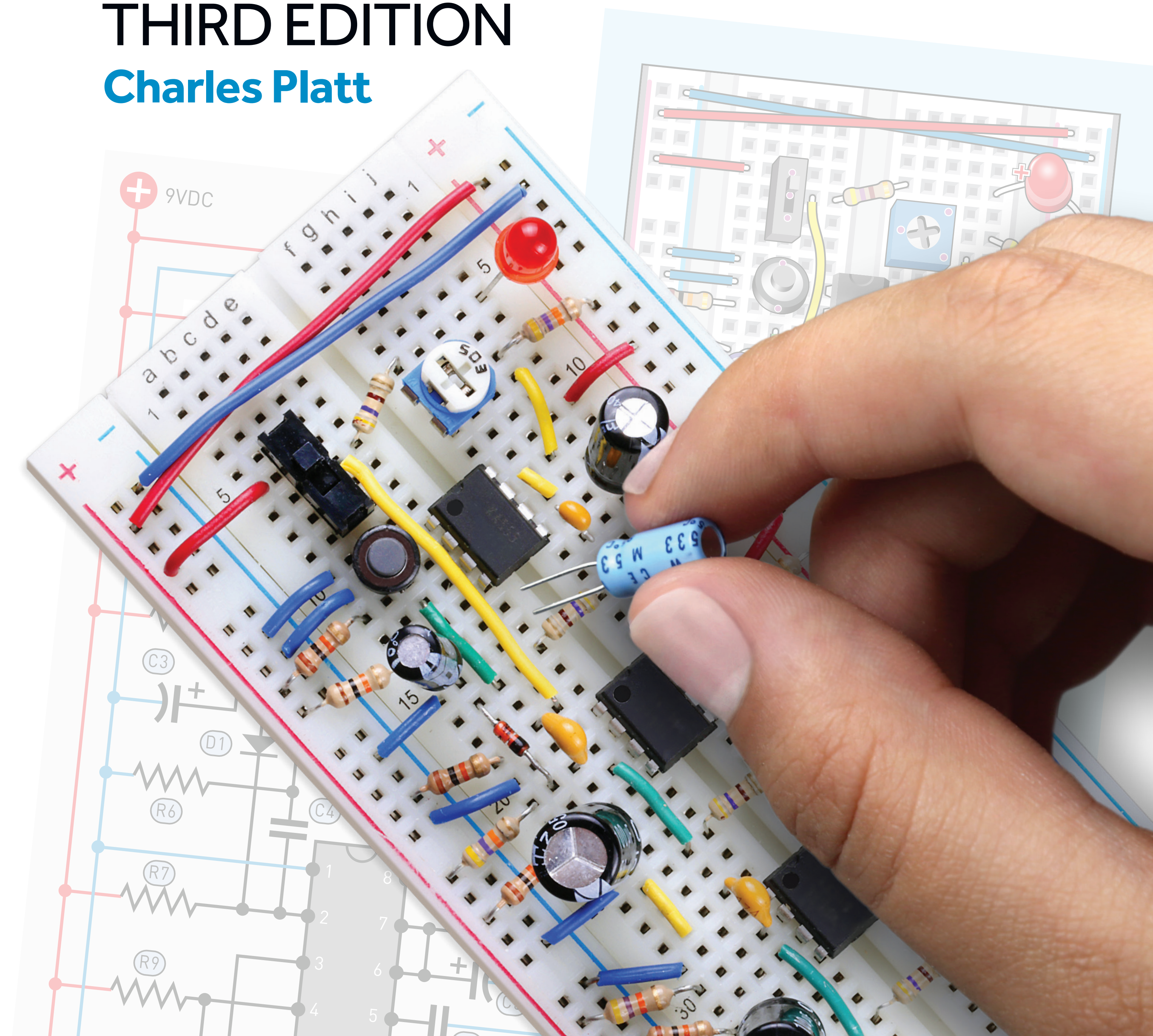
Burn Things Out, Mess Things Up — That's How You Learn.

