Appendix A: Know your Ingredients.

Someone might think that buying a small microcontroller and downloading a few canned programs to light up some LEDs or display “Hello World” is all that is needed to do microcontroller development but I would beg to differ. I consider this much like buying a gooey, prepared, cellophane packaged pastry which you heat up in a microwave and eat it while thinking this has something to do with cooking. Nope, real cooking requires the chef to know about ingredients, learn special techniques, and requires considerable practice to develop culinary skills and judgment. Should I put a teaspoon of cornstarch right out of the box into that too-thin sauce to thicken it? Nope, not unless you want lumps of uncooked starch ruining your sauce. Oh, did you know, using cornstarch dissolved in a little water avoids the lumps but is not always the right thickener to use for acidic liquids? And so it goes. Some knowledge of basic chemistry comes in very handy when training to be the next Julia Child or Jamie Oliver.

Knowing some fundamentals of electronics is required to create more ambitious microcontroller projects. Here we try to get up to speed in a very few examples illustrating basic electronics, components, circuits, and some resources you can peruse for a more complete version. We are merely providing a sketch of ideas here. To really understand how to safely drive a DC motor using an H-bridge requires much more study than we can present here. So, after reading this appendix we recommend you curl up on the sofa with a good book or two on electronics, a cup of coffee or tea, and a plate of cookies just out of the oven. It is time well spent.

Electricity is the movement of electrons. Electrons are all around and inside us so understanding electricity is a matter of learning how to manage the storage and transportation of these invisible little energy bundles. As an analogy, consider letting water out from behind a dam while using the water pressure created by gravity to turn turbines. By exploiting the relative “water vacuum” below the water level and an abundance of water wanting to fill that vacuum, we can accomplish some real work.

By creating an electron vacuum and controlling the flow of electrons (like water in the pipes) through some device which extracts energy from the passing electrons, we can have electrons do some real work as well. Since electrons ‘flow’ through conductors such as metals but are blocked by insulators such as air, rubber, plastics, etc we channel electrons through circuits determined by these materials.

Just to make your life more interesting, you should know that the flow of current in the classical sense was described exactly backwards from what I am describing. That is, early scientists thought current, often considered a kind of elusive fluid, went from positive to negative. We know better now but is is useful to know what is up when you come across this in your readings.

The common flashlight battery is just a layered arrangement of chemicals which charge a metal contact, thus exhibiting electron abundance usually designated as minus (−), and another contact having an electron vacuum, designated as (+). By putting a conducting material, say a thin wire housed inside a glass bulb, between these contacts, we watch as the wire heats to incandescence and, with a tip of the hat to Edison and Swann, we see the common lightbulb in action. Notice this minor miracle should remind us that even small batteries and wires should be handled with care as things can heat up rather dramatically. All the more reason to know as much as you can about electronics before hooking up wires and flipping on the power switch.
Voltage is a measure of strength of an electron vacuum. The standard measure is the volt, named after early experimenter Alessandro Volta. Common battery values are 1.5, 9, and 12 volts. Higher voltages tend to become increasingly dangerous, including the potentially deadly 110 or 220 volts found in US wall outlets. Everything we are going to discuss here will be about low voltage devices but, again, uncontrolled electron flow is to be avoided, just like blowing up a dam blocking a few billion gallons of water is probably bad news for anyone wading downstream.

By the way, voltage can be negative since zero volts or ground is just a convention for any particular circuit. Look at Figure 13 where we designate the center tap of this series arrangement of batteries as zero volts. This gives an output of +5 and -5 volts relative to that choice of baseline voltage. Voltage is just the signed relative measure of electron vacuum between two points in a circuit.

Current is a measure of the flow of electrons with the standard unit being the ampere, named after André-Marie Ampère. One ampere translates to a flow rate of some few gazillions of electrons per second. A bright 100 watt incandescent lightbulb has about one ampere running through it. We can control electron flow, much like we control the flow of water under pressure (voltage, remember?), using switches (on/off valves), small capacity pipes, or filters. Like high pressure water systems, a circuit with higher voltages tends to pull more electrons, thus providing higher current, through the available conductors. The most common current limiting device in electronics is called a resistor. The basic relationship between voltage, current, and resistance can be expressed mathematically as we shall see in a moment.

