the user (you) enters commands into a plain ASCII text file, which the software then reads and processes to create the final output. Code-based computer applications are by their very nature *extensible*, while WYSIWYG (What You See Is What You Get) applications are generally limited to whatever user interface the developer makes for you.

The `GNU/Linux` computer operating system

> There is so much to be said about Linus Torvalds' `Linux` and Richard Stallman's `GNU` project. First, to credit just these two individuals is to fail to do justice to the *mob* of passionate volunteers who contributed to make this amazing software a reality. I first learned of `Linux` back in 1996, and have been using this operating system on my personal computers almost exclusively since then. It is *free*, it is completely *configurable*, and it permits the continued use of highly efficient `Unix` applications and scripting languages (e.g. shell scripts, Makefiles, `sed`, `awk`) developed over many decades. `Linux` not only provided me with a powerful computing platform, but its open design served to inspire my life's work of creating open-source educational resources.

Bram Moolenaar's `Vim` text editor

> Writing code for any code-based computer application requires a *text editor*, which may be thought of as a word processor strictly limited to outputting plain-ASCII text files. Many good text editors exist, and one's choice of text editor seems to be a deeply personal matter within the programming world. I prefer `Vim` because it operates very similarly to `vi` which is ubiquitous on `Unix`/`Linux` operating systems, and because it may be entirely operated via keyboard (i.e. no mouse required) which makes it fast to use.

Donald Knuth's TEX typesetting system

Developed in the late 1970's and early 1980's by computer scientist extraordinaire Donald Knuth to typeset his multi-volume magnum opus *The Art of Computer Programming*, this software allows the production of formatted text for screen-viewing or paper printing, all by writing plain-text code to describe how the formatted text is supposed to appear. TEX is not just a markup language for documents, but it is also a Turing-complete programming language in and of itself, allowing useful algorithms to be created to control the production of documents. Simply put, TEX *is a programmer's approach to word processing*. Since TEX is controlled by code written in a plain-text file, this means anyone may read that plain-text file to see exactly how the document was created. This openness afforded by the code-based nature of TEX makes it relatively easy to learn how other people have created their own TEX documents. By contrast, examining a beautiful document created in a conventional WYSIWYG word processor such as Microsoft `Word` suggests nothing to the reader about *how* that document was created, or what the user might do to create something similar. As Mr. Knuth himself once quipped, conventional word processing applications should be called WYSIAYG (What You See Is *All* You Get).

Leslie Lamport's LATEX extensions to TEX

Like all true programming languages, TEX is inherently extensible. So, years after the release of TEX to the public, Leslie Lamport decided to create a massive extension allowing easier compilation of book-length documents. The result was LATEX, which is the markup language used to create all ModEL module documents. You could say that TEX is to LATEX as `C` is to `C++`. This means it is permissible to use any and all TEX commands within LATEX source code, and it all still works. Some of the features offered by LATEX that would be challenging to implement in TEX include automatic index and table-of-content creation.

Tim Edwards' `Xcircuit` drafting program

This wonderful program is what I use to create all the schematic diagrams and illustrations (but not photographic images or mathematical plots) throughout the ModEL project. It natively outputs PostScript format which is a true vector graphic format (this is why the images do not pixellate when you zoom in for a closer view), and it is so simple to use that I have never had to read the manual! Object libraries are easy to create for `Xcircuit`, being plain-text files using PostScript programming conventions. Over the years I have collected a large set of object libraries useful for drawing electrical and electronic schematics, pictorial diagrams, and other technical illustrations.

`Gimp` graphic image manipulation program

Essentially an open-source clone of Adobe's `PhotoShop`, I use `Gimp` to resize, crop, and convert file formats for all of the photographic images appearing in the ModEL modules. Although `Gimp` does offer its own scripting language (called `Script-Fu`), I have never had occasion to use it. Thus, my utilization of `Gimp` to merely crop, resize, and convert graphic images is akin to using a sword to slice bread.

`SPICE` circuit simulation program

`SPICE` is to circuit analysis as TEX is to document creation: it is a form of markup language designed to describe a certain object to be processed in plain-ASCII text. When the plain-text "source file" is compiled by the software, it outputs the final result. More modern circuit analysis tools certainly exist, but I prefer `SPICE` for the following reasons: it is *free*, it is *fast*, it is *reliable*, and it is a fantastic tool for *teaching* students of electricity and electronics how to write simple code. I happen to use rather old versions of `SPICE`, version 2g6 being my "go to" application when I only require text-based output. `NGSPICE` (version 26), which is based on Berkeley `SPICE` version 3f5, is used when I require graphical output for such things as time-domain waveforms and Bode plots. In all `SPICE` example netlists I strive to use coding conventions compatible with all `SPICE` versions.

