2

Theory and Practice

There are a few fundamentals that will help us get the most out of our electronics. I have no intention of overloading you with theory, so you may find you come back to this chapter as and when you need to. But before we start on any theory, let's look at getting together some of the components we will use.

How to Assemble a Starter Kit of Components

In Chapter 1, we assembled a few tools and did some soldering. The only thing we made used a scavenged computer fan, an off-the-shelf power supply, and a switch.

Certain components you will find that you use over and over again. To get yourself a basic stock of components, I recommend you buy a starter kit. SparkFun sells such a kit (see the Appendix, K1), but it does not contain any resistors, so you will need to buy a resistor set, too (K2). Once you have these, you will have a useful collection of components that should cover 80 percent of what you need.

Other suppliers sell starter kits, and although none of them will contain everything you need for this book, most will give you a very good starting point.

You Will Need

The SparkFun Starter Kit contains the following items, and the items used directly in this book are marked with a *, so if buying an alternative kit, look for one that has the majority of these components. Also see the Appendix for a list of other components used in the book.

Quantity	Item	Quantity	Item
10	0.1uF capacitor *	3	20-pin male header *
5	100uF capacitor *	3	Mini power switch *
5	10uF capacitor *	2	Push buttons *
5	1uF capacitor	1	10k trimpot *
5	10nF capacitor	2	LM358 OpAmp
5	1nF capacitor	2	3.3V regulator
5	100pF capacitor	2	5V regulator *
5	10pF capacitor	1	555 timer *
5	1N4148 diode	1	Green LED *
5	1N4001 diode *	1	Yellow LED *
5	2N3906 PNP transistor	1	Red LED *
5	2N3904 NPN transistor *	1	7-segment red LED
3	20-pin female header	1	Mini photocell *

The separate SparkFun resistor kit (K2) contains resistors of the following values:

0Ω, 1.5Ω, 4.7Ω, 10Ω, 47Ω
110Ω, 220Ω, 330Ω, 470Ω, 680Ω
1kΩ, 2.2kΩ, 3.3kΩ, 4.7kΩ, 10kΩ
22kΩ, 47kΩ, 100kΩ, 330kΩ, 1MΩ

How to Identify Electronic Components

So, what have we just bought here? Let's go through the components in the SparkFun starter kits and explain what they do, starting with the resistors.

Resistors

Figure 2-1 shows an assortment of resistors. Resistors come in different sizes to be able to cope with different amounts of power. High-power resistors are physically big to cope with the heat they produce. Since "parts getting hot" is generally a bad thing in electronics, we will mostly avoid that. Nearly all of the time we can use the 0.25-watt resistors as provided in the SparkFun kit, which are perfect for general use.

As well as having a maximum power rating, resistors also have a "resistance." As the word suggests, resistance is actually

FIGURE 2-1 Assorted resistors

resistance to the flow of current. So a high-resistance resistor will not allow much current to flow, while a low-value resistor will allow lots of current to flow.

Resistors are the most commonly used component you can find. Since we will be using them a lot, we will go into greater detail on the subject in the section "What Are Current, Resistance, and Voltage?" later in this chapter.

Resistors have little stripes on them that tell you their value. You can learn to read the stripes (more in a moment on that) or you can avoid all of this by storing them in a bag or in the drawer of a component box with the value written on the box or bag. If in doubt, check the value with the resistance measurement feature of your multimeter.

However, an essential piece of geekiness is to know your resistor color-codes. Each color has a value, as shown next:

Color	Value
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9
Gold	1/10
Silver	1/100

Gold and silver, as well as representing the fractions 1/10 and 1/100, are also used to indicate how accurate the resistor is. So gold is ±5% and silver is ±10%.

There will generally be three of these bands grouped together at one end of the resistor. This is followed by a gap, and then a single band at the other end of the resistor. The single band indicates the accuracy of the resistor value. Since none of the projects in this book require very accurate resistors, there is no need to select your resistors on the basis of accuracy.