Make:

ELECTRONICS

THIRD EDITION

Charles Platt



TECHNOLOGY & ENGINEERING / Electronics / Circuits / General

Make: ELECTRONICS THIRD EDITION

"This is teaching at its best." —Hans Camenzind, inventor of the 555 timer, the most widely used integrated circuit chip in history

A "magnificent and rewarding book... expertly illustrated with photos and crisp diagrams... This really is the best way to learn." —Kevin Kelly, in Cool Tools

Make: Electronics revolutionized intro-level guides with the concept of "learning by discovery" in 2009 and has sold more than 200,000 printed copies in the United States alone. Now this Third Edition has made the best book even better.

Beginning with the most basic concepts, you can learn from your own hands-on experiments, using affordable parts and tools.

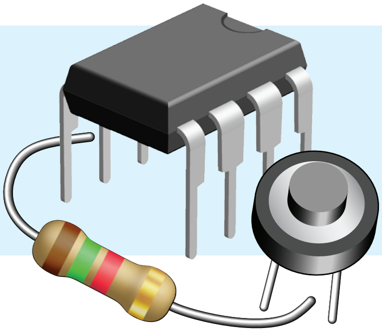
Along the way you can blow a fuse, make a relay buzz, and burn out a light-emitting diode. In *Make: Electronics* there's no such thing as a failed experiment because all experiments are a valuable learning process.

Within a few hours, you'll build a reflex tester, an intrusion alarm, a quiz game, or a combination lock — and modify them to do much more.

After learning the basics of voltage, current, resistance, capacitance, and inductance, you'll discover fundamentals of logic chips, radio, microcontrollers, and electromagnetism. Each project fits on a single breadboard, and most require no soldering.

All of the experiments use safe, low voltages, mostly supplied by a single 9-volt battery.

Today, *Make: Electronics* has attracted readers of all ages, from 10-year-olds to retirees who finally have free time in which to satisfy their curiosity about electronics.



Charles Platt is a contributing editor to *Make:* magazine, and was a senior writer at *Wired* magazine. He became hooked on electronics when he built his own telephone answering machine at the age of 15. He has said, "This is the book I wish I could have read when I was a teenager."

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Third Edition

By Charles Platt

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Acknowledgments

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Cover and back cover design by Juliann Brown, who also provided guidance regarding the preparation and production of this book. Interior design, photographs, diagrams, and schematics are by Charles Platt.

Front cover photograph by Charles Platt of hand by Neon, assisted by C. Dawes, with thumbnail by Family Dollar.

My editor, Patrick DiJusto, gave encouragement. Dale Dougherty and Gareth Branwyn allowed me exceptional freedom to write the first edition of ***Make: Electronics*** in the way that I wanted to write it, before anyone had heard of "Learning by Discovery."

Dedication

This third edition is dedicated to the memory of Hans Camenzind, a brilliant designer of analog integrated circuits who came from Switzerland to the Bay Area in the early days of Silicon Valley. For a while he worked at Signetics, then quit to create the 555 timer entirely on his own. It became the most widely used integrated circuit in history, as many billions of copies were manufactured over a period of fifty years. Even now, it is used at some point by almost everyone who learns electronics.

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Introduction

How to Have Fun with This Book

Make: Electronics reverses the traditional system for learning. Instead of beginning with a theory and then suggesting an experiment to verify it, I prefer to begin with an experiment and then encourage you to figure out the theory. I call this system Learning by Discovery, and I like it for two reasons:

- It's more interesting.
- It's closer to the way in which science is done in the real world.

In experimental science, observations can lead to a new understanding of some natural phenomenon. Why shouldn't someone learning electronics enjoy a similar experience? Discovering how components work sounds more interesting, to me, than knowing the answer before you start.

The only disadvantage of my approach is that to get full value from it, hands-on projects are necessary. Fortunately, component suppliers have developed kits for this book so that you can obtain everything you need with one-stop shopping for a relatively modest price.

What's New in the Third Edition

The first and second editions of *Make: Electronics* have sold hundreds of thousands of printed copies, and there are several foreign-language editions. I've been surprised and delighted by this success, but my book will only continue to do well if it satisfies the needs of readers. With this in mind, I have created the Third Edition.

Much of the text has been rewritten.

Most of the schematics and diagrams have been updated. Breadboard layouts now use clearer images of components.

Suggestions for tools have been updated, partly in response to feedback from readers.

Clearer photographs have been used in many instances.