Andrew D. Hwang's `ePiX` mathematical visualization programming library

This amazing project is a `C++` library you may link to any `C/C++` code for the purpose of generating PostScript graphic images of mathematical functions. As a completely free and open-source project, it does all the plotting I would otherwise use a Computer Algebra System (CAS) such as `Mathematica` or `Maple` to do. It should be said that `ePiX` is *not* a Computer Algebra System like `Mathematica` or `Maple`, but merely a mathematical *visualization* tool. In other words, it won't determine integrals for you (you'll have to implement that in your own `C/C++` code!), but it can graph the results, and it does so beautifully. What I really admire about `ePiX` is that it is a `C++` programming library, which means it builds on the existing power and toolset available with that programming language. Mr. Hwang could have probably developed his own stand-alone application for mathematical plotting, but by creating a `C++` library to do the same thing he accomplished something much greater.

`gnuplot` mathematical visualization software

Another open-source tool for mathematical visualization is `gnuplot`. Interestingly, this tool is *not* part of Richard Stallman's GNU project, its name being a coincidence. For this reason the authors prefer "gnu" *not* be capitalized at all to avoid confusion. This is a much "lighter-weight" alternative to a spreadsheet for plotting tabular data, and the fact that it easily outputs directly to an X11 console or a file in a number of different graphical formats (including PostScript) is very helpful. I typically set my `gnuplot` output format to default (X11 on my Linux PC) for quick viewing while I'm developing a visualization, then switch to PostScript file export once the visual is ready to include in the document(s) I'm writing. As with my use of `Gimp` to do rudimentary image editing, my use of `gnuplot` only scratches the surface of its capabilities, but the important points are that it's *free* and that it *works well*.

`Python` programming language

Both Python and C++ find extensive use in these modules as instructional aids and exercises, but I'm listing Python here as a *tool* for myself because I use it almost daily as a *calculator*. If you open a Python interpreter console and type `from math import *` you can type mathematical expressions and have it return results just as you would on a hand calculator. Complex-number (i.e. *phasor*) arithmetic is similarly supported if you include the complex-math library (`from cmath import *`). Examples of this are shown in the Programming References chapter (if included) in each module. Of course, being a fully-featured programming language, Python also supports conditionals, loops, and other structures useful for calculation of quantities. Also, running in a console environment where all entries and returned values show as text in a chronologically-ordered list makes it easy to copy-and-paste those calculations to document exactly how they were performed.

Appendix D

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Appendix E

References

Hemingway, Ernest, *A Moveable Feast*, Scribner's, United States, 1964.

Appendix F

Version history

This is a list showing all significant additions, corrections, and other edits made to this learning module. Each entry is referenced by calendar date in reverse chronological order (newest version first), which appears on the front cover of every learning module for easy reference. Any contributors to this open-source document are listed here as well.

5 October 2025 – added instructions on how to flash firmware onto a DIGI XBee radio module, courtesy Jacob Stormes.

13-18 September 2025 – minor additions to tips on how to use `sed` within Linux. Also subdivided some of the Linux sections into subsections to make them more easily searched.

4 September 2025 – minor additions to tips on how to use a NanoVNA.

27 August 2025 – added instructions on uploading a BIN file to the EPROM programming software.

13 August 2025 – added another lesson learned on the Linx OOK/ASK 433 MHz radio transmitter and receiver modules, namely that the analog RSSI output pin requires a weak pulldown resistance in order to properly function.

6 August 2025 – substantial additions to the "Digital radio modules and software" chapter, highlighting Linx OOK/ASK 433 MHz radio transmitter and receiver modules.

17 April 2025 – substantial additions to the "Digital radio modules and software" chapter including some section title changes.

11 April 2025 – substantial additions to the "Multimeter tips" chapter.

4-5 April 2025 – added content to the "Solderless breadboard caveats" chapter.

26 March 2025 – added content to the "Multimeter tips" and "Solderless breadboard caveats" and "Linux computer operating system" chapters.

21 March 2025 – added notes on using `spyserver` software to stream software-defined radio data on a network via a Raspberry Pi 4 single-board computer running Debian Linux OS.

18 March 2025 – document first created.

Index