Figure 2-2 shows the arrangement of the colored bands. The resistor value uses just the three bands. The first band is the first digit, the second the second digit, and the third "multiplier" band is how many zeros to put after the first two digits.

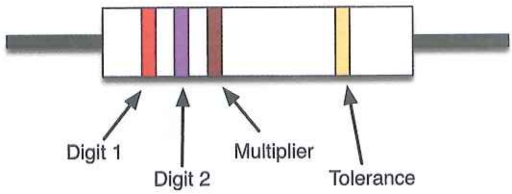


FIGURE 2-2 Resistor stripes

So, a 270Ω (*ohm*) resistor will have first digit 2 (red), second digit 7 (violet), and a multiplier of 1 (brown). Similarly, a 10KΩ resistor will have bands of brown, black, and orange (1, 0, 000).

In addition to fixed resistors, there are also variable resistors (a.k.a., potentiometers or pots). This comes in handy with volume controls, where turning a knob changes the resistance and alters the level of sound.

Capacitors

When hacking electronics, you will occasionally need to use a capacitor. Luckily, you do not need to know much about what they do. They are often used to head-off problems like the instability of a circuit or unwanted noise. Their use is often given a name like "decoupling capacitor" or "smoothing capacitor." There are simple rules you can follow about where you need a capacitor. These will be highlighted as we encounter them in later sections.

For the curious, capacitors store charge, a bit like a battery, but not much charge, and they can store the charge and release it very quickly.

Figure 2-3 shows a selection of capacitors.

FIGURE 2-3 Assorted capacitors

If you look closely at the second capacitor from the left, you will see the number 103. This is actually the value of the capacitor in picofarads. The unit of capacitance is farad, but a 1F capacitor would be considered a huge capacitor, storing a great deal of charge. So, while such beasts do exist, everyday capacitors are either measured in nanofarads (nF = 1/1,000,000,000F) or microfarads (μF = 1/1,000,000F). You will also find capacitors in the picofarad range (pF = 1/1,000,000,000,000F).

Returning to 103. … Rather like resistors, this means 10 and then 3 zeros, in units of pF. So in this case that's 10,000pF or 10nF.

Larger capacitors, like those on the right of Figure 2-3, are called electrolytic capacitors. They are usually in the μF

FIGURE 2-4 An electrolytic capacitor

range and have their value written on their side. They also have a + and a – side, and unlike most other capacitors must be connected the right way around.

Figure 2-4 shows a large electrolytic, with value (1000µF) and its negative lead clearly indicated at the bottom of the figure. If the capacitor has one lead longer than the other, the longer one will normally be the positive lead.

The capacitor in Figure 2-4 also has a voltage written on it (200V). This is the capacitor's maximum voltage. So if you put more than 200V across its leads, it will fail. Big electrolytic capacitors like this have a reputation for failing spectacularly and may burst, spewing forth goo.

FIGURE 2-5 A selection of diodes

Diodes

You will occasionally need to use diodes. They are kind of a one-way valve, only allowing current to flow in one direction. They are therefore often used to protect sensitive components from accidental reverse voltage that could damage them.

Diodes (Figure 2-5) have a stripe at one end. That end is called the cathode, while the other end is called the anode. We will hear more about diodes later.

As with resistors, the bigger the diode physically, the more power it can cope with before it gets too hot and expires. Ninety percent of the time, you will just be using one of the two diodes on the left-hand side of the figure.

FIGURE 2-6 Assorted LEDs

LEDs

LEDs light up, and generally look pretty. Figure 2-6 shows a selection of LEDs.

LEDs are a little sensitive, so you should not connect them directly to a battery. Instead you have to use a resistor to reduce the current flowing into the LED. If you do not do this, the LED will probably die almost instantly.

Later on, we will see how to select the right resistor for the job.

Just like regular diodes, LEDs have a positive and a negative lead (anode and cathode). The anode is the longer of the two leads. There is also usually a flat side to the LED case on the cathode side.

As well as single LEDs, you also get LEDs in more complicated arrangements within a single package. Figure 2-7 shows some interesting-looking LEDs.

