Appendix D   Schematic Guide

Introduction:

This appendix originated a free-standing document to help students in EE283, particularly with their first (digital) project. However, the principles here are also applicable to other types of schematics, with allowances for differences. As it exists now, only electrical schematics are covered.

A schematic generally serves one of two purposes. First, it is used to illustrate a circuit or principle of electrical circuits. (Mechanical or mixed schematics can represent other types of systems.) Generally, this is the use in which most students encounter schematics, circuit diagrams, at first. The second purpose is as documentation. In this capacity, the purpose is not to teach a concept, but to provide an exact record necessary to communicate the details of the circuit to others, for purposes of examination, manufacture, or maintenance. These purposes are quite different, essentially an "engineering drawing." Many details do not matter when the purpose is to convey an idea, such as the exact part or pin numbering. A two input AND gate performs and AND function; that's all that is important. But when the same part is documented for manufacturing, or for someone who will later do maintenance, the exact placement of components and pins will be necessary.

This appendix is broken into two parts specific to digital and analog circuits, with the digital material placed first. In digital circuits, complexity is usually manifest in the large numbers of components and connections, each of which is relatively simple. In analog circuits, the functions performed and the the signals are more complex, while the overall schematic often has fewer components. Each type of circuit has idiosyncrasies, but many of the basic principles are similar.

Digital Schematics

Instructional material, such as directions for a laboratory exercise, often shows logic schematics without giving certain details like pin numbers, because they are inessential to the illustrative purpose. But when a student builds the circuit and submits the design, this corresponds more closely to the uses of a schematic in industry. It should allow a person to not only see the overview, but relate the circuit particulars to the physical device.

This chapter (and the document it is derived from) was prepared to describe the kinds of features that are required for purposes of documentation, and illustrate those with examples. It is important to remember is that a schematic is a tool for communication. Always consider what a potential user might need to know, and how to convey that information as clearly and simply as possible. In particular companies or industries styles will vary from and have more rules than the guidelines below.

Some Basics

There are some basic principles to follow in schematics for almost any purpose.

1. Let signals flow generally from left to right. Where you need to show feedback or other signals flowing right to left, bring them back around the outside of the figure keeping clear of the forward paths. (Usually it is desirable to avoid components in the feedback path, unless they specifically relate to the principle of feedback.) Components that have distinguishable "input" and "output" terminals (true for most digital devices) should have the inputs at left, and outputs at right, unless there is very good reason to do otherwise. See Figure D-1 for an example. Secondarily, signals can be shown going top to bottom.

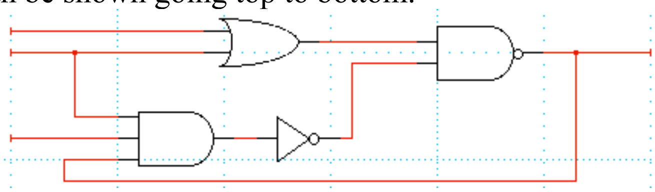

Figure D-1 Left to right signals, with feedback brought back at the bottom

2. Show Ground connections at the bottom, positive supply connections at the top, and negative supply connections at the bottom, of a given part of the schematic. Exceptions can be made in the interests of clarity. (Occasionally it helps to show all power connections at the bottom.) Also, never show ground connections pointed in any direction than toward the bottom of the paper, and all others should be up (at the top) or down (if at the bottom of the circuit).

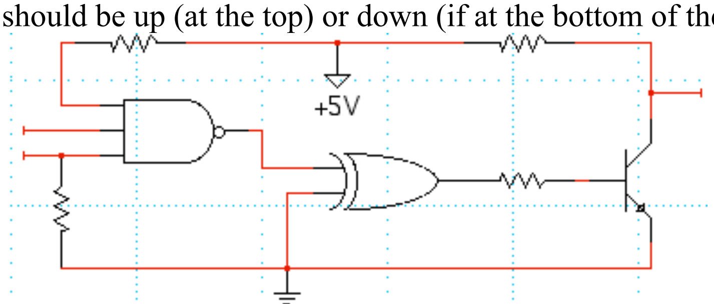

Figure D-2 The way not to show Power and Ground connections.

