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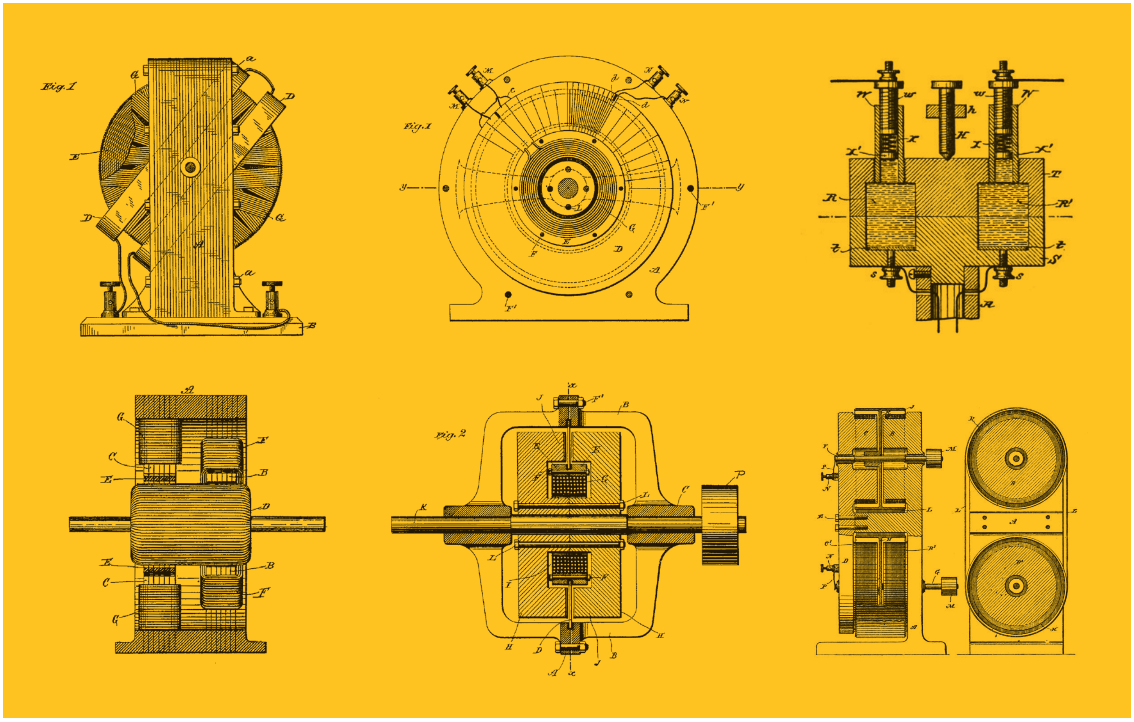
J. M. Hughes

Practical Electronics

Components and Techniques



O'REILLY®

Practical Electronics

Components and Techniques

How much do you need to know about electronics to create something interesting, or creatively modify something that already exists? If you'd like to build an electronic device, but don't have much experience with electronics components, this hands-on workbench reference helps you find answers to technical questions quickly.

Filling the gap between a beginner's primer and a formal textbook, *Practical Electronics* explores aspects of electronic components, techniques, and tools that you would typically learn on the job and from years of experience. Even if you've worked with electronics or have a background in electronics theory, you're bound to find important information that you may not have encountered before.

Among the book's many topics, you'll discover how to:

- Read and understand the datasheet for an electronic component
- Use uncommon but inexpensive tools to achieve more professional-looking results
- Select the appropriate analog and digital ICs for your project
- Select and assemble various types of connectors
- Do basic reverse engineering on a device in order to modify (hack) it
- Use open source tools for schematic capture and PCB layout
- Make smart choices when buying new or used test equipment

John M. Hughes is an embedded systems engineer with over 30 years of experience in electronics, embedded systems and software, aerospace systems, and scientific applications programming. He was responsible for the surface imaging software on the Phoenix Mars Lander and was part of the team that developed a novel synthetic heterodyne laser interferometer for calibrating the position control of the mirrors on the James Webb Space Telescope.

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Electronics

Practical Electronics: Components and Techniques

John M. Hughes

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Practical Electronics: Components and Techniques

by John M. Hughes

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Preface

So, how much electronics do you need to know to be able to create something interesting, or creatively modify something that already exists? Well, that depends on where you start in the creative process. It also depends on your willingness to seek out new knowledge and acquire new skills as you go along.

The primary purpose of this book is to give you a reference for some of the more arcane (and possibly mundane) but essential aspects of electronics. These include things you would typically learn on the job and from years of experience, such as how to read the datasheet for an electronic component, determining how many things can be connected to an interface pin on a microcontroller, how to assemble various types of connectors, how to minimize noise and interference on a signal interface circuit, how to determine the resolution of an analog-to-digital converter, how various types of serial and network interfaces work, and how to use open source tools for schematic capture and PCB layout. And, of course, we will also cover the tools used in electronics work and how they are used, and we'll examine what's available in terms of test equipment beyond the garden-variety digital multimeter.

We'll start off with an introduction to the underlying physics of electricity that dispenses with the water-flowing-in-a-pipe analogy and gets right to the heart of the matter with a look at how atoms pass electrons around. We'll then examine the basic concepts of voltage and current. For those readers who might need or want a more detailed discussion of basic electrical theory, it can be found in Appendix A.

I should point out that this book is not intended to be an in-depth tutorial on electronics theory. There are already many excellent books on that topic, and to repeat that here would just be a pointless exercise in killing trees. So, while there is some introductory material to set the stage, so to speak, the primary intent of this book is to provide you with a reference for topics that aren't usually covered in an electronics text or a step-by-step project book.

With this book, perhaps one or two of the suggested reference works in Appendix C, and your own enthusiasm and ambition, you should be able to create that gadget or system you've been wanting to build and have it work as you intended. And remember, it's not the end of the world if you accidentally convert an electronic component into charcoal. It happens all the time; it's called *learning*.

Who This Book Is For

This book is for anyone with a desire to build an electronic device of some sort, but, to the maximum extent possible, I have made no assumptions about your skill level. What I *have* assumed is that you might not be familiar with the hardware, components, tools, and techniques that are used in electronics, or perhaps you already know something about electronics but could use some help with some of the more arcane aspects of the craft.

With this book as a workbench reference and guide to more detailed sources of information, you should be able to get started on building a nifty gadget and avoid some (hopefully, most) of the pitfalls that await the unwary. I've made the assumption that you will follow the pointers given to learn more about the various topics this book covers, and it covers a lot. It's simply not possible to cover all the topics presented in this book at more than just a surface level; the resulting tome would be huge. In lieu of a lot of details, I've tried to provide enough information to give you a basic understanding of the topics and a foundation to build upon.

So, if you've been thinking about something you'd like to build but aren't sure how to go about it, or you already know a fair amount about electronics but perhaps need some help putting it all together, then this book is for you.

How This Book Is Organized

Each chapter is devoted to a specific topic, ranging from hardware (screws, nuts, and bolts) to tools, and from switches, relays, and passive components to active solid-state parts. Each chapter is designed to allow you to easily find a specific subject and get quick answers to your questions:

Chapter 1: Electrons in Motion
: The first chapter provides a high-level "top-of-the-waves" look at electronics, using the notion of electrons in motion as the key to concepts such as voltage, current, and power.

Chapter 2: Fasteners and Adhesives
: Often overlooked or taken for granted, fasteners and fastening methods are essential to a successful project. The choice of fasteners can also have a major effect on the aesthetics of a project, so getting the right parts for the job can make the difference between elegant and clunky.

Chapter 3: Tools
: This chapter describes the basic tools needed to work with electronics (diagonal cutters, flush cutters, pliers, screwdrivers, etc.), along with some tools not commonly discussed in other texts, including things like crimp tools, rotary tools, step drills, professional grade soldering stations, and magnifiers and microscopes for surface-mount work.

Chapter 4: Tool Techniques

Short sections for each tool discuss its uses and applications, including the correct use of sockets, wrenches, and screwdrivers; how to solder various component types, including surface-mounted components; and how to correctly size the holes needed to mount components like switches, lamps, or printed circuit boards in a chassis or panel.

Chapter 5: Power Sources

An overview of power supplies for both DC and AC current, ranging from batteries to Variac-type devices, this chapter gives special attention to inexpensive DC power supplies in the form of plug-in modules (so-called *wall warts*). It also presents a discussion of fuses and circuit breakers and offers guidance on how to select an appropriate rating for these essential protection devices.

Chapter 6: Switches

This chapter is a survey of the types of switches available and where they are typically used. This covers conventional switches, such as toggles and panel-mount pushbuttons, along with other types, such as PCB-mounted pushbuttons and membrane-type switches.

Chapter 7: Connectors and Wiring

In electronics, almost everything connects to something, somewhere. This chapter describes the various types of connectors available, where they are commonly used, and how to assemble some of the more common types, such as DB-9, DB-25, high-density terminal blocks, and the 0.1-inch grid pin connectors found on Arduino, Raspberry Pi, and BeagleBone boards. It also covers related topics, such as soldering, crimping, and insulation displacement (IDC) techniques for connector assembly. This chapter deals mostly with those connectors that a typical human being can easily assemble without resorting to a microscope and tweezers, or a special tool that costs hundreds of dollars.

Chapter 8: Passive Components

Passive components are the framework on which circuits are built. This chapter describes commonly encountered passive components such as resistors, capacitors, and inductors, including both through-hole and surface-mounted types. It also describes how to read component markings and how to understand component ratings for power, temperature, and tolerance.

Chapter 9: Active Components

This chapter covers various types of active components, from diodes to ICs, with photos and package outline drawings to illustrate the various types. It also discusses key points to bear in mind when working with active components, such as static sensitivity, heat damage from soldering, and some of the package types available for surface-mount components.

Chapter 10: Relays

Relays might be an old technology, but they are still essential in electronics. This chapter covers the various types of relays available and their typical applications. It describes types ranging from low-current, TTL-compatible reed relays to high-power types used to control AC current. It also covers techniques for controlling a relay from a low-voltage circuit.

Chapter 11: Logic

Along with a condensed description of basic logic components (OR, NOR, AND, NAND, etc.), logic families (TTL, CMOS), and some examples of combinatorial logic circuits, this chapter also presents an introduction to microprocessors and microcontrollers, in terms of what is currently available and what you might need or encounter in your own activities.

Chapter 12: Discrete Control Interfaces

This chapter covers the basics of using a discrete signal (a single logic I/O port) to control things in the physical world. It also includes a discussion on the use of buffers, using both individual transistors and ICs, along with a discussion of current sink and sourcing considerations.

Chapter 13: Analog Interfaces

This chapter describes the basics of analog interfaces, both input and output, and includes discussions on resolution, speed, and the effects of quantization. It also covers aspects of analog I/O, such as voltage range, buffering, and circuit design considerations to reduce noise and improve performance.