From left to right, these LEDs are an ultraviolet LED, an LED with both red and green LEDs in the same package, a high-power RGB (red, green, blue) LED that can be controlled to produce any color of light, a seven-segment LED display, and an LED bar graph display.

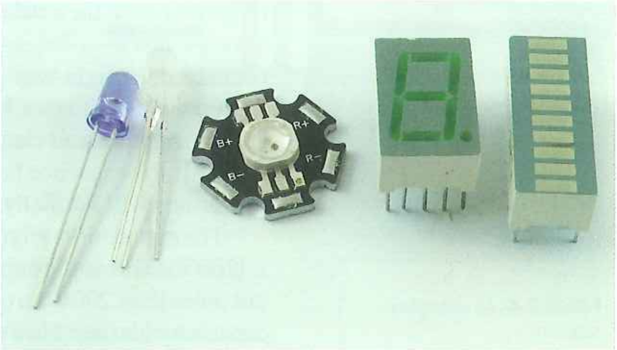


FIGURE 2-7 More LEDs

This is just a small selection of LED types. There are many others to choose from. In later sections, we will explore some of these more exotic LEDs.

Transistors

While transistors can be used in audio amplifiers and in many circumstances, for the casual electronics hacker, the transistor can be thought of as a switch. But rather than a switch controlled by a lever, it is a switch that switches a big current, yet is controlled by a small current.

Generally speaking, the physical size of the transistor (Figure 2-8) determines how big the current that it switches can be before it starts producing smoke.

Of the transistors in Figure 2-8, the right-hand two are quite specialized and employed for high power use.

Generally, the rule for a component is that if it's ugly and has three legs, it's probably some kind of transistor.

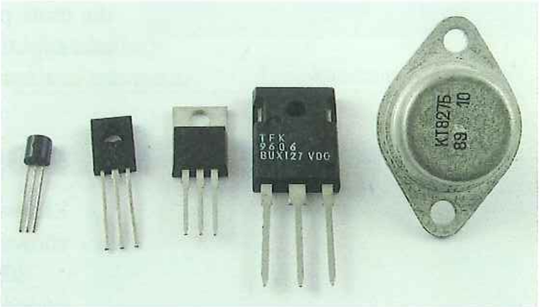


FIGURE 2-8 Transistors

Integrated Circuits

An integrated circuit (IC), or just "chip," is a load of transistors and other components printed onto silicon. The purpose of the IC varies wildly. It can be a microcontroller (mini-computer), or an entire audio amplifier, or a computer memory, or any one of thousands of other possibilities.

ICs make life easy, because as they say, often "there's a chip for that." Indeed, if there is something you want to make, there may well be a chip for it already, and if there isn't, then there will probably be a general-purpose chip that takes you halfway there.

ICs look like bugs (Figure 2-9).

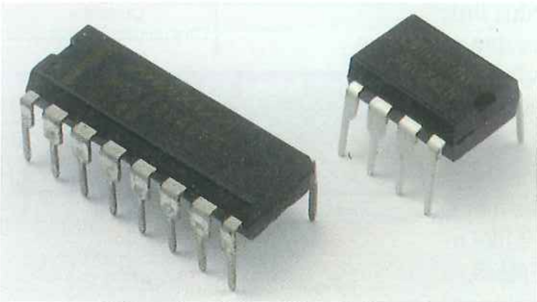


FIGURE 2-9 Integrated circuits

Other Stuff

There are so many other components out there, some of which are very familiar, such as batteries and switches. Others are less familiar and include potentiometers (variable resistors found in volume controls), phototransistors, rotary encoders, light dependent resistors, and so on. We will explore these as they arise later in the book.

Surface Mount Components

Let's touch a little on the subject of surface mount devices (SMDs). These components are just resistors, transistors, capacitors, ICs, and so on, but in tiny packages designed to be soldered onto the top surface of circuit boards by machines.

Figure 2-10 shows a selection of SMDs.