3. Do not attempt to show power supply wiring unless the schematic is specifically concerning the power supply. For example, don't try to connect different connections to Ground, or to a common +5 Volt supply. Show individual connections to the supply locally. This eliminates a lot of wiring clutter. Don't do your schematic as shown in Figure D-2. Much better is the style shown in Figure D-3.

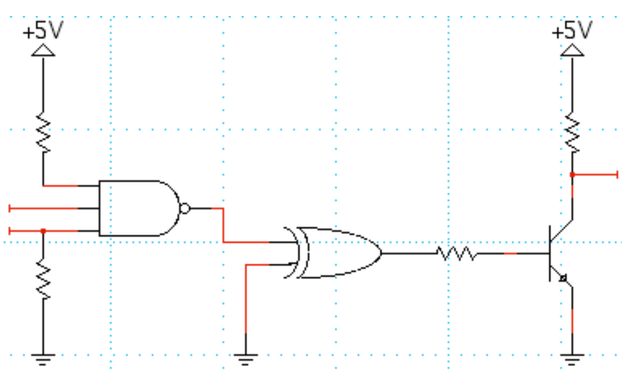

Figure D-3 Better way to show Power, Ground connections

4. Avoid unnecessary kinks or jogs in showing connections. Use straight long lines as much as is practical. Avoid crossings as much as possible consistent with clarity. If there are several related signals, say a 3 bit bus consisting of signals having a significance of 1, 2, and 4 to make a 3 bit binary number, run these signals together in an organized fashion as much as possible. Consider grouping them together as a "bus" allowing the use of one line instead of 3.

5. For documentation purposes, identify each device and (where necessary) its distinct terminals. Use standard labeling conventions: R1, R2, etc. for resistors, C1, C2, C3 etc. for capacitors, L1 etc. for inductors, Q1, Q2, etc. for transistors, D1, D2, etc. for diodes, T1 etc. for transformers, and U1, U2, etc. for integrated circuits. (There are other more or less standard labeling that you are less likely to encounter, such as V1 etc. for vacuum tubes, X1 for a crystal, and M1, M2, etc. for meter movements or FET transistors.) Since for common resistors the terminal assignment does not matter, the terminals do not need to be identified. For transistors and diodes, the symbol identifies the different terminals, such as Anode, Base, and Emitter, so it often is not necessary to identify terminals by numbers. But for integrated circuits, pin numbering is a necessity. For transformers, it is often useful to identify terminals by numbers or by color of wire, as they may be identified. This is particularly true of transformers having several windings. Assign numbers to the devices in a reasonable fashion. For example, R2 should be close to R1 and farther to the right, if the first two resistors a signal encounters are close together.

6. Label important signals, especially inputs and outputs of your overall circuit or important parts of it. Use meaningful labels. For simple circuits, things like Vin and Vout are sufficient, but on more complex ones you may need more symbols. Choose names that convey the meaning where possible. For busses (related signals that convey a value, in digital circuits), label signals with symbols like D0 to D7 (for 8 data wires, in this example). In this case D0 would be the least significant and D7 would be the most significant bit on this bus. (Sometimes sequential letters, such as D, C, B, A are used. The first letter (A) in such a group is, by convention, the least significant.

7. Put an easily seen dot where wires connect. Try to avoid a dotted connection where wires exit in both perpendicular directions, since this is easier to mistake the intersection for a crossing with no connection. See Figure D-4 for a few Dos and Don'ts.