Here we note that essentially all we talk about below concerns direct current or DC. Alternating current or AC comes from rapidly changing voltage sources which swing from positive to zero to negative to zero to positive again and again. It turns out this AC is what we find coming from an alternator (or electric motor turned by hand) when we measure voltage across its coil windings. So, there is an entire part of electronics we are sidestepping here to concentrate on DC circuits. Almost all computer circuits are DC, so just add a notation ‘look up AC theory’ to your TODO: list.

Figure 12 displays a typical schematic of a circuit abstracting a battery providing voltage V, with wires connecting a resistor so arranged to allow current flow I from the battery cathode, a fancy term for the negative or ground contact, through the resistor of value R, and into the positive battery anode. The current flowing through the resistor releases energy as heat so we must choose a resistor capable of dissipating this energy. Standard copper wire has extremely low resistance so it does not heat up, unlike the resistor. So, exactly how much current will be going through our resistor in this case? We are glad you asked, the answer is given by the fundamental Ohm’s Law.

Given a potential V volts across a resistor of value R, the current I passing through the resistor satisfies

\[ V = I \times R \]

The unit of resistance, the ohm, designated using Greek Ω, was designed to make Ohm’s law equation work out in whole numbers so we almost never see resistors with fractional values. Typical resistor values available in ohms are 10, 100, 220, 1000 or 1K, 2.2K, 10K, and 1,000,000 Ω = 1 megohm. The
physical size of a resistor is not an indicator of its resistance but is closely related to the amount of energy it can dissipate.

Big, hulking ceramic resistors in some unknown device are an indication of large current flows, not necessarily high resistance. Touch them at your peril; they may be very hot!

By the way, power dissipated by our circuit above is computed in W watts as: \( W = V \times I \). Now you can see why a typical 100 watt light bulb consumes about an amperes of current. Given common lighting voltage of 110 volts and 100 watt bulb, we have 100 watts = 110 volts \( \times \) I amperes, so I is about 0.9 amperes.

Not all devices are battery powered so we do some more abstraction and disconnect the positive and negative into a generic source of voltage, usually denoted V and a common ground. Positive supply voltage is often denoted \( V_{cc} \) or \( V_{dd} \) while ground is denoted \( V_{ss} \) or simply GND.

Figure 14 shows a very common circuit powered by voltage source V and using two resistors, with values \( R_1 \) and \( R_2 \), called a voltage divider. Using Ohm’s law for each resistor and noticing that the same current, call it I, runs through both resistors, along with the fact that resistors in series add to get a total resistance, you should work out the details to show that the voltage \( V_{out} \) present at point A is given by

\[
V_{out} = V \frac{R_2}{(R_1 + R_2)}
\]

The diode is a semi-conductor since it allows electron flow in one direction but not in the reverse direction, sort of like a check valve in plumbing. Figure 15 shows a circuit on the left using a diode D to block the flow of current and another orientation on the right allowing current to flow.

A terrific and familiar variant on the basic diode is a light emitting diode or LED which actually emits light, big surprise, when sufficient current flows through the device. Figure 16 shows a typical LED controlled by a voltage divider with required(!) current limiting resistor \( R_3 \) keeping the current flow through the LED within device bounds. You should verify that the LED is brightest when the variable resistor R4, or potentiometer, is set at its highest resistance. LEDs come in many colors, sizes, and shapes and often provide a simple feedback device to determine if a circuit is working as desired or when the power switch is on.

Most electronic components are chosen to limit and control flow of electrons in a circuit. The capacitor can also block current but is somewhat different as it also provides storage capability for electrons. Capacitors are essentially two parallel metal foil plates separated by a thin layer of insulator.