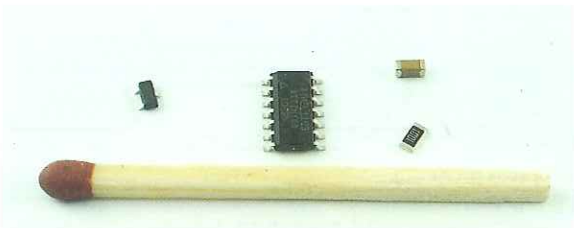


FIGURE 2-10 Surface mount components

The matchstick shows you just how small these devices are. It is perfectly possible to do surface mount soldering by hand, but you need a steady hand and a high-quality soldering iron. Not to mention a lot of patience. You are also likely to need a means of making circuit boards, as they are not easy to use with breadboard or other prototyping tools.

In this book, we mostly look at using the conventional "through-hole" components rather than SMDs. However, as your experience grows and you feel you might like working with SMDs, do not be afraid to try.

What Are Current, Resistance, and Voltage?

Voltage, current, and resistance are three properties that are fundamental to almost everything you will do in electronics. They are intimately related, and if you can master the relationship between them, you will be a wise hacker indeed.

Please take the time to read and understand this little bit of theory. Once you understand it, many other things should automatically fall into place.

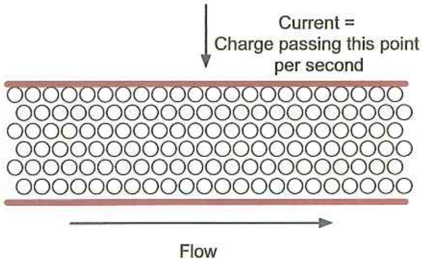


FIGURE 2-11 Current

Current

The problem with electrons is that you cannot see them, so you just have to imagine how they do things. I like to think of electrons as little balls flowing through pipes. Any physicists reading this will probably be clutching their heads or hurling this book to the floor in disgust now. But it works for me.

Each electron has a charge and it's always the same—lots of electrons, lots of charge, few electrons, and a little bit of charge.

Current, rather like the current in a river, is measured by counting how much charge passes you per second (Figure 2-11).

Resistance

A resistor's job is to provide resistance to the flow of current. So, if we keep thinking about our river, it is like a constriction in a river (Figure 2-12).

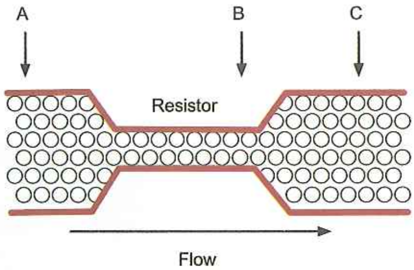


FIGURE 2-12 A resistor

The resistor has reduced the amount of charge that can pass by a point. And it doesn't matter which point you measure at (A, B, or C) because, if you look upstream of the resistor, the charge is hanging around waiting to move through the resistor. Therefore, less is moving past A per second. In the resistor (B), it's restricted.

The "speed" analogy does not really hold true for electrons, but one important point is that the current will be the same wherever you measure it.

Imagine what happens when a resistor stops too much current from flowing through an LED.

Voltage

Voltage is the final part of the equation (that we will come to in a minute). If we persist with the water-in-a-river analogy, then voltage is like the height that the river drops over a given distance (Figure 2-13).

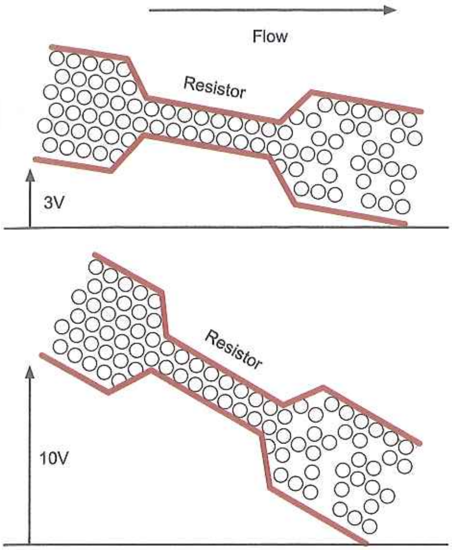


FIGURE 2-13 Voltage

As everyone knows, a river that loses height quickly flows fast and furious, whereas a relatively gently sloped river will have a correspondingly gentle current.