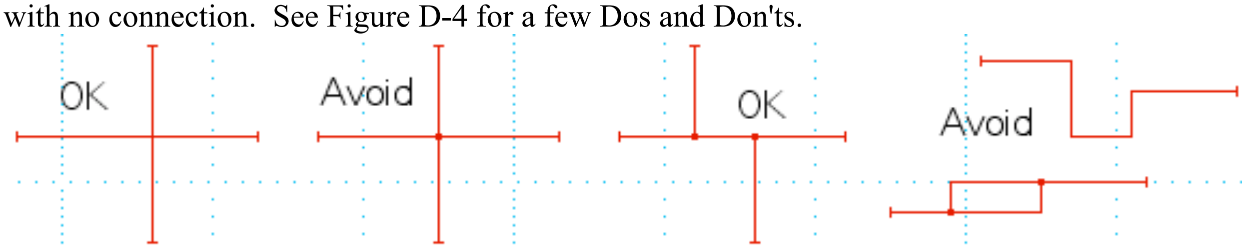

Figure D-4 Wiring illustrations.

Parts, Part Numbering, and Pin numbering

Many electrical devices perform only one function. A resistor, capacitor, transistor, or Op-amp is usually a discrete package. Digital devices, especially gates, often occur as several functional units in one package. For example, a 74LS08 is a 14 pin device that includes four 2 input AND gates. How should this device appear on a schematic? There are two choices: as a single device, or as 4 separate units. Figure D-5 below shows what happens if you make each device a separate item.

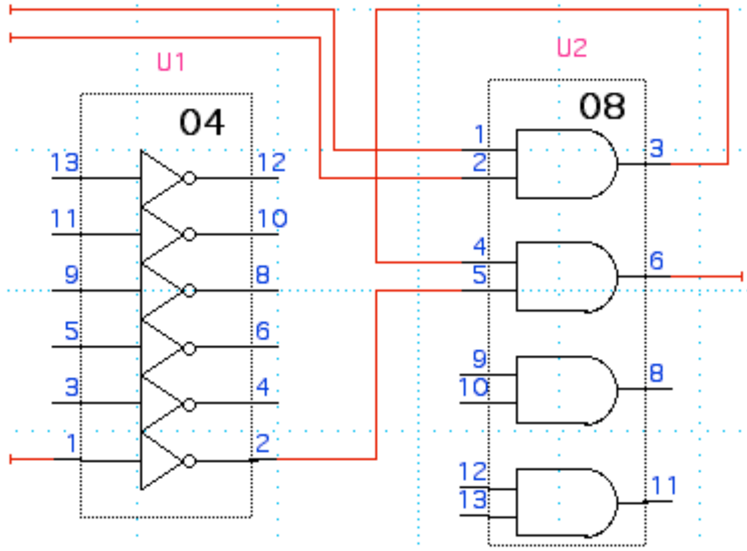

Figure D-5 Digital devices as unitary components (Don't Do This!)

The problem here is that the signal from the first AND gate to the second one must wrap back around. This looks like feedback, but it really isn't. It also requires a wire crossing, which is something we would like to avoid if possible. Once the connections to the other gates and inverters are added, this could be quite a mess, since each wire must be brought to a centralized location for the device, while the different functions of the units of a given device may not have much to do with each other. Notice that the pin numbers are shown above as they correspond to the functional organization of the device, rather than being arranged as the pins are physically.

Also, the Figure D-5 schematic commits you to use a specific gate on IC U2, at the first three pins. But, perhaps later on you will find it more convenient to use the one at pins 11 to 13. You either have to go back and fix the schematic or have it wrong. A better approach is shown in Figure D-6.

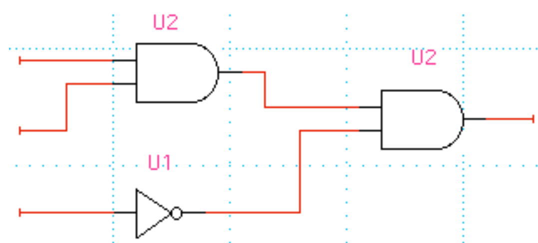

Figure D-6 Digital devices as individual units (Preferred)

Now all signals go left to right, no wires cross, and the relationship of the two AND gates to each other is much clearer. The physical relationship of both AND gates being on the same device is established by labeling both gates as "U2." (The other two may be widely separated from this part of the circuit.) We also do not need to show units that may be left unconnected and unused. No commitment is yet made to which gates on the device will be used for either gate shown in the schematic; that's a decision deferred to a more detailed step in the design process.