Chapter 14: Data Communication Interfaces

Topics include common interfaces, from board-level SPI and I^2C to RS-232, RS-485, USB, and Ethernet. This chapter also covers wireless interfaces, such as generic 2.45 GHz devices, 802.11 wireless networking, ZigBee, and Bluetooth. Serial and parallel, the two primary interface families, are introduced, followed by a discussion of synchronous and asynchronous modes of operation. The remainder of the chapter is organized into sections that cover each topic with a high-level technical discussion, and representative component part numbers are provided where applicable.

Chapter 15: Printed Circuit Boards

This chapter is an overview of PCB design and layout, with a focus on technique rather than specific tools. The chapter starts off with an introduction to PCB technology and concepts, including circuit board substrate materials and circuit trace (or track, if you will) pattern etching and plating techniques. An example from a real project is used to demonstrate the basic steps involved in creating a double-sided PCB layout. The chapter wraps up with a collection of general guidelines and tips.

Chapter 16: Packaging

A guide to the various options available for physically housing electronics, this chapter includes a discussion of plastic versus metal, sources for chassis components, and the use of unconventional enclosures to create unique packaging prototypes. Examples are given for commercial off-the-shelf packages in the form of small plastic enclosures, metal enclosures using both aluminum and steel sheet metal, extruded aluminum packages, and heavy-gauge kits for more demanding applications.

Chapter 17: Test Equipment

A short tour of inexpensive test equipment, this chapter starts with the ubiquitous digital multimeter and moves on to oscilloscopes, signal generators, and logic analyzers. The examples include readily available, low-cost devices such as single- and dual-channel pocket digital oscilloscopes from China, and a multi-waveform signal generator module for the Arduino. The intent is to give you some suggestions that don't involve breaking the bank to purchase high-end test equipment (not that there's anything wrong with high-end gear—it's generally excellent; it just happens to be rather expensive).

Appendix A: Essential Electronics and AC Circuits

For anyone interested, or anyone who could benefit from it for their projects, this appendix presents a terse, high-level overview of basic electronics theory beyond what Chapter 1 provides. Topics covered include capacitance, series and parallel resistor and capacitor circuits, basic AC circuit theory, inductance, noise, impedance, and grounding techniques.

Appendix B: Schematics

This appendix defines the basics of schematic drawings, with examples of commonly encountered symbols. Light on text but heavy on graphics, this appendix is intended to be a place where you can quickly find the definition for a particular symbol. It also describes some available open source tools for creating schematic diagrams.

Glossary

The glossary provides definitions of many key terms and acronyms used in this book.

Appendix C: Bibliography

This appendix provides a bibliography of the suggested reference texts presented throughout the book, organized by topic.

Appendix D: Resources

This appendix includes URLs for electronics distributors, sources for mechanical components, and vendors of surplus components of various types, as well as a brief discussion of buying electronics components and other items from vendors on eBay, with some guidance and caveats.

Appendix E: Components Lists

This appendix lists most all of the IC components and modules mentioned in this book. While this collection is by no means comprehensive, it does contain enough representative parts from each category to provide a solid starting point for a new design.

Conventions Used in This Book

The following typographical conventions are used in this book:

Italic

Indicates new terms, URLs, email addresses, filenames, and file extensions.

`Constant width`

Used for program listings, as well as within paragraphs to refer to program elements such as variable or function names, databases, data types, environment variables, statements, and keywords.

`Constant width bold`
Shows commands or other text that should be typed literally by the user.

`Constant width italic`
Shows text that should be replaced with user-supplied values or by values determined by context.

TIP This element signifies a tip or suggestion.

! This element indicates a warning or caution.

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Acknowledgments

This book would not have been possible without the enduring patience and support of my family. In particular, I would like to acknowledge the photography and organizational assistance of my daughter, Seren, who put up with my fussiness and took yet another picture of something or other in the light tent for me when I didn't like the pose or lighting of the first (or second, or third) attempt. And, of course, my lovely wife, Carol, who would bring me things to eat in my shop and fret about me losing sleep.

Special thanks to Mike Westerfield for his technical review and input. It's always good to have more than one pair of eyes on the details, and Mike pointed out some rough spots that needed some editing and clarification. The end result is a better book, and it just goes to show why review is a crucial part of any development process.

The feedback from readers of the early release has been invaluable. Special thanks to those who suggested additions for the bibliography in Appendix D (you know who you are) and for the many helpful comments and constructive criticisms.

I would also like to thank the editorial staff at O'Reilly for the opportunity to work with them once again, especially Brian Sawyer for his willingness to put up with me in general, Mike Loukides for giving me this opportunity to write another book for O'Reilly, and the Atlas team for responding to my technical issues in a timely and helpful manner.

CHAPTER 1

Electrons in Motion

The field of electrical theory and electronics is huge, and it can be somewhat daunting at first. In reality, you don't need to know all the little theoretical details to get things up and running. But to give your efforts a better chance at success, it is a good idea to understand the basics of what electricity is and how, in general terms, it works. So that's what we're going to look at here.

The main intent of this chapter is twofold. First, I want to dispense with the old "water-flowing-in-a-pipe" analogy that has been used in the past to describe the flow of electrons in a conductor; it's not very accurate and can lead to some erroneous assumptions. There is, I believe, a better way to visualize what is going on, but it does require a basic understanding of what an atom is and how its component parts work to create electric charge and, ultimately, electric current. It might sound rather like something from the realm of physics (and, to be honest, it is, along with chemistry), but once you understand these concepts, things like fluorescent lights, neon signs, lightning, arc welders, plasma cutting torches, heating elements, and the electronic components you might want to use in a project will become easier to understand. The old water-flowing-in-a-pipe model doesn't really scale very well, nor does it translate easily to anything other than, well, water flowing through a pipe.

Second, I'd like to build on this atom-based model to introduce some basic concepts that will come up later as you work on your own projects. By the end of this chapter, you should have a good idea of what the terms *voltage*, *current*, and *power* mean and how to calculate these values. If you need more details on a lower level, you'll find them in Appendix A, including overviews of serial and parallel circuits, and basic AC circuit concepts. Of course, numerous excellent texts are readily available on the subject, and I encourage you to seek them out if you would like to dig deeper into the theory of electronics.

If you are already familiar with the basic concepts of electronics, feel free to skip this chapter. Just don't forget to take advantage of Appendix A and the suggested references in Appendix C if you run into a need for further details somewhere along the line.

Atoms and Electrons

In common everyday usage, the term *electricity* is used to refer to the stuff that one finds inside a computer, in a wall outlet, in the wires strung between poles beside the street, or at the terminals of a battery. But just what *is* this stuff, really?

Electricity is the physical manifestation of the movement of *electrons*, little specks of subatomic matter that carry a negative electrical charge. As we know, all matter is composed of *atoms*. Each atom has a nucleus at its core with a net positive charge. Each atom also has one or more negative electrons bound to it, each one whipping around the positively charged nucleus in a quantum frenzy.

It is not uncommon to hear of the "orbit" of an electron about the nucleus, but this isn't entirely accurate, at least not in the classical sense of the term *orbit*. An electron doesn't orbit the nucleus of an atom in the way a planet orbits a star or a satellite orbits the earth, but it's a close enough approximation for our purposes.

In reality, it's more like layers of clouds wrapped around the nucleus, with the electrons being somewhere in the layers of the cloud. One way to think of it is as a probability cloud, with a high probability that the electron is somewhere in a particular layer. Due to the quirks of quantum physics, we can't directly determine where an electron is located in space at any given time without breaking things, but we can infer where it is by indirect measurements. Yes, it's a bit mind-numbing, so we won't delve any deeper into it here. If you want to know more of the details, I would suggest a good modern chemistry or physics textbook, or for a more lightweight introduction, you might want to check out the "Mr. Tompkins" series of books by the late theoretical physicist George Gamow.

The nucleus of most atoms is made up of two basic particles: *protons* and *neutrons*, with the exception of the hydrogen atom, which has only a single positive proton as its nucleus. A nucleus may have many protons, depending on what type of atom it happens to be (iron, silicon, oxygen, etc.). Each proton has a positive charge (called a *unit charge*). Most atoms also have a collection of neutrons, which have about the same mass as a proton but no charge (you might think of them as ballast for the atom's nucleus). Figure 1-1 shows schematic representations of a hydrogen atom and a copper atom.

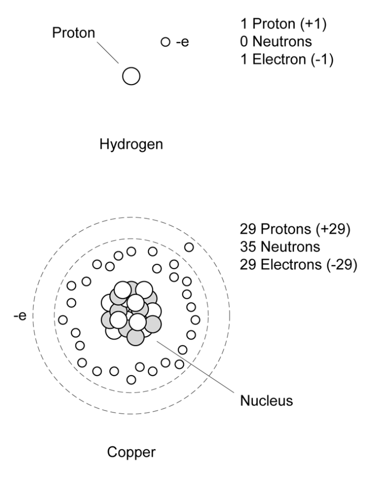

FIGURE 1-1. Hydrogen and copper atoms

The +1 unit charges of the protons in the nucleus will cancel out the –1 unit charges of the electrons, and the atom will be electrically neutral, which is the state that atoms want to be in. If an atom is missing an electron, it will have a net positive charge, and an extra electron will give it a net negative charge.

The electrons of an atom are arranged into what are called *orbital shells* (the clouds mentioned earlier), with an outermost shell called the *valence shell*. Conventional theory states that each shell has a unique energy level and each can hold a specific number of electrons. The outermost shell typically determines the chemical and conductive properties of an atom, in terms of how easily it can release or receive an electron. Some elements, such as metals, have what is considered to be an "incomplete" valence shell. Incomplete, in this sense, means that the shell contains fewer than the maximum possible number of electrons, and the element is chemically reactive and able to exchange electrons with other atoms. It is, of course, more complex than that, but a better definition is way beyond the scope of this book.

For example, notice that the copper atom in Figure 1-1 has 29 electrons and one is shown outside of the main group of 28 (which would be arranged in a set of shells around the nucleus, not shown here for clarity). The lone outermost electron is copper's valence electron. Because the valence shell of copper is incomplete, this electron isn't very tightly bound, so copper doesn't put up too much of a fuss about passing it around. In other words, copper is a relatively good conductor. An element such as sulfur, on the other hand, has a complete outer shell and does not willingly give up any electrons. Sulfur is rated as one of the least conductive elements, so it's a good insulator. Silver tops the list as the most conductive element, which explains why it's considered useful in electronics. Copper is next, followed by gold. Still, other elements are somewhat ambivalent about conducting electrons, but will do so under certain conditions. These are called *semiconductors*, and they are the key to modern electronics.

This should be a sufficient model for our purposes, so we won't pry any further into the inner secrets of atomic structure. What we're really interested in here is what happens when atoms do pass electrons around, and why they would do that to begin with.

Electric Charge and Current

Electricity involves two fundamental phenomena: electric charge and electric current. *Electric charge* is a basic characteristic of matter and is the result of something having too many electrons (negative charge), or too few electrons (positive charge) with regard to what it would otherwise need to be electrically neutral. An atom with a negative or positive charge is sometimes called an *ion*.