Some experiments have been revised in response to feedback from readers.

A couple of the projects have been redesigned to use fewer components in circuits that I think are now easier to understand.

The last three chapters introducing the Arduino have been revised, and I added an overview of other types of microcontrollers.

I worked with a leading supplier of kits for this book in an effort to reduce and simplify the range of components needed in the experiments, so that you will be able to pursue them at lower cost.

One consequence of these improvements is that kits for the Second Edition won't provide the exact range of components that you need for this Third Edition of the book. I will mention this repeatedly, because I don't want readers to be disappointed if they buy an old kit, only to find that it doesn't quite match the new text. Please look carefully for the words "Third Edition" if you buy a kit.

The Purpose of This Book

Everyone uses electronic devices, but many people are not clearly aware of what goes on inside them.

You may feel that you don't need to know. You can drive a car without understanding the workings of an internal combustion engine, so why should you learn about electricity and electronics?

I think there are three reasons:

- By learning how technology works, you become better able to control your world instead of being controlled by it. When you run into problems, you can solve them instead of feeling frustrated by them.
- Learning about electronics can be fun, so long as you approach the process in the right way. Also, it is affordable.
- Knowledge of electronics can enhance your value as an employee, or perhaps even lead to a whole new career.

Messing Things Up

One important aspect of Learning by Discovery is that you should expect to make mistakes. A circuit may not work, or you may burn out some components.

I think of this as a positive aspect, as mistakes are a valuable way to learn. I want you to burn things out and mess things up, to see for yourself the behavior and limitations of the parts that you are dealing with. The very low voltages used throughout this book may damage sensitive components, but they will not damage you.

Never be afraid to make errors. Transistors and LEDs are inexpensive and easy to replace.

Will It be Difficult?

I assume that you're beginning with no prior knowledge. Consequently, the first few experiments will be extremely simple, and you won't even use a prototyping board or a soldering iron.

I don't believe that the concepts will be hard to understand. Of course, if you want to study electronics more formally and do your own circuit design, that can be challenging. But in this book I have kept theory to a minimum, and the only math you'll need will be addition, subtraction, multiplication, and division. You may also find it helpful (but not absolutely necessary) if you know how to multiply and divide by 10 by moving decimal points from one position to another.

How This Book Is Organized

Most of the information is presented in tutorial form, with just a few sections that are intended for future reference.

I have introduced concepts and topics in a cumulative sequence. You can dip into the book at random, but the experiments in later chapters require knowledge that you gain in the earlier chapters, so I suggest that you proceed through them in numerical order, skipping as few as possible.

If Something Doesn't Work

Usually there is only one way to build a circuit that works, while there are hundreds of ways to make mistakes that will prevent it from working. Therefore, the odds are against a happy outcome if you don't work in a methodical manner.

I know how frustrating it is when components just sit there doing nothing, but if you build a circuit that doesn't work, getting annoyed with it is counter-productive. The only way to find the problem is by examining every detail systematically.

All of the experiments have been bench-tested, so I know that the circuits are good. If something doesn't work for you, these are the most likely problems:

- You made a wiring error. Everyone makes wiring errors; I made one myself, just today. Your chances of seeing the error will improve if you walk away from your work table for half an hour, and do something else before returning to take another look.
- You may have overloaded a component such as a transistor or a chip, so that it doesn't work anymore. Try to keep some spares, just in case.
- There may be a bad connection between a component and a breadboard. Try wiggling loose components, measuring voltages, and if necessary, moving key components to a slightly different location on the board.

I will have more detailed advice on fault-tracing later in the book. I'm mentioning the topic here because I need to advise you on your ultimate recourse if you can't get a circuit to work: Unlike most writers, I maintain an email address that you can use to contact me directly. All I ask is that you should follow some guidelines.

Asking a Question

My time is obviously limited, but I try to answer all messages. Please be patient. Sometimes I can reply the same day, but at other times I may take a week to respond.

If you contact me, please:

- Attach photographs of any project that doesn't work. I must be able to see details such as the colors of stripes on resistors.
- Tell me which project you have been working on, and mention the title of the book in which it appears. Bear in mind, I have written several books about electronics, so I need to know which one you are using.
- Describe the problem clearly! Tell me about the problem in the same style as if you were describing a physical symptom to a doctor and asking for a diagnosis.