One occasion when the device symbol may be preferable is when the units work together to perform one function. Suppose we have four related signals representing a binary number, a "bus" of 4 bits. A 74LS86 Quad "Exclusive Or" is used to either invert all of the bits or leave them uninverted. (An Exclusive OR has the same function as an OR except that two 1 inputs gives a 0 output.) Figure D-7 shows this. Notice the signal labeling. Generally, use numbers (often as subscripts) to indicate the place of each of several related signals. Here D3 would be the most significant and D0 the least significant. (Occasionally, such as on the 74LS160 counters used in EE283, letters are used to indicate significance, such as D, C, B, and A for inputs and QD, QC, QB, and QA for outputs. Your design may have many such devices, so your signal labeling needs to be different so that they can be distinguished.) If no commitment is being made to specific pin numbers at this stage in the design, the pin numbers should be deleted.

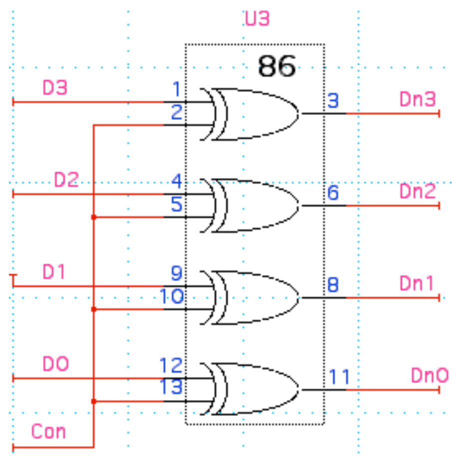

Figure D-7 Digital device operating on related signals (OK in special circumstances)

Power connections

Avoid cluttering up your schematic with power connections. Notice that none of the earlier figures show the power connections to pins 14 and 7. But you do need to document them. For digital circuits, and sometimes others, this is usually done in a table, which can also serve the purpose of identifying the specific part number. The table is generally found in one of the lower corners of the schematic. Figure D-8 shows an example that would apply to the above figures. Usually we restrict this to the actual power connections to the device. Sometimes there are more than two. Note that U5 has two Ground connections. Pin 14 is not really a power connection; it is the Clear signal. For a signal (as opposed to a power connection) it is usually better to show that connection (in this case to ground) in the schematic proper, rather than in this table. If there are several power supplies, say +5, +12, and -12, then there would be more columns in this table.

Part	Device	Power (5V)	Ground
U1	74LS04	pin 14	pin 7
U2	74LS08	pin 14	pin 7
U3	74LS86	pin 14	pin 7
U4	74LS04	pin 16	pin 8
U5	74LS193	pin 16	pins 8,14

Figure D-8 Table to show power connections

If you do not include such a table, it is important to label each device as shown in Figure D-9 below, so that the reader will know exactly which of the many types of AND gate this is. Occasionally this annotation is given as "1/4 74LS08" to indicate that the unit shown is a given fraction of the physical device. Occasionally in such cases (where no table is given) the power connections are shown attached to one of the several units in each particular device.

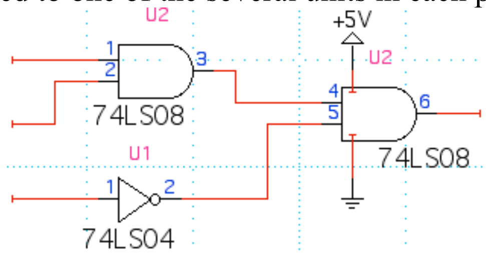

Figure D-9 Units labeled with part type identification.