This analogy helps with the concept of voltage being relative. That is, it does not matter if the river is falling from 10,000 ft to 5,000 ft or from 5,000 ft to 0 ft. The drop is the same and so will be the rate of flow.

Ohm's Law

Before we get into the math of this, let's think for a moment about current, voltage, and resistance and how they relate to each other.

Try this little quiz. Think in terms of the river if you find it helps.

1. If the voltage increases, will the current (a) increase or (b) decrease?
2. If the resistance increases, will the current (a) increase or (b) decrease?

Did you get the answers (a) and (b) correct, respectively?

If you write this down as an equation, it is called Ohm's law and can be written as:

$$I = V / R$$

I for current (I guess "C" was already taken), V for Volts, and R for resistance.

So, the current flowing through a resistor, or any wire connecting to it, will be the voltage across the resistor divided by the resistance of the resistor.

The units of resistance are in Ω (the abbreviation for ohms), while units of current are in A (short for amps, which is short for amperes) and in voltage V (the easy one).

So, if we have a voltage of 10V across a resistor of 100Ω the current flowing will be:

$$10V / 100\Omega = 0.1A$$

For convenience, we often use mA (1/1000 of an amp). So 0.1A is also 100mA.

That's enough about Ohm's law for now, we will meet it again later. It is the single most useful thing you can know about electronics. In the next section, we will look at the only other truly essential math you will need—power.

What Is Power?

Power is all about energy and time. So, in a way, it's a bit like current. But, instead of being the amount of charge passing a point, it is the amount of energy transformed into heat per second when a current passes through something that resists the flow (like a resistor). Forget the river, it doesn't really help much here.

Restricting the flow of a current generates heat, and the amount of heat generated can be calculated as the voltage across a resistor times the current flowing through it. The units of power are the watt (W). You would write this in math as:

$$P = I \times V$$

So, in our earlier example, we had 10V across a 100Ω resistor, so the current through the resistor was 100mA and will generate 0.1A × 10V, or 1 W of power. Given that the resistors that we have from the SparkFun kit are 250 mW (0.25 W). Our resistor will get hot and may eventually break.

If you don't know the current, but you do know the resistance, another useful formula for calculating the power is:

$$P = V^2 / R$$

Or, power is voltage squared (times itself) divided by the resistance. So, for the example earlier:

$$P = 10 \times 10 / 100 = 1 \text{ W}$$

That's reassuringly the same answer as we got before.

Most components have a maximum power rating like this, so when selecting a resistor, transistor, diode, and so on, it is worth doing a quick check and multiplying the voltage across the component by the current that you expect to flow through it. Then, choose a component with a maximum power rating comfortably greater than the expected power.

Power is the best measure of how much electricity is being used. It is the electrical energy being used per second, and unlike current it can be compared for devices operating from

Device	Power
Battery-powered FM radio (volume down)	20 mW
Battery-powered FM radio (volume up)	500 mW
Arduino Uno microcontroller board (9V supply)	200 mW
Home WiFi router	10 W
Compact fluorescent (low-power) light bulb	15 W
Filament light bulb	60 W
LCD TV 40-inch	200 W
Electric kettle	3000 W (3 kW)

TABLE 2-1 Power Usage

both 110 volt outlets and low voltage. It is good to have a basic understanding of just how much—or how little—electricity devices use. Table 2-1 shows some devices you might find around the home and lists how much power they use.

So, now you know why you don't get battery-powered kettles!

How to Read a Schematic Diagram

Hacking electronics often involves trawling the Internet, looking for people who have made something like the thing you want to make or adapt. You will often find schematic diagrams that tell you how to make and do things. So you need to be able to understand these schematics in order to turn them into real electronics.