Send your message to

`make.electronics@gmail.com`

and put HELP in the subject line.

Reporting a Mistake

When I'm writing a book, I have even more ways to make mistakes than when you are building a circuit. Naturally I do everything I can to minimize errors, but if you find one, please report it. You can use my personal email address for that purpose, or you can go to the "errata" page maintained by O'Reilly and Associates, who distribute this book. The advantage of writing to me is that I can respond personally to you and discuss the problem if necessary. The advantage of the O'Reilly system is that you can read other people's reports, and see if you have run across something that has already been resolved. Also, after you make a report to the O'Reilly web site, other people can read it. The O'Reilly site is here:

`www.oreilly.com/catalog/errata.csp?isbn=9781680456875`

Receiving Updates

Even if you don't have any problems or requests, I encourage you to register your email address with me. I will be able to use it for the following purposes:

- I will notify you if any significant errors are found in this book or in its sequel, *Make: More Electronics*, and I will provide workarounds.
- I will notify you of any errors or problems relating to kits of components sold in association with this book or in *Make: More Electronics*.
- I will notify you if there is a completely new edition of this book, or of my other books. These notifications will be only at intervals of one or two years.

I won't use your email address for any other purpose, and I won't sell it or share it with anyone. (I wouldn't actually know how to sell email addresses, or who might want to buy them.)

If you register your email address, I will send you an unpublished electronics project with construction plans as a two-page PDF. It will be fun, it will be unique, and it will be relatively easy. You won't be able to get this in any other way.

The reason I am encouraging you to participate is that if there's an error in my work, and I have no way to tell you, and you discover it later on your own, you're likely to get annoyed. This will be bad for my reputation, so I want to avoid a situation where you have a complaint.

Just send a blank email (or include some comments in it, if you like) to

`make.electronics@gmail.com`

Please put REGISTER in the subject line.

I have to process emails manually, because sometimes people want a personal reply, even when they are just registering. Do not expect an immediate automated registration process! If I go on vacation, you may not receive your "special bonus project" for a couple of weeks. But you will get it eventually. Delays are the inevitable consequence of me doing things on my own.

Going Public

If you get frustrated, you may want to complain, and one way in which people complain is in reader reviews, especially on amazon.com. If you want to do this, please contact me first to see if I can address your complaint.

Be aware of the power that you have as a reader, and please use it fairly. A single negative review can create a bigger effect than you may realize. It can certainly outweigh half-a-dozen positive reviews. In a couple of cases, people have been annoyed over small issues such as being unable to find a source for a component. I would have been happy to help them if they had asked me.

Online sales are my primary source of income, and my four-and-a-half-star rating is important. Of course, if you simply don't like the way in which I have written this book, you should say so.

Going Further

After you work your way through *Make: Electronics,* you will have grasped many of the basic principles involved. I like to think that if you want to know more, my sequel *Make: More Electronics* is the ideal next step. It is slightly more difficult, but uses the same "Learning by Discovery" method. My intention is that you will end up with what I consider an "intermediate" understanding of electronics.

I am not qualified to write an "advanced" guide, and consequently I don't expect to create a third book with a title such as *Make Even More Electronics.*

You may consider buying the reference books that I wrote: *The Encyclopedia of Electronic Components* is in three volumes, two of which were written in collaboration with a very smart researcher named Fredrik Jansson. The components are listed by category, so that if you look one up and it isn't exactly what you want, the very next one in the book—which you may have never heard of—could be the answer to your problem.

And just in case you know someone who is younger, with a short attention span, I wrote a much briefer book titled *Easy Electronics* which I like to think is the simplest possible introduction to basic ideas. A kit is available for that book, and the projects are so easy, you don't even need tools to assemble them. Imagine that: A hands-on book that doesn't require tools!

If you have an interest in fabricating things, I must mention my book *Make: Tools,* which is a guide to using hand tools, following the same hands-on approach as *Make: Electronics.* It begins by describing the use of a hand saw, and ends by showing you how to build little enclosures out of plastic—which could be just the thing for your electronics projects.