Organize busses and use subcircuits

When the various bits on a bus connect to a variety of places, it helps to organize the signals as shown in Figure D-10. Here the bus values and their complements are arranged vertically so that it is easy to connect the gates using horizontal wiring. In this "half adder" the two input signals, A and B, and their complements, /A and /B, are shown as a bus, parallel signals routed together (rather than as a bus symbol) even though they do not convey a single binary value. This helps organize the schematic. In larger circuits this becomes much more important than in this simple case. Notice the use of labeled "port" symbols to show that these signals connect to something that is off the page (more about that next).

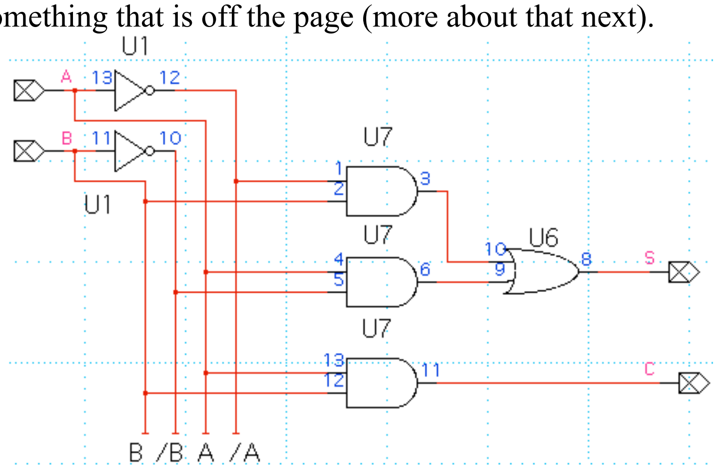

Figure D-10 Illustration of organized sets of signals

When a design gets too complex, organize it into a hierarchy of subcircuits. For example, rather than include a circuit for a half adder several times, it could be made a separate stand-alone schematic, and incorporated as if it is a part into a higher level schematic. For example, the half adder schematic could be associated with a created part called a "HalfAdder," several of which are incorporated into a 3 bit adder as shown in Figure D-11.

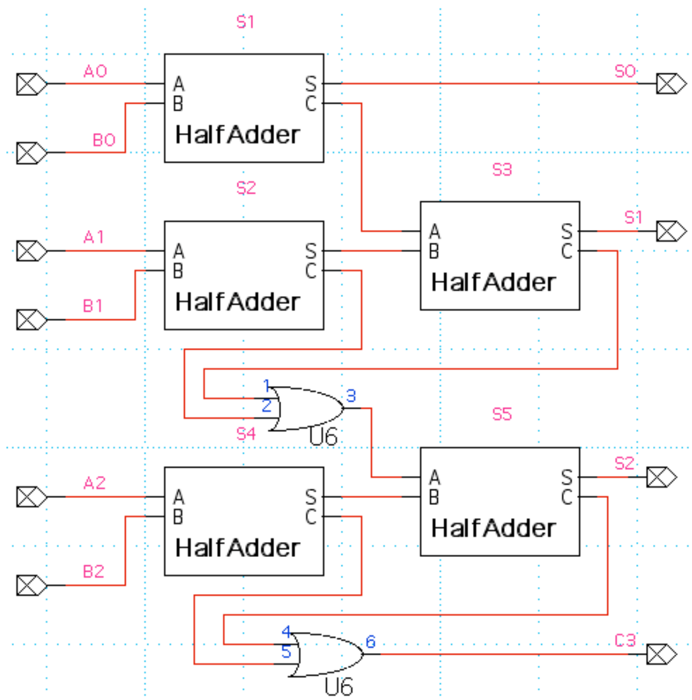

Figure D-11 Use of Subcircuits

The ports of the half adder in Figure D-10 are the "pins" of the five "HalfAdder" parts shown in Figure D-11. The tricky part of this is parts identification, since each HalfAdder may use parts of different integrated circuits. This would probably be best accomplished with a separate table than by using the identification scheme shown. This subcircuit approach works best where subcircuits do not share devices. Notice that, as shown, this 3 bit adder could itself be a subcircuit of something more complex. (Note: the schematics shown in the preceding figures were all prepared using Capilano's *Logicworks 3*).