A basic characteristic of electric charges is that charges of the same kind repel one another, and opposite charges attract. This is why electrons and protons are bound together in an atom, although under most conditions they can't directly combine with each other because of some other fundamental characteristics of atomic particles (the exceptional cases are a certain type of radioactive decay and inside a stellar supernova). The important thing to remember is that a negative charge will repel electrons, and a positive charge will attract them.

Electric charge, in and of itself, is interesting but not particularly useful from an electronics perspective. For our purposes, really interesting things begin to happen only when charges are moving. The movement of electrons through a circuit of some kind is called *electric current*, or *current flow*, and it is also what happens when the static charge you build up walking across a carpet on a cold, dry day is transferred to a doorknob. This is, in effect, the current (flow) moving between a high potential (you) to a lower potential (the doorknob), much like water flows down a waterfall or a rock falls down the side of a hill. The otherwise uninteresting static charge suddenly becomes very interesting (or at least it should get your attention). When a charge is not in motion, it is called the *potential*, and yes, we can make an analogy between electrical potential and mechanical potential energy, as you'll see shortly.

Current flow arises when the atoms that make up the conductors and components of electrical circuits transfer electrons from one to another. Electrons move toward things that are positive, so if you have a small light bulb attached to a battery with some wires (sometimes also known as a *flashlight*), the electrons move out of the negative terminal of the battery, through the light bulb, and return back into the positive terminal. Along the way, they cause the filament in the lamp to get white-hot and glow.

Figure 1-2, a simplified diagram of some copper atoms in a wire, shows one way to visualize the current flow. When an electron is introduced into one end of the wire, it causes the first atom to become negatively charged. It now has too many electrons. Assuming a continuous source of electrons, the new electron cannot exit the way it came in, so it moves to the next available neutral atom. This atom is now negative and has a surplus electron. In order to become neutral again (the preferred state of an atom), it then passes an extra electron to the next (neutral) atom, and so on, until an electron appears at the other end of the wire. So long as there is a source of electrons under pressure connected to the wire and a return path for the electrons back to the source, current will flow. The pressure is called *voltage*, which "Current Flow in a Basic Circuit" on page 5 will discuss in more detail.

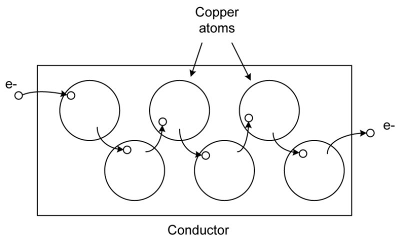

FIGURE 1-2. Electrons moving in a wire

Figure 1-3 shows another way to think about current. In this case, we have a tube (a conductor) filled end to end with marbles (electrons).

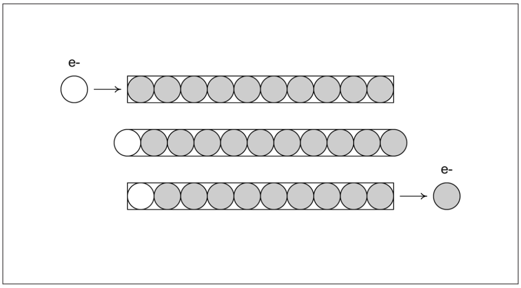

FIGURE 1-3. Modeling electrons with marbles in a tube

When we push a marble into one end of the tube in Figure 1-3, a marble falls out the opposite end. The net number of marbles in the tube remains the same. Note that the electrons put into one end of a conductor are not necessarily the ones that come out the other end, as you can see from Figures 1-2 and 1-3. In fact, if the conductor is long enough, the electrons introduced at one end might not be the ones that appear at the other end, but electrons would appear, and you would still be able to measure electron movement in the conductor.

Current Flow in a Basic Circuit

Electricity flows when a closed circuit allows for the electrons to move from a high potential to a lower potential in a closed loop. Stated another way, current flow requires a source of electrons with a force to move them, as well as a return point for the electrons.

Electric current flow (a physical phenomenon) is characterized by four fundamental quantities: voltage, current, resistance, and power. We'll use the simple circuit shown in Figure 1-4 as our baseline for the following discussion. Notice that the circuit is shown both in picture and schematic form. For more about schematic symbols, refer to Appendix B.

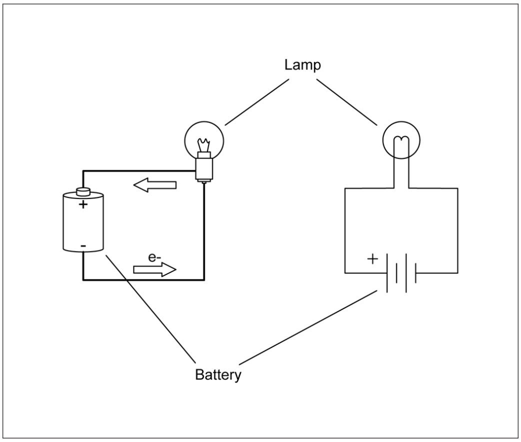

FIGURE 1-4. A simple DC circuit

A few words about the term *current* are in order here. The word has more than one meaning in electronics, which can be confusing at first. In one sense, current refers to the flow of electrons through a conductor of some kind. It is a reference to the movement of charge carried by the electrons. In the other sense, current refers to the number of electrons moving through the conductor. In this sense, it specifies the volume of electrons moving past some point in the circuit at some point in time. In other words, the measurement of current is the determination of the quantity of electrons in motion.

One way to think about current is to remember that it cannot be measured without movement, so when you see or hear the word *current*, it is usually referring to movement. To make the distinction clear, the term *current flow* is often used to mean movement of electrical charges. Static charges, even if just at the terminals of a common battery, have no current flow and hence no measurable current.

Current that flows in only one direction, as in Figure 1-4, is called *direct current* (DC). A common battery produces DC, as does the DC power supply in a typical computer system. Current that changes direction repeatedly is called *alternating current* (AC). AC is what comes out of a household wall socket (in the US, for example). It is also the type of current that drives the loudspeakers in a stereo system. The rate at which the current changes direction is called the *frequency* and is measured in cycles per second in units of Hertz (abbreviated Hz). So, a 60 Hz signal is made up of a current flow changing direction 60 times per second. When AC is used to drive a loudspeaker, a signal with a frequency of 440 Hz will be A above middle C to our ears.

By convention, DC is described as flowing from positive to ground (negative), whereas in reality, electrons flow from the negative terminal to the positive terminal of the power source. In Figure 1-4, the arrows show the electron flow. Basically, the discrepancy stems from an erroneous assumption made by Benjamin Franklin, who thought that electrons had a positive charge and flowed from positive to negative terminals. He guessed wrong, but we ended up with a convention that was already well ingrained by the time physicists figured out what was really going on. Hence we have conventional current flow and electron current flow. Although you should be aware of this discrepancy, from this point onward, we'll use conventional current flow, since that is what most of the electronics industry uses.

A *volt* (V) is the unit of measurement used for electric potential difference, electric potential, and electromotive force. When the term *voltage* is used, it usually refers to the electric potential difference between two points. In other words, we say that a static charge has a value of some number of volts (potential), but there is a certain amount of voltage between two points in a circuit (potential difference).

Voltage can be visualized as a type of pressure, or driving force (although it is not actually a force in a mechanical sense). This is the electromotive force (emf) produced by a battery or a generator of some type, and the emf can drive a current through a circuit. And even though it may not look like a generator, a power supply (like the one that plugs into the wall socket to charge a cell phone) is really nothing more than a converter for the output of a generator at a power plant somewhere.

Another way to think of voltage is as the electric potential difference between two points in an electric field. It is similar to the difference in the potential energy of a cannonball at the top of a ladder as opposed to one at the top of a tall tower. Both cannonballs exist in the earth's gravitational field, they both have potential energy, and it took some work to get them both into position. When they are released, the cannonball on the top of the tower will have more energy when it hits the ground than the cannonball dropped from the top of the ladder, because it had a larger potential energy due to its position.

These two descriptions of voltage are really just opposite sides of the same coin. In order to create a potential difference between two points, work must be done. When that energy is lost or used, there is a potential drop. When the cannonball hits the ground, all of the energy put into getting it into position against the pull of gravity is used to make a nice dent in the ground.

The main point here to remember is that a high voltage has more available electrical energy (pressure) than a low voltage. This is why you don't get much more than a barely visible spark when you short out a common 9-volt battery with a piece of wire, but lightning, at around 10,000,000 volts (or more!), is able to arc all the way between a cloud and the ground in a brilliant flash. The lightning has more voltage and hence a larger potential difference, so it is able to overcome the insulating effects of the intervening air.

Whereas voltage can be viewed as electrical pressure, current is the measure of the quantity, or volume, of electrons moving through a circuit at some given point. Remember that the term *current* can have two different meanings: electron movement (flow) and the volume of the electron flow. In electronics, the word *current* usually means the quantity of electrons flowing through a conductor at a specific point at a single instant in time. In this case, it refers to a physical quantity and is measured in units of amperes (abbreviated as A).

Now that we've looked at voltage and current, we can examine some of the things that happen while charge is in motion (current flow) at some particular voltage. No matter how good a conventional conductor happens to be, it will never pass electrons without some resistance to the current flow (superconductors get around this, but we're not going to deal with that topic here). *Resistance* is the measure of how much the current flow is impeded in a circuit, and it is measured in units of ohms, named after German physicist Georg Simon Ohm. "Resistance" on page 9 has more details about the physical properties of resistance, but for now, let's consider how resistance interacts with current flow.

You might think of resistance as an analog of mechanical friction (but the analogy isn't perfect). When current flows through a resistance, some of the voltage potential difference is converted to heat, and there will be a voltage drop across the resistor. How much heat is generated is a function of how much current is flowing through the resistance and the amount of the voltage drop. We'll look at this more closely in "Power" on page 8.

You can also think of resistance as the degree of "stickiness" that an atom's valence shell electrons will exhibit. Atoms that can give up or accept electrons easily will have low resistance, whereas those that want to hold onto their electrons will exhibit higher resistance (and, of course, those that don't readily give up electrons under normal conditions are good insulators).

Carbon, for example, will conduct electricity, but not as easily as copper. Carbon is a popular material for fabricating the components called resistors used in electronic circuits.

Chapter 8 covers passive components, such as resistors.

Ohm's Law

As you may have already surmised, there is a fundamental relationship between voltage, current, and resistance. This is the famous equation called *Ohm's law*. It looks like this:

$$E = IR$$

where *E* is voltage (in volts), *I* is current (in amperes), and *R* is resistance (in ohms).

This simple equation is fundamental to electronics, and indeed it is often the only equation that you really need to get things going. In Figure 1-4, the circuit has only two components: a battery and a lamp. The lamp comprises what is called the *load* in the circuit, and it exhibits a resistance to current flow. Incandescent lamps have a resistance that varies according to temperature, but for our purposes, we'll assume that the lamp has a resistance of 2 ohms when it is glowing brightly.