—Charles Platt

Unavailable Components

Early in 2023 I was surprised to learn that a component required for several projects in this book would be unavailable for six to twelve months. The component is an **LM7805** voltage regulator made by Texas Instruments. Although it has been a popular choice for more than 50 years, apparently old stocks were depleted before a new version could be manufactured and delivered.

If you buy a kit for the projects, a compatible regulator will be included. If you buy your own components, you can use a substitute from a different manufacturer. The L7805CV or MC7805ACTG will work instead of the LM7805. See Appendix B for a list of online component suppliers and advice about using their web sites.

What if supply-chain issues cause other parts to be temporarily unavailable? You can follow these steps:

1. Try multiple vendors online. Again, see Appendix B for advice.
2. Check eBay, where obsolete parts are often available, especially from suppliers in Asia.
3. Go to a large U.S. source such as `www.mouser.com` and search for only the numbers in the middle of the part identifier. In the case of an LM7805CV, search for 7805 and then select the type of component from the list that should pop up. In this example, you should see Voltage Regulator in the list. Before buying a substitute part, compare its datasheet with the datasheet of the original component. Experiment 2 in this book provides guidance for reading datasheets.

If you are still unable to find a necessary component, contact me at `make.electronics@gmail.com` and put the word HELP in the subject line.

Section One

The Basics

This section contains experiments 1 through 5.

In Experiment 1, I want you to get a taste for electricity—literally! You'll experience electric current and discover the nature of electrical resistance.

In experiments 2 and 3 you'll use a meter to measure current and voltage, and in Experiment 4 you'll calculate wattage. Along the way you can burn out an LED, blow a fuse, and deduce a fundamental law in electronics.

Experiment 5 will be an entertainment, using everyday items to generate electricity on a tabletop.

These experiments will clarify some important concepts. Please give them a try before venturing into the rest of the book, even if you have some prior knowledge.

Necessary Items for Section One

Each section of this book begins with pictures and descriptions of the tools, equipment, components, and supplies that you will need. If you lack experience in buying some of these things, you'll find more details in Appendix A, beginning on page 290. If you need to know about where to find components and supplies online or in stores, sources are listed in Appendix B, beginning on page 299.

If you prefer not to buy your own components, at least two ***kits*** are currently available, containing parts that you need for projects in this book. The kits are created by independent suppliers, and I have no control over them or financial interest in them, but I have verified that the components are correct. The suppliers are listed in Appendix B.

Kit vendors may ship their products overseas, but unfortunately postage from the US to other countries is expensive because the United States Postal Service is not government-subsidized. If you live outside of the US, you may do better to buy components from Asian sources, where postal rates are lower and the components themselves are cheaper.

The Multimeter

A handheld ***multimeter*** is the most essential tool when you are learning electronics. It will tell you what's going on inside a circuit, just as an MRI machine tells a doctor what's happening inside the human body.

The "multi" in "multimeter" means that it can measure multiple functions, the most important ones being voltage, current, and electrical resistance. When electronics engineers refer casually to "a meter," they probably mean a multimeter. Initially it may appear complicated or intimidating, but really it's simpler than a modern phone, and no more difficult to use than a camera.

The type of meter you need is properly known as a ***digital multimeter,*** because it has a digital display. You can sometimes find an ***analog multimeter*** which moves a needle across a scale, but it's not so easy to use, and I don't recommend it.

One of the smallest, simplest meters that I have seen is shown in Figure 1-1. Its specification was set by one of the kit manufacturers for this book, referenced in Appendix B, but you can find similar meters online. If you want to minimize the amount that you spend, a product like this will be sufficient to take you through all the experiments from 1 through 30, and you can skip the rest of my discussion regarding meters. On the other hand, if you want to know how you may benefit by spending a little extra money, read on.

Auto vs. Manual

The most obvious feature that you can get in a more expensive meter is *auto-ranging*. To explain this, imagine that you want to measure temperature. If you're using an oven thermometer, you'll be happy if it's accurate within five degrees in a range from 200 to 500 degrees Fahrenheit. But if you want to measure body temperature, you'll want an accuracy of maybe 0.1 degrees in a narrow range from 95 to 105.

The situation is similar when measuring voltage or other values in electronics. Sometimes you're interested in low numbers and high accuracy, but other times you want high numbers, and you'll accept less accuracy.