Physical layout

Some way of identifying where the devices are physically located is usually necessary in practical cases in industry. (This is not necessarily required in assignments.) A diagram showing placement something like that given in Figure D-12 is generally used.

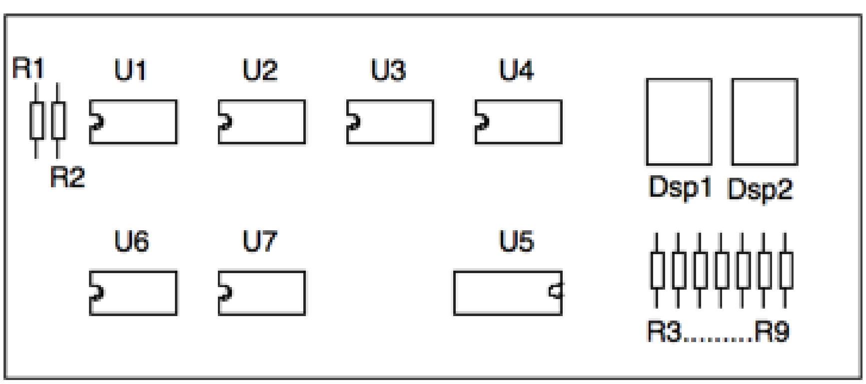

Figure D-12 Physical Layout (Floor plan) Example

Analog Schematics:

Analog schematics follow most of the same principles that digital schematics do. Signal flow is generally left to right, power supply wiring is minimized, feedback is most often shown at the bottom, and clarity is the preeminent concern. For analog circuitry, it is usually necessary to define more quantitative data. For examples, resistors will need to be specified by resistance, often power rating as well, and tolerance. So, labeling is often needs more attention. Figure D-13 shows a relatively complex analog circuit, the inductive sensor system from EGR222 Mechatronics. (This and the following figures were drawn in ORCAD/PSpice 10.0 and transferred by screen shot.)