The battery is 1.5 volts, and for the purposes of this example, we'll assume that it is capable of delivering a maximum current of 2,000 milliamps (or mA) for one hour at its rated output voltage. This is the battery's total rated capacity, which is usually around 2,000 mAh (milliamp-hour) for a typical alkaline AA type battery. A *milli* is one-thousandth of something, so 2,000 mA is the same as 2 amps of current.

Applying Ohm's law, we can find the amount of current the lamp will draw from the battery by solving for *I*:

$$I = E/R$$

or:

$$I = 1.5/2$$

$$I = 0.75 \text{ A}$$

Here, the value for *I* can also be written as 750 mA (milliamperes). If you want to know how long the battery will last, you can divide its capacity by the current in the circuit:

$$2/0.75 = 2.67 \text{ hours (approximately)}$$

Power

In the simple circuit shown in Figure 1-4, the flow of electrons through the filament in the lamp causes it to heat up to the point where it glows brightly (between 1,600 to 2,800 degrees C or so). The filament in the lamp gets hot because it has resistance, so current flows less easily through the filament than it does through the wires in the circuit.

Power is the rate of doing work per unit of time, and is measured in watts. One watt is defined as the use or generation of 1 joule of energy per second. In an electrical circuit, a watt can also be defined as 1 ampere of current moving through a resistance at 1 volt of potential, and when charges move from a high voltage to a low voltage (a potential difference) across a resistive device, the energy in the potential is converted to some other form, such as heat or mechanical energy.

We can calculate power (*P*) in a DC circuit by multiplying the voltage by the current:

$P = EI$

In the case of the simple flashlight circuit, the power expended to force the current through the filament is expressed as heat, and subsequently as light when the filament gets hot enough to glow. If you want to know how much power the light bulb in our circuit is consuming, simply multiply the voltage across the bulb by the current:

$P = 1.5 \times 0.75$

$P = 1.125$ watts, or 1.125W

Let's compare this power value with the rating for a common incandescent light bulb with a 100W rating. An old-style 100W light bulb operating at 110 VAC (volts AC, typical household voltage in the US) will use:

$I = PE$

$I = 100/110$

$I = 0.9A$

Amazing! The large light bulb consumes only a bit more current than the tiny light bulb connected to a battery! How can this be?

The difference lies in the voltage supplied to the light bulbs and their internal resistance. Now that you have an estimate of the amount of current flowing through a 100W bulb, you could easily work out what its internal resistance might be. You should also be able to see why leaving lights on (or using old-style light bulbs at all) is wasteful. The current adds up, and each watt of power costs money.

Resistance

Now let's look at the phenomenon of resistance more closely, since it is such a fundamental aspect of electronics. Formally stated, 1 ohm is equal to the resistance between two points of a conductor when a potential of 1 volt produces a current of 1 ampere. This is, of course, the relationship defined by Ohm's law, discussed in "Ohm's Law" on page 8.

Resistance is a key factor in electric circuits, which is why it is one of the three variables in the Ohm's law equation. As stated earlier, every circuit has some amount of resistance, except for things like exotic superconductors. Even the wires connecting a battery to a device have some intrinsic resistance.

Switches have internal resistance, as do connectors and even the copper traces on a printed circuit board (PCB). Figure 1-5 illustrates this by showing a simple DC circuit and its resistance equivalent.

You might notice in Figure 1-5 that even the battery has some internal resistance. Appendix A discusses series and parallel resistances, and how to calculate their values, but the point here is to show how nothing is free in the world of circuits. Resistance is everywhere, as far as electrons are concerned.

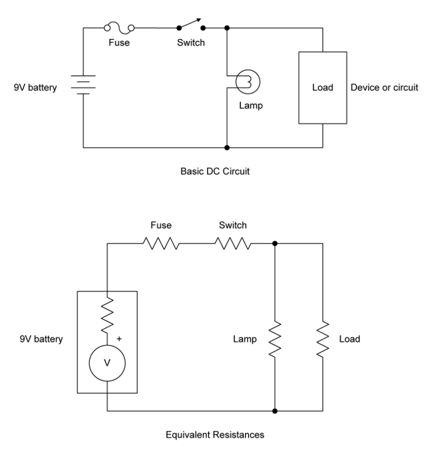

FIGURE 1-5. Circuit resistance example

Normally, this intrinsic resistance is ignored, as it tends to be small and doesn't really impact the overall operation of a device. However, if the device is a low-current one intended to run for a long time without the battery being changed, then it starts to become something to consider. Resistance to current flow means that energy is being expended pushing electrons through the resistive element, and that energy is dissipated as heat. Unless you are intentionally using a resistance as a heater (which is what electrical heating elements do), it is being wasted.

In electronics, the passive components called *resistors* are probably the most commonly used parts. Resistors come in a range of values and power ratings, from ultra-tiny little flecks for surface-mount use to huge devices used in diesel-electric locomotives to dissipate excess energy created during dynamic braking. Figure 1-6 shows a typical 1/4-watt carbon composition resistor. See Chapter 8 for more information about resistors and other passive components.

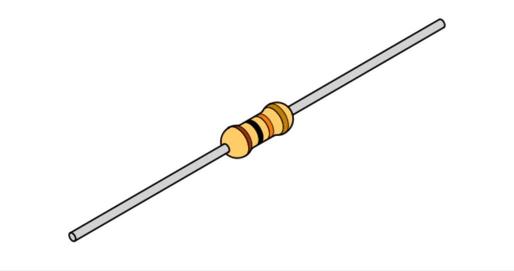

FIGURE 1-6. A typical resistor

Resistors can be used to limit current, reduce voltages, and supply a specific voltage at a particular location in a circuit. Resistance plays a big role in analytical applications such as network analysis (electrical networks, not data networks), equivalent circuits theory, and power distribution modeling.

Example: Building a Voltage Divider

You can do a lot with just a power supply of some sort, a couple of resistors, and Ohm's law. For example, let's say that you wanted to supply a circuit with 5V DC from a 9V battery. Provided that the circuit doesn't draw very much current (perhaps a few milliamps or so), and you are not too concerned about how stable the 5V supply will be, a simple thing called a *voltage divider* (shown in Figure 1-7) will do the job.

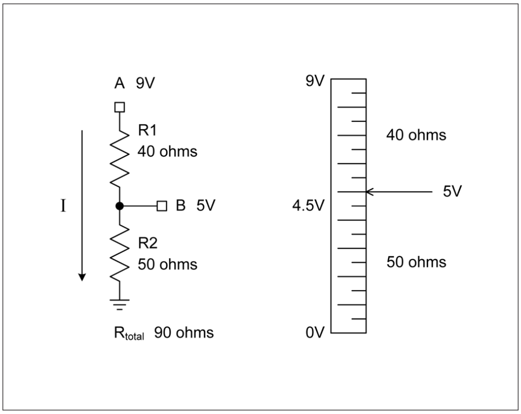

FIGURE 1-7. A simple voltage divider

We want the voltage at point B to be 5V when we apply 9V to point A. I've selected resistor values that will result in 100 mA of current flowing through both of the resistors. I've not taken into account the current consumed by the circuit connected to point B, but since the assumption here is that it will draw very little current, it won't have that big of an effect on the voltage level at point B.

Notice that the two resistors in the voltage divider of Figure 1-7 aren't the same values. One is 40 ohms; the other is 50 ohms. If both R1 and R2 were the same value, the voltage at point B would be 4.5V, not the 5V we want.

So how did I get those values? First, we determine the total resistance of the divider circuit. Since we already know the input voltage and the amount of current we want to pass through the resistors, the solution looks like this:

$$R = E/I$$

$$R = 9/0.1$$

$$R = 90$$

And, since there are two resistors in the divider, the sum of their values must be equal to the total resistance:

$$R1 + R2 = 90$$

If we use the current and the target output voltage of the divider (point B), we get the value of the second resistor, R2:

$$R2 = 5/0.1$$

$$R2 = 50$$

R1 is just whatever is left over:

$$R1 = 90 - R2$$

$$R = 40$$

The ratio between R1 and R2 and the resulting voltage at point B is illustrated graphically in Figure 1-7 by the vertical scale on the right side of the figure.

Another way to do this doesn't require any knowledge of the current through the divider, but instead uses the ratio of the two resistors:

$$V_{out} = V_{in} \times (R2/(R1 + R2))$$

Now, how long will the 9V battery last? A typical garden-variety 9V alkaline battery has a capacity rating of about 550 mAh. We can apply the same math used with the simple lamp circuit earlier. If we divide the battery's capacity rating by the current consumption of the voltage divider, we get this:

$$550/100 = 5.5$$

So, with this circuit, the battery will last for about 5.5 hours in continuous use.

As an exercise, calculate how much power this simple circuit will dissipate. Since resistors are rated in terms of both resistance and power dissipation, it should be quickly obvious that the two components will need to be rated for around 1 watt each. This circuit would overwhelm a small 1/8 watt component.

Also, I mentioned earlier that I was assuming that whatever was connected to the divider at point B wouldn't be drawing very much current. You could probably increase the values of the resistors by an order of magnitude (× 10), thereby reducing the total current to 10 mA, and still have enough margin to provide a very small current at around 5V. This would increase the battery life to 55 hours or so and significantly reduce the power rating requirement for the resistors. When you are using a voltage divider to produce a reference voltage for an active component in a circuit, the current draw is often very small (perhaps in the microamps range), since it's the voltage that matters. In cases like this, the values of R1 and R2 can be very large to further reduce the amount of current consumed by the divider.

This little exercise should make a few things readily apparent. First, you really don't want to use a voltage divider to try to create the equivalent of a power supply. Active regulators do a much better job and don't waste lots of energy as heat without doing any meaningful work. We will take a look at power supplies in Chapter 5 and active components like voltage regulators in Chapter 9.

Second, with multiple variables to work with, there is a lot of room to seek out solutions, some better than others. Don't settle on the first solution that pops up, because there might be a better way. Lastly, batteries are great for portability, but they really don't last long in continuous use when significant current is involved.

Summary

In this chapter, we've looked at the basics of atomic structure and how that contributes to how electrons move. We've also looked at the basic concepts of voltage, current, power, and resistance. In the process, we discovered that something rated for 100 watts of power at 110 volts uses only slightly more current than something at 1.25 watts at 1.5 volts, with the voltage being a major factor in the power difference.

With what you've seen so far, you should be able to determine how much power an electronic device is dissipating and determine how long a battery will last in a given situation, so long as you know the amount of current the battery is called upon to supply.

That should be enough basic theory to get things moving along, and later chapters will introduce additional concepts as necessary. If you really want to dig into the theoretical end of things to gain a deeper understanding, I would suggest one of the excellent reference works listed in Appendix C. Also note that Appendix B contains a listing of various schematic symbols commonly encountered in electronics work, as well as a write-up on using a schematic capture tool to create neat and tidy drawings of your circuits.