A *manual-ranging* meter requires you to choose a range of values by turning a dial before you make the measurement. For example, to test the voltage of a 1.5-volt AA battery, you would set the meter to measure up to 2 volts, after which it will tell you the actual voltage with good accuracy.

An *auto-ranging* meter would sense the voltage and choose an appropriate range by itself. That sounds nice, and auto-ranging meters are becoming more affordable—but personally, I don't really like them. The meter takes a couple of seconds each time it tries to decide which range to use, and I tend to be an impatient person. Also, because you didn't select the range, you won't know immediately what the numbers mean on the display. Suppose you see `1.48`. Would that be volts or millivolts? The display will show a little V or mV to tell you, but if you forget to look, mistakes are possible.

- I suggest you should use a manual-ranging meter. You'll have fewer chances to make errors, it should cost less than a comparable auto-ranging meter, and it will be less frustrating, if you're impatient like me.

How do you tell if a picture on a web site is of an auto-ranging meter or a manual-ranging meter? If a meter does auto-ranging, usually the product description will tell you—but when in doubt, inspect the dial on the front. An auto-ranging meter won't have a lot of numbers, and may look like the example in Figure 1-2. A manual-ranging meter may look more like the one in Figure 1-3.

The rest of my discussion about meters will mostly refer to those that do manual ranging.

Figure 1-1. A bare-bones digital multimeter. The squares behind it are at intervals of 1 inch.

Figure 1-2. An auto-ranging meter.

Figure 1-3. A manual-ranging meter.

The Price

Offering advice on how much to spend when buying a meter is like advising someone on buying a car. The ratio between the price of the cheapest car and the price of the most exotic model may be around 100:1, and the same is true of meters. Also, prices may change over time.

I'll address this issue by referring to the meter in Figure 1-1 as the ***baseline model***. What will you gain if you buy a meter that costs more?

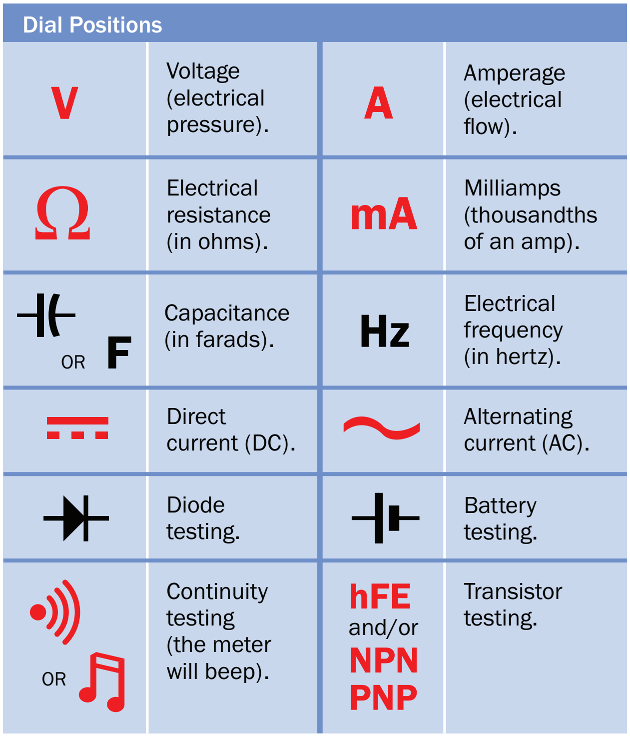
One answer may be longevity. I haven't used that particular meter for a prolonged period, but generally speaking, the contacts of the selector switch on the front of the meter may wear out over time. This may not matter to you if you don't know, yet, about your long-term interest in electronics.

You can also acquire more features by spending more money, but this is a difficult topic, because features entail some terminology. I haven't explained anything about voltage and amperage yet, let alone transistor testing—so I'll just show you the symbols and abbreviations that you are likely to see around the dial on the front of a meter, and I'll suggest which ones are important. You'll learn their exact meaning as you continue through the book.

In Figure 1-4, the items in red are essential. The ones in black are nice to have, but not essential for the experiments in this book.