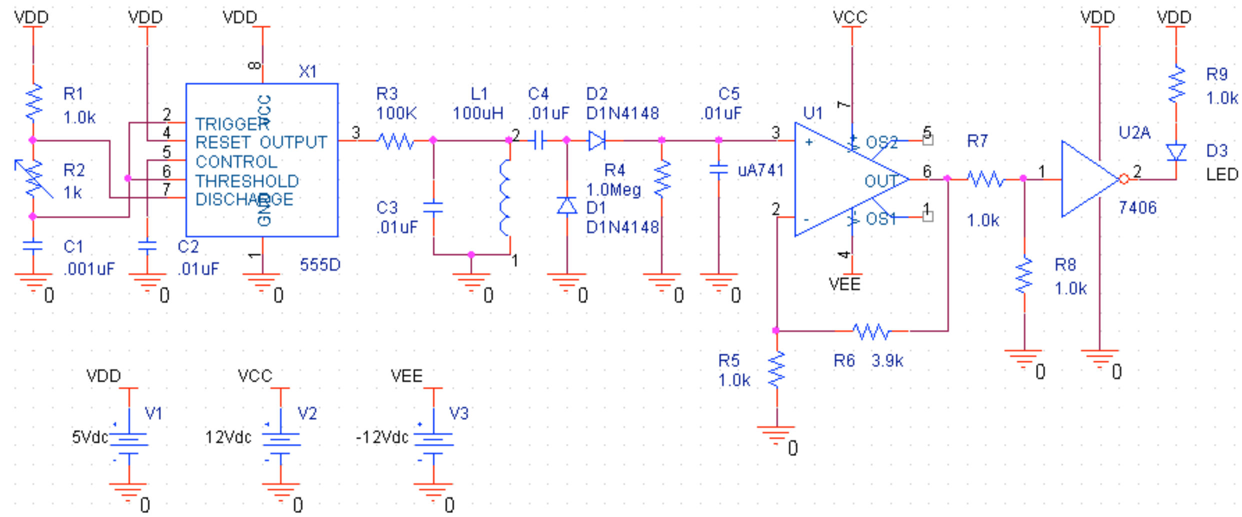

Figure D-13 Inductive Sensor Circuit from EGR222 Mechatronics

Notice in this figure the use of "Power" connections (both ground and power supplies) by symbol rather than by drawing wires back to the power sources. That means that the left to right horizontal wires (and some of the vertical ones) are signal connections. The power wiring does not distract. Indeed, the power sources themselves, three of them in this circuit, have been removed to the otherwise vacant lower left hand corner where they are there to be seen, but do not distract. Because there are three different power supply Voltages, they are labeled correspondingly in the figure as VCC, VEE, and VDD. That establishes which supply is connected where. (The choice of VDD for a name may seem odd. The Op-amp needs +/- 12 Volts, normally labeled VCC and VEE. Yet, the 5V supply needed for the 74xx digital device, also used for the LM555 timer, is also normally labeled VCC. You can't use the symbol VCC for both. VDD normally applies to MOSFET circuits, but can reasonably be borrowed in this case due to necessity.) Compare Figure D-13 with Figure D-14, which shows wires for power wiring. It is a lot more difficult to discern the functioning of the circuit.

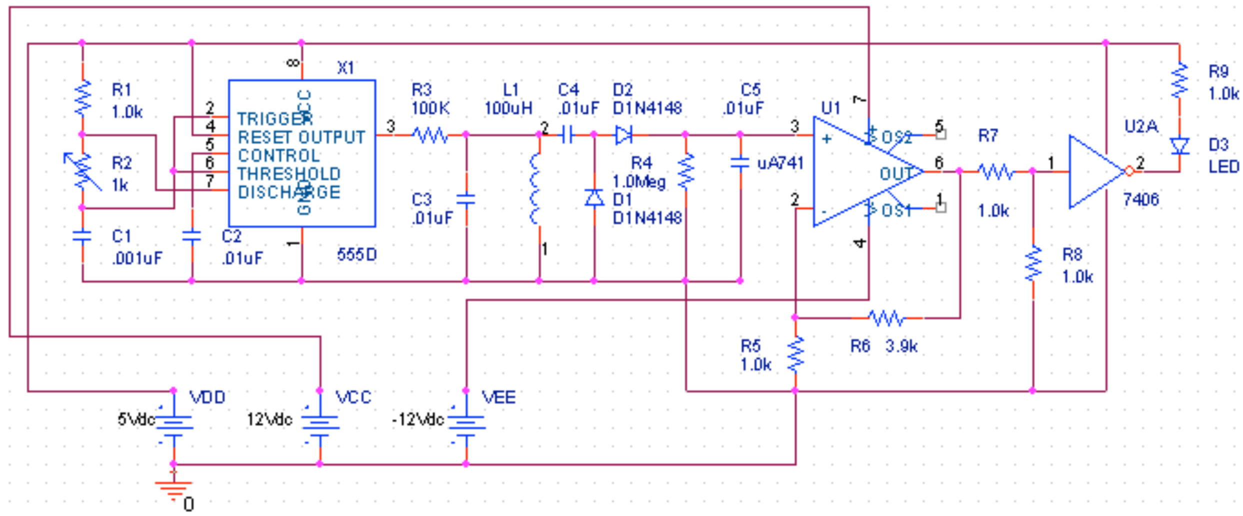

Figure D-13 Same circuit as Figure D-12, but with power wiring shown – cluttered; not as clear!