CHAPTER 2

Fasteners and Adhesives

Creating something new often entails attaching something to something else, and modifying something to adapt it to another purpose can entail attaching things where nothing was attached before. Then there's the issue of making sure things will stay attached. Fasteners and fastening techniques are key to creating reliable attachments, or building a solid, reliable chassis and enclosure for a circuit or electro-mechanical device. As a prelude to the upcoming chapters on tools and their uses, this chapter presents some of the more common hardware and adhesives used to fasten two or more things together. In Chapter 16, we'll look at enclosures and other packaging topics and see how fasteners and adhesives are used.

Fasteners come in a range of types and sizes. Some, such as screws and bolts, are familiar to just about everyone. Other types, such as rivets, are not as common but are widely used in a variety of applications. Still other types are designed for specialized applications. But regardless of the type or size, all fasteners are intended to do just what their name implies: fasten something to something else.

Although you might first think of nuts, bolts, and screws, a fastener isn't always a metallic part. Some reusable snap-on plastic fasteners are available for use with cardboard materials and are excellent for building disposable toys and play sets for children (among other applications), and screws and bolts are available in various nonmetallic materials, such as nylon, Teflon, wood, and ceramics.

Note that the word *fasteners* does not exclude things like adhesives (i.e., glues, silicon rubber, and other chemical compounds), and this chapter also includes a brief discussion of the various types of adhesives available. Adhesives are a handy way to attach things, and if done correctly, the bond is as strong and reliable as those made with screws or rivets. The concept of fastening can even be extended to include brazing, welding, and soldering, but this chapter won't cover those topics. Soldering is covered in Chapter 4 and elsewhere in this book. Brazing (a technique like a form of high-temperature soldering using an oxy-acetylene torch) and welding are art forms unto themselves, and there are numerous excellent reference and how-to books available. Also, many community colleges and vocational schools offer classes in both techniques.

Screws and Bolts

Various standards describe threaded fasteners, but there is no generally accepted definitive distinction between a *screw* and a *bolt*. Some sources define the difference on the basis of how the part is used, with bolts being mounted through something and tightened with a nut, and screws being inserted into a part with preformed threads or cutting their own threads as they are driven into position (*self-tapping* screws). Size also matters for naming threaded fasteners, with small parts often referred to as screws and larger pieces called bolts.

In any case, both bolts and screws use a spiral thread cut or pressed into a rod (usually metal but nylon, plastic, and wood have been used as well) to exert an axial force, which in turn is applied to hold two or more things in a fixed relationship to one another.

Figure 2-1 shows a sample of the various kinds of screws and bolts that are available. Just bear in mind that what might be a screw in one context could also be referred to as a bolt in another. This book will apply the terms *screw* and *bolt* based on the general criteria of size and usage stated previously.

FIGURE 2-1. Various screws and bolts

The variety of available screw types is staggering, and Figure 2-1 shows just a small sample. Fortunately, you don't need to be familiar with every type to make sensible choices; nor do you need to have a stockroom with stacks of containers full of fasteners to do useful work.

Distinguishing bolts from screws

The apparent ambiguity in the designation of a fastener as either a bolt or a screw is reflected in the official publication ICP013, "Distinguishing Bolts from Screws" from the US Customs and Border Protection division of the Department of Homeland Security. This document attempts to provide some guidance regarding how to determine whether a fastener is a bolt or a screw, but in the end, it still basically comes down to size and usage.

As the document puts it: "if it doesn't meet the primary criteria (and of course, if it doesn't conform to a fastener industry standard for a bolt), then it probably is a screw." In this case, the "primary criteria" is that a bolt is big and used with a nut, whereas a screw is small and not used with a nut. Except in those cases where a screw might be used with a nut (a machine screw). Or it's a really big bolt with a sharp tip that can cut its own threads. It gets confusing sometimes.

You can generally do most of the necessary fastener work you might encounter with a selection of machine screws in sizes 2, 4, 6, and 8, with a selection of lengths for each gauge, ranging from 1/4 inch long to 2 inches. A list of suggested sizes and types of machine screws to have on hand is shown in Table 2-1. The following section examines common gauge sizes in detail.

TABLE 2-1. A suggested inventory of screws (and associated washers and nuts)

Size	Type	Drive	Length
4-40	Pan	Phillips	1/4"
4-40	Cap	Hex Socket	1/4"
4-40	Pan	Phillips	1/2"
4-40	Cap	Hex Socket	1/2"
6-32	Pan	Phillips	1/4"
6-32	Cap	Hex Socket	1/4"
6-32	Pan	Phillips	1/2"
6-32	Cap	Hex Socket	1/2"
6-32	Pan	Phillips	3/4"
6-32	Pan	Phillips	1"
8-32	Pan	Phillips	3/8"
8-32	Pan	Phillips	1/2"
8-32	Pan	Phillips	3/4"
8-32	Pan	Phillips	1"

TIP For definitions of the head types and drives, see "Screw and Bolt Head Styles" on page 20 and "Screw and Bolt Drive Types" on page 19.

If you purchase the suggested hardware in Table 2-1 as stainless steel parts in boxes of 100 each, you'll spend between $2.25 to $6.50 per box, and 14 small boxes don't take up much room at all. Also be sure to get nuts, flat washers, and locking washers for each size. "Washers" on page 23 discusses the various types of washers that are available. Of course, you can always just buy small quantities of what you need from a well-stocked hardware store, but you'll pay less per piece by buying parts by the box.

TIP One of the best ways to become familiar with what fasteners are available and how they are used is to disassemble some electronic devices and observe what was used to hold things together (and, as a bonus, you might find some interesting bits to use in your own projects). You will find everything from cap head to Phillips, UTS/ANSI and metric, self-tapping types for both plastic and metal, and even some odd-looking things with star-shaped drive holes or even three slots (*Y* or *tri-wing* types, popular with some Asian manufacturers). If you have a military or industrial surplus outlet nearby, these can be a goldmine for hardware.

SCREW AND BOLT SIZES

Fortunately, unless you have a specific need to use an uncommon type of screw or bolt, you can do almost everything with five or so different sizes.

The Unified Thread System (UTS) commonly used in the US defines screws in terms of both diameter and thread pitch. The UTS is controlled by ANSI, the American National Standards Institute, and throughout this book, I'll use UTS and ANSI interchangeably when referring to bolt and screw sizes other than metric. Typical sizes encountered in electronics include diameter gauges of 2, 4, 6, 8, and 10. Common thread pitches include 40, 32, and 24. The *pitch* refers to the number of threads per unit of length in inches. So, a UTS screw or bolt size is defined as *gauge-pitch* (e.g., 4-40 or 6-32). Table 2-2 lists some common UTS screw and bolt sizes. The fractional diameter is the nearest value.

TABLE 2-2. UTS/ANSI machine screw diameter sizes

Gauge	Diameter (inches)	Decimals
0	1/16	0.06
1	5/64	0.07
2	3/32	0.08
3	7/64	0.09
4	7/64	0.11
5	1/8	0.12
6	9/64	0.13
8	5/32	0.16
10	3/16	0.19
12	7/32	0.21
14	1/4	0.24

Just because a gauge size is defined in Table 2-2, that doesn't necessarily mean that hardware in that size can be easily purchased. Fasteners in sizes 2, 4, 6, 8, and 10 are readily available. You can find other sizes (#1, for example) if you're willing to look hard enough, but if you need to special-order a gauge, a supplier won't be too interested unless you are willing to commit to purchasing a large quantity of the parts. Stick to the common sizes if at all possible. It's much easier that way.

Also be aware that with sizes of 1/4 inch or larger, the parts are often specified in diameter-pitch nomenclature, rather than gauge-pitch. In other words, while saying you want to use a 14-20 is technically correct, you may find that 1/4-20 is how the parts are stocked at the distributor or hardware store.

You should keep in mind that the gauge size numbers used with machine screws and bolts are also used with self-tapping screws, both sheet metal and wood. Be aware, however, that the actual diameter of a part can vary somewhat from the ideal value given in Table 2-2. The amount of variance depends on the tolerances applied by the manufacturer and the process used to create the threads, but it is generally no more than +/– 0.01 inches. This is important to remember when sizing holes and selecting drill bits, as discussed in Chapter 4.

In the metric-speaking world (which is almost everywhere outside of the US) a large range of metric screw and bolt types is available. These are defined in the international standard ISO 68-1, and the ISO 262 standard specifies a number of predefined sizes. Based on the standards, a metric screw with a shaft diameter of 1 mm may have a coarse thread of 0.25 mm or a fine thread of 0.2 mm. So, to specify a 1 mm screw with a coarse thread, you would use M1x0.25.

The remainder of this book will largely stick to UTS/ANSI nomenclature except when discussing things like tapping and clearance holes, but generally, everything you might

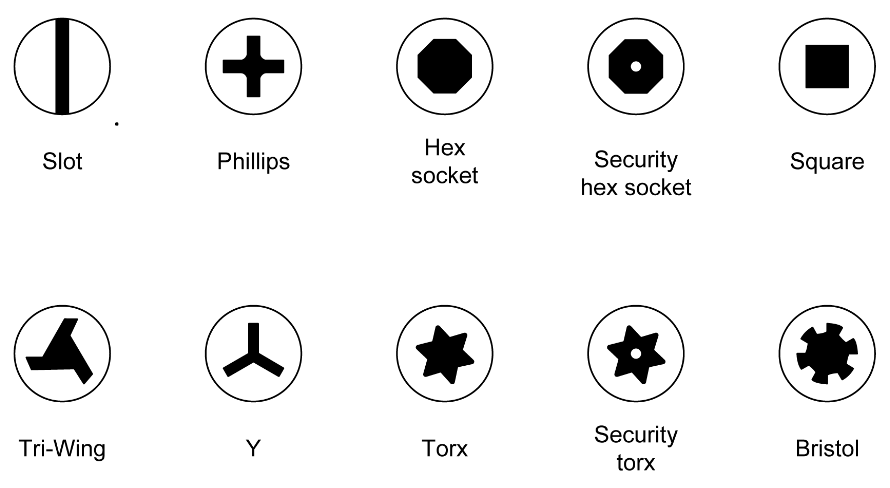

FIGURE 2-2. Screw and bolt drive styles

say about using a UTS screw or bolt also applies to its metric equivalent.

TIP It seems inevitable that eventually the entire world, the US included, will go to the metric system. In industry this has already begun, with many US manufacturers shifting to metric parts to accommodate a global market and the use of parts and subassemblies from foreign suppliers. If you want to employ some "future-proofing" into your designs, you might want to consider learning how to work with metric parts, and metric units of measurement in general.

SCREW AND BOLT DRIVE TYPES

The two most commonly encountered screw drive types are slotted and Phillips. Figure 2-2 shows the drive types you might regularly encounter, but other specialty types are also in use. These are the common names; other names are also encountered, such as cross for Phillips, and Robertson for the square drive. Browsing through the website or catalog of a supplier such as McMaster-Carr, Microfasteners, or AmazonSupply (formerly SmallParts) can be very informative.