Electrons on the negative plate are attracted to the close-by electron vacuum on the positive plate, thus uncharacteristically crowd onto the negative plate, making a ready power concentration.
The values of capacitors are measured in farads but due to the original choice of units, most capacitors have values in fractions of microfarads, each microfarad being $1 \times 10^{-6}$ farads. Adding a capacitor $C_1$ to a simple resistor and LED circuit as shown in Figure 17 illustrates how we can accumulate a positive charge on the capacitor anode when the push button switch is closed. When the switch is opened, this charge slowly drains away through the resistor while the LED light slowly fades. This circuit is also less susceptible to LED light variation if our power voltage or current suddenly varies since the capacitor provides a ready store of electrons and corresponding (+) anode attraction thus smoothing out the effects of small periodic or transient voltage changes.

We now move from these passive components to active components which use signals to control the flow of electricity. Transistors come in a number of packages and varieties and are used to control the flow of electricity. Transistors, invented in the 1950’s, dramatically changed the design of circuits and ushered in the age of extremely small, low power, inexpensive devices and made it possible for you own an MP3 player, holding 10,000 songs, which is as small as a 1950’s pack of chewing gum.

Figure 18 shows an NPN bipolar junction transistor $Q_1$ which acts as an electronic switch. When a small current is pulled from the base of the BJT, the resistance between the collector and emitter decreases, allowing proportionally more current flow from the emitter to the collector. At full saturation, a few milliamps of current from the base will make the emitter-collector junction act much like a forward biased diode, exhibiting negligible resistance, thus turning on this electronic switch.

When there is no current flow from the base, the emitter-collector junction acts like a reversed biased diode, effectively blocking any current flow. BJT devices require current limiting base resistors to prevent too much current through the base which can overheat and destroy the transistor. Between saturation and cutoff, BJT’s act as current amplifiers, remember I said proportionally above, which is where they excel. We are interested in logical operations so are more interested in transistors as switches, on or off, and not amplifying a small analog signal coming from a CD player into a fender-rattling boom-box car audio system.

You should verify that the voltage present at point $V_{out}$ in Figure 18 is essentially the opposite from the base input so this circuit acts as an inverter, or logical NOT gate. Consult the classic Horowitz and Hill [2] for corresponding details for PNP transistors where current into the base amplifies current flow in the collector-emitter direction.

Field effect transistors operate in much the same way at our JBT but the conductivity between the equivalent of the emitter-collector junction, now called the source and drain, is controlled by the presence of voltage, not current, at the gate. Figure 19 shows P-channel (top) and N-channel (bottom) MOSFET transistors in a totem pole configuration acting as a logic inverter. N-channel MOSFETs act as closed switches when the gate is positively biased, P-channel MOSFETs are similarly activated when their gate is zero or negatively biased. In our inverter circuit shown, if the input $A$ is at zero volts or logic 0, transistor $Q_3$ acts as an open switch (extremely high resistance) while $Q_4$ conducts so $V_{out}$ is pulled high to about $V_{CC}$, hence logic 1. If $A$ is near $V_{CC}$, the transistor roles are reversed.
and Q3 conducts from GND while Q4 is open. This pulls $V_{out}$ to GND, or logic 0. Notice MOSFETs can avoid the need for a gate current limiting transistor since there is negligible gate current. This makes a more efficient switch for basic logic operation circuits.

It is worth observing this improved switch circuit also allows current flow both into and out of the $V_{out}$. This means we have two choices on how to hook up an LED, say, to such a switch. Along with the usual current limiting resistor, we can put our LED in either orientation but the logic signals for driving the LED are reversed. So, to light an LED we must choose whether to pull $V_{out}$ low or high depending on which orientation we choose. This capability to both sink and source current from these devices makes them very useful.