In a schematic, the alternative of not showing power supply connections at all, and referencing them in a table, as for digital schematics, is also acceptable, perhaps even preferable. However, if the schematic in PSpice is also being used for simulation, using the power arrangements shown are necessary, and might as well be used in the report figure to better show the reader how simulation was performed. The power connections for "U2A", the 7406 open collector inverter device, was not part of the PSpice symbol. The power supply connections were added to the schematic as shown for the sake of the report figure, but don't actually connect to anything. (The same would be true if you used the generic Op-amp part instead of the particular op-amp uA741.)

Note the difference between signals that are grounded, or connected to power, and power supply connections. For the LM555 timer, X1, the signal "Reset" is connected to VDD as a way of not causing reset. Even if you were to remove power supply connections to a table, this should remain shown on the schematic.

You may notice (in Figure D-13) that while in most cases component connections to ground (or power) are shown with separate ground connections, for example at the bottom of D1, R4, and C5, the two components L1 and C3 share a single connection to ground. That is to emphasize that these two components act as a unit to form the "tank" circuit, an LC element that resonates at the chosen frequency when no nearby metal object changes the inductance. That is, the shared ground connection indicates a signal importance of the fact that these two components connect together at both ends. Physically, they should be grounded at the same point or in very close proximity.

Notice that resistor values have been modified to indicate "1.0K" Ohms instead of "1K" in order to show the appropriate number of significant digits for a 5% tolerance resistor. It would be a helpful addition to note on the schematic somewhere that, "All resistors are 1/4W, 5%." It might also be appropriate to annotate capacitors with special characteristics where needed. In this circuit, none of the capacitors happen to be polarized. Note that power supply bypass capacitors are not shown; if they are shown, they would be shown shunted across the respective power supply sources. Finally, note that some care has been taken to align the ground and power symbols for the sake of presentation.

After drawing this circuit, it was edited to compress the spacing as much as possible, especially in the lateral direction. This made it necessary to move some labels, for example L1 and its value of 100μH. By compressing laterally, the figure as transferred into Word remains legible. If the figure is so large that even with careful compression it will not be readable, consider using a full page and rotating the figure into landscape mode.

A few remarks will be made about PSpice oddities. This circuit was done with the freely downloadable "eval" version, so not all devices needed were available. In particular, there is no "LED" part. The 1N4002 was used instead, with the label edited. If accurate LED diode electrical behavior was needed, the diode characteristics could be edited. That's not necessary for a schematic. The inductor part has terminal numbers. These could have been edited out. Notice that "u" is used to mean "μ". You cannot use "M" to mean "Meg" because PSpice is not case sensitive, "M" means the same as "m", "milli-". That's why "Meg" is needed for R4. For the op-amp, pins 1 and 5 are the offset connections, which are not used and are left unconnected. For a just a schematic, these could have been omitted. Variable resistor R2 is actually a three-terminal potentiometer, that the student adjusts to the value needed to adjust the LM555 circuit to give resonance. It is left labeled a "1K" Ohm part, because that is what it physically is, but in simulation the value would be edited as the system is developed to the right value needed. (In an engineering drawing this would be shown as the three-terminal potentiometer; the variable resistor symbol is used here because that better describes the function.)

For a report figure, it would have been preferable to change the schematic display preferences to suppress the grid points, which show up as a stipple of dots in the figure. For a laboratory report, the inclusion of the grid points might be acceptable as long as they are not prominent. As with digital circuits, it is often helpful to label signals, especially if reference is made to those particular signals in the text. That was not done in this case, so the text would need to refer to signals by the part numbers where they appear. For example, "The DC Voltage indicating the degree of resonance is generated at the cathode of D2, then amplified by the op-amp."

Conclusion

This appendix is a start at things to consider when documenting circuit schematics. You will find that some conventions carry over to other contexts, such as power and mechanical systems, and others don't. Remember that the purpose is clarity in communication. Always think about what your reader will need to know.