Some types of fasteners are available with a six-sided (hex) hole for use with a hex wrench (also called a hex key or an Allen wrench). These *hex socket* types are usually found with button and cap head styles (see "Screw and Bolt Head Styles" on page 20) and are common in robotics and in scientific and metrology equipment such as interferometers, optical spectrometers, and telescopes. A hex socket drive allows for greater torque without tool slippage, which is a problem with both slot and Phillips drives.

Larger bolts often have a hex head suitable for use with a socket tool (i.e., the entire head of the bolt is the drive), and small sizes in this style are also available. The large sizes will be familiar to anyone who has ever worked on an automobile, and the small sizes can sometimes be found in scientific and military-grade equipment.

A small hex head part can be difficult to drive without a special socket wrench made specifically to seat flush around the head. Most common sockets sold at auto supply and home improvement centers will not work reliably, because they have a slightly rounded edge that will prevent the socket from fully seating on the sides of the head. The tool will likely slip and damage the head of the fastener. Chapter 4 discusses how to modify a socket to fit flush on a small hex head fastener.

If you elect to use a hex head screw or bolt, it is worth bearing in mind that while the part can be tightened (torqued) to a greater degree without tool slippage (or tool breakage) than a Phillips or a hex socket head part, it can be awkward to use in tight places where the socket to drive the screw or bolt won't easily fit. In other words, consider the tool that will need to be used to deal with the fastener in its eventual location.

Drive types such as tri-wing, Y, Torx, and other security variations are intended to discourage unauthorized access. They require special tools made expressly for that drive type, and the tools usually aren't available at the local home improvement center. Avoid them if at all possible.

TIP You can defeat a security Torx or hex socket type drive by carefully knocking out the small pin-like column in the center of the drive hole using a pin punch and a ball-peen hammer. Alternatively, you can sometimes drill out the security pin with a good drill press if you first securely clamp down the work piece and use a drill bit not much larger than the security pin. Then again, if you expect to work with these types of fasteners on a regular basis, the tools to deal with them aren't that expensive and you can find them on eBay.

SCREW AND BOLT HEAD STYLES

Figure 2-3 shows some common head types for screws and bolts. The hex head is typically found on bolts (larger than common screws), and the button and cap head types typically have a hex socket and are used with a hex wrench. Notice that the cap head is shown with knurling, which allows for hand-tightening if the head is large enough or your fingers are small enough. The other head types can have either a slot or Phillips drive, and even a hex socket drive variation is available for the flat and oval head styles.

The round and pan head styles are most common around the home. Woodworkers routinely employ flat-head wood screws to keep the screw head flush with the surface of the wood. Consumer electronics tend to use a lot of flat-head machine screws and self-tapping types, again to keep things smooth and flush.

Be aware that the flat and oval head types require a countersunk hole to seat correctly. These are typically used in situations that require low-profile (or flush, in the case of the flat head types) screws or bolts. Chapter 4 covers drilling a countersunk hole, but basically, it involves creating a hole in the material, larger than the hole for the shaft of the screw, for the screw head to seat into.

SELECTING SCREWS AND BOLTS

Selecting the appropriate screw or bolt for a particular application involves taking into consideration several factors. If you want to fasten a plastic back onto a plastic case, a self-tapping screw would do the job. The back plate of a metal chassis box is usually fastened with self-tapping sheet metal screws. The screws used to mount things to a chassis, panel, or other surface can be 8-32, 6-32, or 4-40, depending on the size and mass of what is being mounted.

As a general rule of thumb, the larger the screw or bolt, the more load it can bear. Small screws (#2, for example) are fine for lightweight tasks, but a larger #6 or #8 screw should be considered for items or situations where the screw must resist a force (as with hinges or attaching a metal panel). Also, the use of multiple screws or bolts can increase strength and reliability, but at the cost of extra weight and expense. Without knowing the type of materials being used and the forces expected, it's impossible for me to give specific recommendations for maximum loads, but Table 2-3 can serve as a rough guide.

TABLE 2-3. Machine screw clamp loads

Size	Clamp load
4-40	200
6-32	350
8-32	500
10-24	700
1/4-20	700

Clamp load is the amount of load applied to a bolted joint to hold the parts together and avoid relative motion (shear slippage). In Table 2-3 this is a maximum de-rated value derived from various references, and it assumes the lowest grade of part. It does not

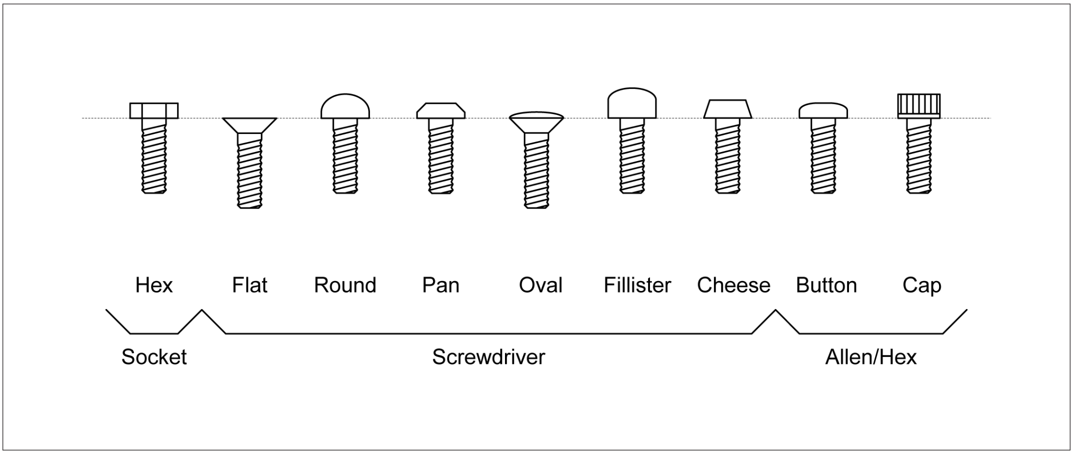

FIGURE 2-3. Common screw and bolt head types

take into account any additional stresses that may be placed on the fastener.

In general, parts with a nut tend to resist pull-out (axial failure) better than screws in a tapped hole, but the amount of the screw's threads engaged by the nut or the inside threads of a tapped hole plays a significant role. Likewise, the material the screw or bolt is used with has a big effect on the ability of the part to resist pull-out. Consider the case of a #4 stainless steel screw in a tapped hole in a piece of soft 1/10-inch (10-gauge) aluminum. Odds are, the inside threads in the hole in the aluminum will probably fail before the screw itself does, particularly if the hole was threaded using a 50% thread instead of a 75% cut. See Chapter 4 for more on threads and how to make them.

Shear strength is another consideration. If a screw or bolt is used to attach two pieces that may have a tendency to move parallel to each another, then there's a distinct risk that the fastener can be sheared off between the pieces. One way to compensate for this is to use the largest screw or bolt size possible. Another approach is to set hardened steel alignment pins into the pieces so that when they are mated, the pins will help take the stress if the pieces shift.

MIL-HDBK-60 from the US government contains a lot of useful information about threaded fasteners, along with definitions and formulas for various applications. You can download it for free at EverySpec. Fastenal also provides a good online fastener guide. Although it mainly addresses large bolts and nuts, the information can be easily scaled down for smaller fasteners.

The drive type is another important selection criteria. The two most common choices are Phillips and hex (i.e., Allen) drives. When selecting a Phillips drive, be careful not to get confused with a JIS cross-drive type screw head, which looks a lot like a Phillips but doesn't behave the same way (it won't "cam out," for example). See Chapter 4 for more on the JIS drive type.

Hex drives are popular in aerospace subsystems, military gear, and scientific instruments. Generally, you'll find hex drive screws and bolts in applications where there is a need to apply a significant and specific amount of torque to a fastener. A Phillips drive part will determine how much maximum torque you can apply by virtue of its design, while a hex drive will not stop you from twisting a hex wrench into two peices if you're not careful (or shearing the head off a bolt or screw). For this reason, hex drive fasteners are often installed with a torque wrench.

TIP Never use a slotted-head screw or bolt if you can avoid it. Screwdrivers tend to slip out of the slot, and it doesn't take much to damage the slot to the point where it is unusable. For this reason, the Phillips drive was invented about 80 years ago to minimize damage to fasteners by "camming out" when the screw stalled at maximum tightness. A Phillips or hex socket drive is a much better choice than a single-slot part.

Use a screw that is just long enough to do the job; self-tapping screws can cause damage if they drive too far, especially in the case of plastic self-tapping types. Holes that are sized and tapped for a particular screw, such as the mounting holes in the aluminum frame of a hard disk drive, will accept only a screw of a specific maximum length. A screw that is too long either won't drive in completely, or it might drive through into something that it will damage (such as a circuit board in the path of the screw).

When using a nut, also try to use the shortest possible screw. A screw or bolt that protrudes out beyond the nut can interfere with other components and might get bent. A bent screw with a nut on it can be very difficult to remove gracefully without resorting to a cutting tool of some type.

WASHERS

Washers are essential when using fasteners to create a reliable load-bearing mounting point and help prevent the screw from working itself out and coming loose over time. A flat washer under the head of the screw or bolt helps to distribute the force applied by the screw. With metal, a washer slightly wider than the head of the screw is usually sufficient. If you are attaching to something thin or soft, such as polystyrene plastic, use a larger flat washer to help spread out the stress on the material. The same reasoning applies to soft materials like wood.

Figure 2-4 shows some of the available washer styles, and Figure 2-5 shows the typical assembly order for a screw and nut with washers.

FIGURE 2-4. Various types of washers

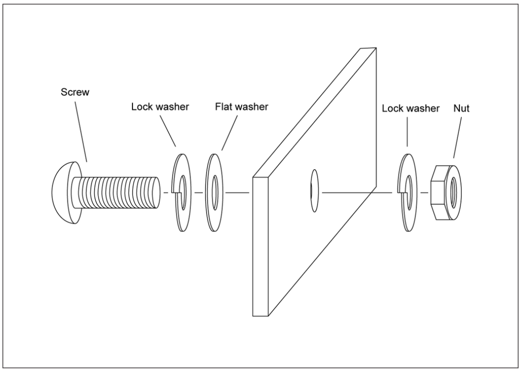

FIGURE 2-5. Using washers

A flat washer is also sometimes used as a spacer, although it is not a good idea to use a stack of washers to try to compensate for a screw or bolt that is too long to begin with. Occasionally an assembled bolt stack will include a flat washer under the lock washer beneath the nut. Although this does somewhat reduce the effectiveness of the lock washer, it also helps to prevent marring the underlying surface when the lock washer "bites" into the material.

A lock washer helps prevent a nut from becoming loose. These types of washers come in three basic styles: split-ring, inner-tooth, and outer-tooth. Figure 2-6 shows how a split-ring lock washer works.