Circuits to compute standard logic operations such as AND, OR, NOT, XOR, NAND, and NOR gates are created from these efficient MOSFET transistors used in saturation (logic 1) or cutoff (logic 0) modes. Several such basic gates often are packaged in dual inline package (DIP) modules as well as smaller form factors such as small outline integrated circuit (SOIC). These surface mount packages are very small and less expensive but make soldering for mere mortals harder when trying to attach these devices to a printed circuit board. Combining these on a single printed circuit board with passives such as resistors and capacitors, we can create an endless number of combinatorial circuits acting as oscillators, encoders, decoders, and so on.

Expanding these circuits to add binary numbers (just add cascading logic operations using AND, OR, and XOR gates) as well as our standard logic operations leads to arithmetic-logic units or ALUs. Adding in some additional control, timing, shifting, multiplexing kicks it up a notch to a full fledged central processing unit or CPU. Finally, we add general input/output data buses, RAM, EEPROM, analog to digital converters, more clocks, timers, interrupt controllers and we have arrived at a microcontroller squeezed into a DIP package the size of a raisin with as few as eight pins needed to connect to the circuit board. Wow, how is that for a really, really fast overview of a huge territory from about 50,000 feet? For the details, look into Maxfield [3] and Horowitz and Hill [2].

Next we introduce two sample circuits to illustrate the subtlety of even simple arrangements of components and peek at a commercial PCB kit design which invites a full analysis of a more complex circuit.

Microprocessors and microcontrollers often have a reset pin which will restart the chip initialization and then execute the current application in RAM or EEPROM. Often a reset occurs when the active low $\text{RESET}$ pin is pulled to 0 volts, or logic zero. Using a simple push button switch making and breaking connections between $\text{RESET}$ and GND is prone to noise. Switch contacts ‘bounce’ by making and breaking contact many times before they fully close or open. The resulting transient signals may rapidly reset our device a number of times, not just once. This same problem is found in pushbuttons meant to count up or down with each press. Receiving a train of brief ‘glitches’ on an input pin can result in lots of spurious counts. These problems can be solved using hardware, software, or a combination of the two.
Figure 20 shows an improved switch debouncing circuit using a simple hardware design. Before reset, the RC network and following special inverter, called a Schmitt trigger, prevent switch bounces in several ways. On power up, the input to the inverter is low until the capacitor is charged through resistors R8 and R9. When the capacitor is almost fully charged, the voltage at the inverter input rises almost to VCC which is needed to ‘snap off’ the Schmitt trigger inverter, so it very rapidly drops its output low. With the capacitor now fully charged, upon closing the push button switch S2, the brief bounce signals are not of long enough duration to discharge the capacitor through R9 to reduce the voltage level of the Schmitt trigger inverter, which requires a very low gate voltage before it changes state. Once the capacitor discharges sufficiently, this low voltage level is reached so the inverter immediately raises its output high. Finally, on releasing the push button, again the brief signal line noise spikes are too brief to keep the slower resistor-capacitor combination from charging until the noise has abated and the input to Schmitt trigger rises to a sufficient level. The exact values chosen for resistors and capacitor depends on the supply voltage and a generous estimate of the maximum time we expect to encounter noisy spikes when the switch changes state. Just for a tiny bit of analysis, what role does resistor R8 play in this circuit? Should I pick a value for R8 to be quite high or quite low resistance? Why?

As a last word, if you have yet to go in the kitchen, er, workshop and parboil a complete working circuit from components, we suggest you consider doing this ASAP. We are not encouraging wanton e-waste but building a simple solder kit and tracing through its schematic so you understand how it works in exquisite detail is very, very useful in grasping and retaining all this chef’s knowledge. Inexpensive kits are available from many dealers and several can be adapted to work with the microcontroller recipes.
in this book. Here is a schematic of a commercial sound activated LED display kit from Velleman. You will notice some differences between US and European schematic symbol conventions. Resistors are designated as rectangles, the potentiometer is the resistor with a stake driven through its heart, and the microphone is the crystal ball lying on its side. Try and describe precisely the changes in voltages and current at various points in this circuit when we speak into the microphone M300, thus lighting some of LEDs based on the sound volume. This is a fun exercise in understanding a modest transistor device.