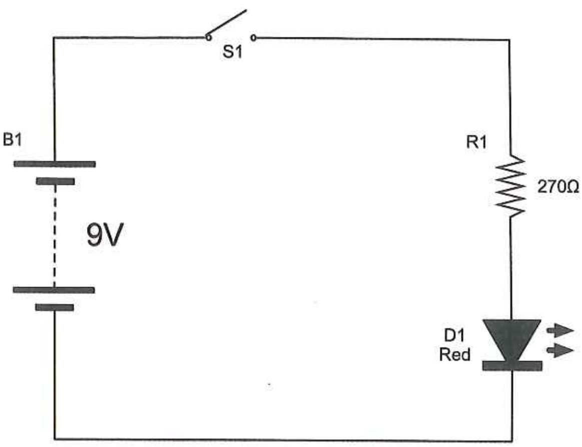


FIGURE 2-14 A simple schematic

These may at first sight seem a little baffling, but schematics obey a few simple rules and tend to use the same patterns over and over again. So there is a lot less to learn than you might think.

Ponder Figure 2-14 while we consider some of these rules—or more accurately conventions—because sometimes they are broken.

Figure 2-14 goes a long way to explaining why we sometimes talk of electronic circuits. It's kind of a loop. The current is flowing out of the battery, through the switch (when it's closed), through the resistor and LED (D1), and then back to the battery. The lines on the schematic can be thought of as perfect wires without any resistance.

The First Rule of Schematics: Positive Voltages Are Uppermost

A convention that most people follow when drawing a schematic is to put the higher voltages near the top, so on the left-hand side of the diagram, we have a 9V battery. The bottom of the battery is at 0V or GND (Ground), while the top of the battery will by 9V higher than that.

Notice that we draw the resistor R1 above the LED (D1). This way, we can think of some of the voltage as being lost across the resistor, before the remainder is lost through the diode and flows back to the negative connection of the battery.

Second Rule of Schematics: Things Happen Left to Right

Western civilization invented electronics and writes from left to right. You read from left to right and, culturally, more things happen from left to right. Electronics is no different, so it is common to start with the source of the electricity—the battery or power supply on the left—and then work our way from left to right across the diagram.

So, next we have our switch, which controls the flow of the electricity, and then the resistor and LED.

Names and Values

It is normal to give every component in a schematic a name. So, in this case the battery pack is called B1, the switch S1, the resistor R1, and the LED D1. This means that when you go from a schematic to a breadboard layout and eventually a circuit board, you can see which components on the schematic correspond to which components on the breadboard or circuit board.

It is also normal to specify the value of each of the components where appropriate. So, for example, the resistors' value of 270Ω is marked on the diagram. The rest of the components don't need much else said about them.

Component Symbols

Table 2-2 lists the most common circuit symbols you will encounter. This is nothing like a complete list, but we will discuss other symbols later in the book.

There are two main styles of circuit symbol: American and European. Fortunately, they are similar enough to avoid difficulties in recognizing them.

In this book, we will use the U.S. circuit symbols.

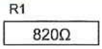
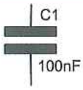
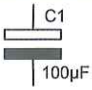
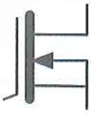
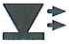
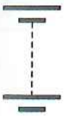
Symbol (U.S.)	Symbol (European)	Photo	Component	Use
			Resistor	Resisting
			Capacitor	Temporary charge storage
			Capacitor (polarized)	
			Transistor (bipolar NPN)	Using a small current to control a larger current
			Transistor (MOSFET N-channel)	Using a very small current to control a larger current
			Diode	Prevents current from flowing in the wrong direction
			LED	Indication and illumination
			Battery	Power supply
			Switch	Turning things on and off; control

TABLE 2-2 Common Schematic Symbols

Summary

In the next chapter, we get a much more practical look at some basic hacks and hone our electronic construction skills. This includes using prototyping boards and taking our soldering beyond simply connecting wires to other wires.

We will also learn how to use solderless breadboard so we can build electronics quickly and get underway.