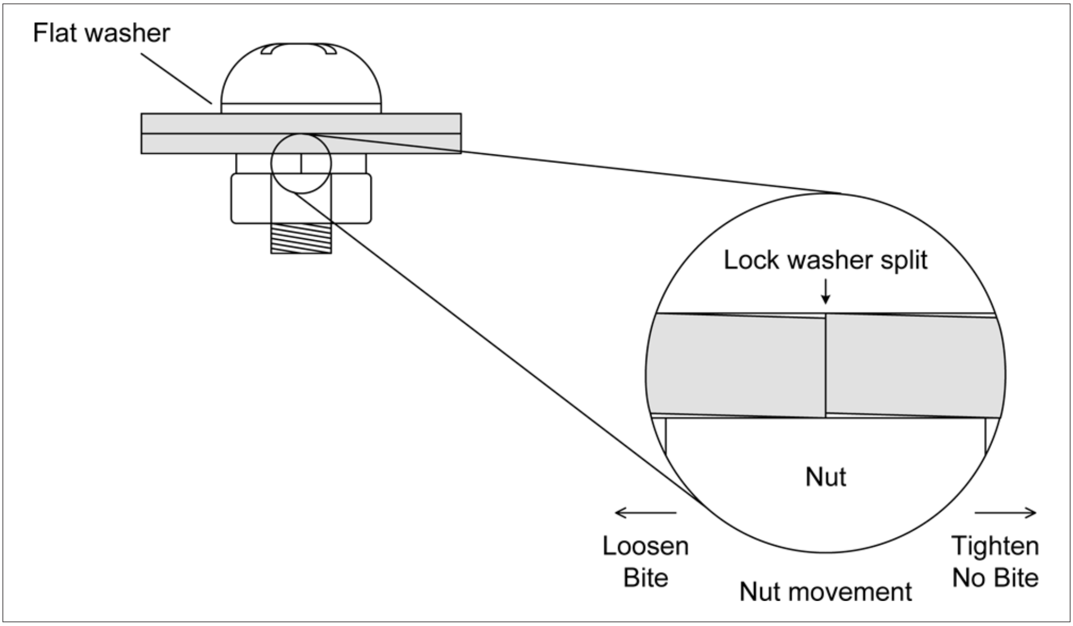

FIGURE 2-6. Split-ring lock washer

The edges of the split are bent slightly so that the nut will move over them smoothly when turned in the tightening direction, but the sharp edges will catch (or bite) on both the nut and the underlying surface if the nut moves in the loosening direction. This isn't enough to prevent the removal of the nut, but it is enough friction to help keep the nut secure. Be careful not to overtighten a split-ring lock washer, as it can be pressed flat, effectively disabling the locking capability of the washer.

The inner- and outer-tooth washers work in basically the same way, except that with these types, each tooth is bent slightly to bite into the nut and surface material if it starts to loosen. Figure 2-7 shows a selection of toothed washers. Toothed washers are often used with soft materials, such as plastic or sheet aluminum. Toothed washers are also used for establishing a ground connection, as the teeth can cut through paint or an anodized finish into the underlying metal.

FIGURE 2-7. Toothed lock washers

When you are using a screw in a prethreaded hole, there is, of course, no nut to lock, so the lock washer is placed under the head of the screw. A flat washer may also be used to protect the underlying surface, if necessary, but the smooth flat washer may reduce the effectiveness of the lock washer.

SELF-TAPPING SCREWS

Sometimes it makes sense to let a screw cut its own threads, and that is just what a self-tapping screw is designed to do. If you've ever worked with wood or wallboard (sheetrock), you've probably encountered a self-tapping screw. A self-tapping wood screw can cut its own threads as it is driven into place in a soft material such as wood.

Figure 2-8 shows a selection of different self-tapping screws.

FIGURE 2-8. Self-tapping screws

Plastic is another material that works well with self-tapping fasteners, and they can also be used with soft or thin sheet metal. The small enclosures and electronics chassis sold by companies such as Hammond and LMB often use self-tapping sheet-metal screws to affix covers and panels to the main box or chassis.

As handy as they might appear, you should avoid self-tapping fasteners if possible. If you are working with something already built with self-tapping screws, sometimes you can't avoid them, but once a self-tapping screw goes in and comes out, it will almost never go back in as securely as it did the first time. This is especially true of sheet metal, because the original hole in the metal will be deformed by the screw when it is first installed. Chapter 4 describes a handy trick you can use when reinstalling a self-tapping screw.

Rivets

Rivets are commonly used to fasten sheet material, such as the aluminum skin sections of aircraft, fiberglass panels on a golf cart, and aluminum canoes. With suitable washers or purpose-made rivets, rivets can also be used to attach sheet plastic to a metal framework.

It is interesting to note that at one time (about 100 years ago), rivets—in the form of large red-hot chunks of metal shaped like a threadless bolt—were used to build the frameworks of skyscrapers, bridges, and the *Titanic*. In fact, until the widespread acceptance of arc welding and other modern methods of attaching one piece of metal to another, rivets and large bolts were the primary fasteners for large structures.

In electronics applications, rivets come in handy for creating small metal enclosures, attaching a bracket to something like, say, a metal can for use as a 2.45 GHz antenna, or even attaching a small metal enclosure to a section of metal pipe (like a light-beam sensor or sender on a chain-link fence post).

The type of rivet most commonly used for electronics work is relatively small, about the size of a #6 screw. Figure 2-9 shows some of the sizes available. Figure 2-10 shows an example of the tool used to install rivets.

FIGURE 2-9. Small blind rivets

FIGURE 2-10. Hand-operated blind rivet installation tool

The items shown in Figure 2-9 are so-called *blind rivets*, which means that they are designed to be installed from one side of the work without requiring someone with another tool to apply pressure on the opposite side. They are sometimes also called *pop rivets*, after the brand name POP originally used for these products.

Blind rivets are available in a variety of head styles, including domed, flat, flush, and countersunk types. They also come in a range of sizes, lengths, and materials.

Blind rivets are installed with a tool that pulls a metal rod through the rivet body to cause the rivet to expand in a hole. The tool then trims off the excess length of rod flush with the exposed seat of the rivet. Chapter 4 covers riveting tools and how to use them. Chapter 16 discusses how blind rivets can be used to fabricate electronics enclosures or modify existing equipment or devices.

Adhesives and Bonding

Another way to fasten two (or more) things is with adhesives. Numerous types are available, ranging from cyanoacrylates (sometimes called "super-glue"), to single- and multi-part epoxies, to silicon rubber formulations like the adhesive used to glue the heatshield tiles onto the space shuttle. Adhesives are a science unto themselves, and some companies specialize in nothing but adhesives for special applications.

If you think you want or need to use an adhesive, it would be wise to do some research and see what is available. If nothing else, just reading the packages at the hardware store can be informative. When you are applying an adhesive, a pair of latex or nitrile gloves can save your hands (but make sure the adhesive won't attack the gloves!), and a wooden popsicle stick or medical tongue depressor can easily be trimmed with a sharp knife to make a disposable spreading and mixing tool.

GLUES, EPOXIES, AND SOLVENTS

Water-based glues work by creating a rigid matrix of linked chemical bonds in the adhesive material between two parts to be attached. Generally speaking, when the glue is "wet" it is in a liquid or semiliquid form, and the molecules in the glue can move and slide around quite easily. Wet glue has very little internal cohesive strength. It also has the ability to flow into the microscopic pits, bumps, and pores of the parts it is applied to. Some examples of water-based glues are the common white glue found in school classrooms or the wood glues used by carpenters.

For a water-based adhesive to form a tight bond, it needs to interface with the parts being bonded. With materials like wood or paper, this isn't a problem, since these are porous materials. Water-based adhesives usually don't work well with nonporous materials such as plastic or metal.

When a glue "dries" through evaporation or chemical reaction, the molecules in the glue can no longer move, and the internal cohesive force increases. Some types of glues also shrink, thereby pulling the glued parts closer to one another, while others expand slightly. The main point, however, is that the glue forms a hard interface between two parts that both adheres to the parts and is internally cohesive so it won't break apart under normal stress.

An *epoxy* is a type of adhesive that utilizes a chemical reaction (curing) to create internal cohesive bonds. Epoxy adhesives are based on an epoxy resin, which may be any of a number of compounds from what is called the *epoxide functional group*. The word *epoxy* actually refers to the cured form of epoxy resin.

An *epoxy resin* is a type of polymer that consists of chains of molecules. When the resin reacts with a hardener agent, either contained within the resin itself or applied as an additive, the reaction causes a chemical reaction involving cross-linking that is referred to as *curing*.

Epoxy adhesives come in various forms. There are one-part formulations that use light (typically UV) to start the curing action, while others work on contact with the air. A two-part epoxy consists of a resin and a hardener. These are mixed just prior to use. The shelf life of two-part epoxy is long, often on the order of years. Once the parts are mixed there is a period of time, typically between 5 and 30 minutes, when the epoxy can be worked before it starts to set and become too stiff to manipulate. Full curing can take up to 24 hours, depending on the formulation.

There is a vast range of applications for epoxy-based adhesives, and more for nonadhesive applications. Epoxies are known for excellent adhesion, good chemical and heat resistance, good-to-excellent mechanical properties, and excellent electrical insulating properties. With the appropriate formulation, epoxies can be used to bond materials such as metal, glass, wood, ceramics, plastics, and other resin-based materials (e.g., fiberglass and carbon-fiber materials). Some types of epoxies feature high thermal insulation, while other types offer thermal conductivity combined with high electrical resistance.

Unlike adhesion, *plastic bonding* is the process of causing two parts to partially dissolve at the point where they meet, and then allowing that joint to re-harden so that the two different parts actually become one. This applies only to plastics, and it is the plastic equivalent of welding two metal parts to one another. Bonding can be accomplished using heat generated by focused ultrasonic vibrations, applied by a heated metal tool, or chemically using a solvent. Here we will be looking at the chemical approach to plastic bonding; and if you have ever built a plastic model car or airplane or assembled PVC plumbing or conduit, then you are probably already familiar with plastic bonding. The ever-popular “clamshell” packaging is an example of ultrasonic thermal bonding, and cheap plastic toys are sometimes assembled with hot flat-tip tools that press a molded stub down into another piece and weld the two at that point.

Adhesives that utilize bonding work by attacking and literally melting the plastic to create a welded connection, and the plastic can react to the solvent very quickly. One chemical of this type is known as methyl ethyl ketone, or MEK, also referred to as butanone. It is particularly effective with polystyrene plastics. It also works with polyvinylchloride (PVC) and clear acrylic plastic. MEK can be purchased in small amounts at most hardware and home improvement stores. It is typically a thin liquid that will evaporate rapidly, and it must be used with good ventilation.

WORKING WITH WOOD AND PAPER

You can glue wood easily using adhesives specifically formulated for that purpose, although you can also use a general-purpose epoxy and get good results if you are careful and pick the correct one. Depending on how strong you want the joint to be, and whether or not it needs to be waterproof, you can use standard white glue, general-purpose glue, or specialty carpenter’s wood glue. Even hot glue will work for some applications.

The same general caveats for wood apply to working with paper in all its various forms. A wide range of paper products is available, from heavy poster board to corrugated cardboard. These are useful for assembling a prototype enclosure or creating a scale model of something. Common white glue works well with paper (as any creative child can testify), and most wood glues will also work. Hot glue is popular with the arts-and-crafts crowd because it adheres reasonably well in the short term and is easy to apply.

Although it might tempting because of its convenience, resist the urge to use hot glue for anything except cardboard, fiberboard, and craft projects. Hot glue can be very unreliable; it’s somewhat brittle when cool, and its adhesive properties on nonporous surfaces like metal or plastics are rather poor. It’s great for making throwaway holiday decorations, but for long-term applications, not so much. Hot glue can also deliver some nasty burns if it comes into contact with bare skin while still in the molten state.

WORKING WITH PLASTIC

Plastics are a good place to consider using adhesives, but you need to be aware of just what type of plastic you are working with. Polyethylene, for example, is often heat-fusion-bonded to seal different pieces together, as standard adhesives and resins don’t adhere to it very well. If you are working with something like polystyrene or PVC, you have a number of adhesive choices available.

TIP There are multiple methods for identifying plastics, ranging from burning a sample sliver to laboratory spectroscopy. Another way is to take a sliver or sample piece and apply the adhesive you want to use. If you are using MEK or a MEK-like solvent-based adhesive, then the sample will show signs of a reaction with the adhesive (sagging, melting, deformation, softness, etc.). If it does nothing, then you will need to consider a different adhesive formulation, like a two-part epoxy.

Epoxies are a good choice, provided that the epoxy is formulated for the materials to be bonded. The downside to epoxies is that they tend to take some time to properly cure, so if you are in a hurry, you might want to consider something else. Also, because plastics are nonporous, the glued joint may be prone to breaking if it is overstressed by being bent or twisted. If it does break, it will most likely be at the place where the epoxy meets the material; the epoxy itself is tough and usually stays intact.

When you're working with polystyrene, PVC, or ABS materials, the best choice is to use a solvent-type bond (also known as *solvent welding*), unless there is some compelling reason not to. If you purchase MEK (described in "Glues, Epoxies, and Solvents" on page 26), you might want to consider making your own "glue" rather than try to work with the MEK in its liquid form. To make it thicker and easier to use, you can dissolve some bits of scrap polystyrene into it. The resulting goo is basically what you get from a tube of model cement from the hobby store, and it's a whole lot cheaper, too.

Note that a solvent like MEK won't work with some plastics. PEX, for example, seems to be unaffected by MEK, as is nylon. For these, you'll need to select a different adhesive, or resort to bolts, nuts, and brackets.

WORKING WITH METAL

Joining metal can be challenging, because the smooth, nonporous metal surfaces don't really offer much for the adhesive to grip. Water-based glues such as white glue and wood glue won't work, and solvent-based bonding methods are useless with metal.

Some types of specialty epoxies will grip metal surfaces, if the surfaces are properly prepared. When using an epoxy to join metal parts, be sure to follow the manufacturer's directions to the letter. As with plastics, an epoxy joint with metal parts is susceptible to shear forces. In other words, it might have good tensile strength, but it can break if twisted or bent.

Another method involves the silicon rubber adhesive mentioned earlier. It comes in a variety of types and colors, with some types useful for things like caulking a shower stall, and other grades suitable for use with the gaskets on automobile engines. Some high-temperature formulations are also available (such as what was used with the space shuttle). The downside is that silicon rubber works best for attaching large, flat surfaces. It doesn't work well for something that is small or narrow, such as when you're trying to glue one plate to another at a right angle.

In reality, the two best methods for attaching metal are to use fasteners or some kind of welding process. Epoxies come in third, but there is the issue of shear weakness. Silicon rubber works if there is a lot of surface area to work with, but otherwise it might not be a good idea.

SPECIAL-PURPOSE ADHESIVES

Be careful when working with cyanoacrylate adhesives. These glues work quickly and can create strong bonds, but they should be used with caution. Cotton or wool materials can react with cyanoacrylates in an exothermic reaction, and the heat generated can be high enough to cause a fire to break out. Cyanoacrylates also tend to have low shear strength, so while you might have trouble pulling a bond apart, applying sideways force will typically break it loose. These adhesives also tend to have a short shelf life, on the order of a year in an unopened package, and less than a month after they've been opened.

Summary

There are numerous ways to attach one thing to another. The best method depends on the material, the necessary strength, the desired reliability, and how much effort you want to put into it. Starting with bolts and screws, which are very strong fasteners when used correctly, we moved on to look at rivets, and finally adhesives. We did not cover gas, arc, or spot welding here.

With the information presented in this chapter, you should be able to make informed decisions about the types of fasteners that are suitable for your projects, and also be able to identify some of the less common types when modifying or re-purposing an existing device.

Although this chapter has mentioned in passing some of the tools used, and provided some warnings about selecting the right tool for a particular fastener, Chapters 3 and 4 provide further details about tools and their correct usage. Chapter 16 presents some examples of how to select and use various fastening techniques to create finished packages.

CHAPTER 3

Tools

There is much more to tools for electronics than just screwdrivers and pliers. While most of the common tools can be found at a local hardware or home improvement store, many are unique to the electronics industry. These specialized tools have evolved over many years, in some cases starting out as modified versions of common hardware store types, and in other cases designed from the outset to fulfill a specific need.

For the most part, you shouldn't need to spend a lot of money on odd-ball tools if you stick to the common hardware described in Chapter 2 and avoid things like surface-mounted components with ultra-fine pitch leads. If you need to use an integrated circuit (IC) with something like 144 leads with hair-width spaces between the leads, then you should probably consider paying someone to mount it for you using screened solder paste and a reflow soldering system. For just a single project, it might not be worth the expense of acquiring a decent bench microscope and a fancy surface-mount soldering station and then learning to use it.

This chapter is a survey of some of the common tools you should consider owning for working with modern electronics. It is not intended to be a definitive or comprehensive guide. There are hand tools, power tools, and bench-mounted tools for tightening, cutting, drilling, and trimming. Other tools are used for soldering, inspecting, and finishing. I would suggest obtaining a selection of catalogs from companies such as Digikey and Mouser and perusing the tool sections. If you have a good electronics supply outlet nearby, it might be useful to browse its display racks to get an idea of what's available and examine the tools in person.

> ! Some of the tools described in this chapter can severely injure you if used incorrectly or carelessly. Always wear safety glasses when working with power tools, and always read and follow the manufacturer's safety precautions provided with the tool.

Screwdrivers

For every screw type there is a screwdriver. For most tasks, a basic selection of screwdrivers, such as the ones shown in Figure 3-1, is all you'll need.

FIGURE 3-1. Screwdrivers

However, if you plan on disassembling consumer electronics or a toy, then you might also need some rather odd screwdriver types. A set of miniature and specialty screwdrivers, such as the one shown in Figure 3-2, is essential for these types of situations. You can find sets like this on eBay. Just bear in mind that these imported tools are generally not made from the highest-quality metal (that's why they are so inexpensive), and they can be easily ruined if used incorrectly.

FIGURE 3-2. Miniature screwdrivers

Combination driver sets are available that use a common handle and a selection of driver bits. Figure 3-3 shows a set with slotted, Phillips, hex, Y, and other styles.

FIGURE 3-3. Combination driver set

TIP Although inexpensive combination sets might seem like the answer to all your driver needs, you should bear in mind that you get what you pay for. The tool bits in these sets aren't always made from the best metal and tend to be brittle. The handles can also become loose or even break if stressed too much. That being said, sometimes the only place to find that oddball driver you really need is in one of these imported combination kits.

Pliers

The pliers available from a hardware store or other locations are acceptable for many tasks, but they are not always ideal for working with electronics. Figure 3-4 shows a selection of typical tools you might find at an auto parts or home improvement store.

FIGURE 3-4. Selection of various common pliers

The large jaws of the common pliers are good for gripping stubborn bolts or holding a stiff spring while maneuvering it into position. But those same large jaws cannot really deal with things like resistor leads. For that type of task, you need a different tool.

Specialty pliers are available with narrow tips, and even with a 90-degree bend. Needle-nose pliers, shown in Figure 3-5, are a common tool in any electronics toolbox. But, as with any tool, they are intended for a specific set of applications, which are discussed in Chapter 4.

FIGURE 3-5. Needle-nose pliers

So-called *lineman's pliers* are a familiar tool for anyone who deals with household or industrial electrical wiring. They were originally developed for use by electrical linemen, hence the name. These tools are rugged and versatile and can be used to bend large-gauge wire, cut screws and small bolts, and pull cable through narrow channels or conduit, and some types have cut-outs to crimp lug-type connectors. They are sometimes used to hammer a screw or concrete anchor into a starting position, earning them the nickname of *electrician's hammer*. Figure 3-6 shows a typical example. You can find them at hardware and home improvement stores, online suppliers, and most electrical supply outlets.

FIGURE 3-6. Lineman's pliers

Wire Cutters

As with pliers, the typical wire cutters from the hardware store are suitable for cutting wires for home wiring and automotive work, but they are not designed for electronics. Specialty cutters are available with blades designed to cut flush against a surface to trim component leads on a printed circuit board (PCB) as close as possible, and some types have built-in retainers to prevent cut leads and wires from flying off. Figure 3-7 shows the so-called *flush cutter* type, which is most commonly used in electronics.

FIGURE 3-7. Flush wire cutters

The diagonal cutters shown in Figure 3-8, along with a pair of end cutters (also known as *nippers*), are common types of wire-cutting tools. As mentioned earlier, these are not designed specifically for electronics work, but they can, and should, be used for tasks that are too demanding for the flush cutters.

FIGURE 3-8. Diagonal wire cutters and end cutters (nippers)

Diagonal cutters come in a range of sizes, from small ones like the tool shown in Figure 3-8 to large cutting tools used by electricians and in industry. The end cutters are useful for nipping off wires close to a surface and can be used to (carefully!) remove small brads or finishing nails, provided that you are careful not to apply excessive force and put a notch in the blades.

There is one important thing to keep in mind when you are using wire cutters intended for electronics work: do not cut hard items that can create a nick or notch in the blades. In other words, use a pair of lineman's pliers or heavy cutters for things like clothes hanger wire or spring steel, diagonal cutters for large-gauge insulated wire, and flush cutters for the leads of components and thin wire only. Once your flush cutters have been nicked, that portion of the blade is useless (except perhaps for stripping small-gauge wires, but there are better tools for that).

Wire Strippers

Trying to strip the insulation from wire using something like a pair of flush or diagonal cutters is risky, at best. Unless you are very, very good, there is a distinct possibility that the wire will be nicked, and when that happens, the nicked spot can cause the wire to break. Some types of pliers include built-in wire strippers, but they don't always work that well, and they are fixed for one size of wire. A better option is a tool made specifically to strip wires, like the one shown in Figure 3-9.