Meter manufacturers are constantly coming up with additional features that look impressive, but many of them aren't very useful. Here are some examples that you don't really need:

- ***NCV*** means "no contact voltage" testing. When you hold the meter near an electrical outlet or a wire in your home, the meter will tell you if voltage is present. This is not relevant to *Make: Electronics*.
- ***Temperature measurement.*** The meter may be able to find out if a component is overheating, but for our purposes, touching a component with your finger will be good enough.
- ***Max/Min*** and ***Hold*** buttons. Useful if you are trying to capture a value that varies rapidly, but you are unlikely to be doing that.



Dial Positions			
V	Voltage (electrical pressure).	**A**	Amperage (electrical flow).
Ω	Electrical resistance (in ohms).	**mA**	Milliamps (thousandths of an amp).
—|(— OR **F**	Capacitance (in farads).	**Hz**	Electrical frequency (in hertz).
⎓	Direct current (DC).	~	Alternating current (AC).
—▶|—	Diode testing.	—|▌—	Battery testing.
🔊 OR ♫	Continuity testing (the meter will beep).	**hFE** and/or **NPN** **PNP**	Transistor testing.

Figure 1-4. The most widely used symbols and abbreviations selectable on multimeters. Those in red are essential.

- ***Backlighting*** of the display. Generally you'll use a good desk lamp when working with components, in which case your meter does not need backlighting.

The six letters and symbols in the top half of Figure 1-4 are often preceded by ***multipliers***. For instance, **m** is a multiplier with a value of 1/1,000, so the term **mV** means 1/1,000 of a volt, which is a ***millivolt***. The Greek letter **μ** (pronounced "mew") is a multiplier with a value of 1/1,000,000, so the term **μA** means 1/1,000,000 of an amp, which is a ***microamp***. Multipliers are summarized on the next page in Figure 1-5.

- Note that a lowercase **m** means "divide by 1,000." Uppercase **M** means "multiply by 1,000,000." Try to avoid getting them mixed up!

At the bottom of Figure 1-5 I have shown the ranges that you may find in a meter. Some meters don't use range values beginning with 2; their values may begin with 4, as in 40, 400, 4K, and so on. Some meters have range values beginning with 6. For the experiments in this book, I don't feel there's a particular advantage either way.

Multipliers			
p	"pico" 1/1,000,000,000,000	**m**	"milli" 1/1,000
n	"nano" 1/1,000,000,000	**k**	"kilo" x 1,000
µ	"micro" 1/1,000,000	**M**	"meg" or "mega" x 1,000,000

Ranges						
V (volts) DC	200m	2	20	200		
V (volts) AC	200m	2	20	200		
A (amps) DC	200µ	2m	20m	200m	10 or 20	
A (amps) AC	200µ	2m	20m	200m	10 or 20	
Ω (ohms)	200	2K	20K	200K	2M	20M
F (farads)	2n	20n	200n	2µ	20µ	200µ

Figure 1-5. Multipliers and ranges that are often used by meters.

A wider range of values is nice to have, but may entail spending more money. I think the red values are the most important, while the ones in black are optional.

Where **F** (farads) is concerned, the range that I've shown is irrelevant if your meter doesn't measure this unit—but if it does, these are the values you would hope to find.

Now I'll show you a couple more meter dials to illustrate how the ranges appear in real life. In Figure 1-6 the panel around the circular selector is divided into sections, each identified with a letter or symbol such as **V** or **A**. **V** is the Volts section. This range applies to both AC and DC, selectable by a switch, which I have circled. If you aren't entirely sure what the difference is between AC and DC, this isn't important right now. Notice that the range from 200mV to above 200V is a little better than my suggested range in Figure 1-5.

Continue around the dial, and you will see that the important items from Figure 1-4 are all there, circled, and the ranges are complete. This meter looks like a good choice.

Now check Figure 1-7. This meter doesn't have a switch to select AC or DC. Instead, it provides dedicated positions on the dial. On the left, you see letter **V** with the symbol that means DC. On the right, another **V** has a wavy line beside it which means AC, and refers to the two white switch positions beside it. The lightning-bolt symbol simply means "caution," and indeed you should be cautious if you are planning to measure 600 volts, although I can't imagine when you might want to. Low voltages are more important for our purposes, and this meter doesn't have a low range for AC volts. I'm not happy about that, because you may want to measure fluctuating voltages sometimes—in the output from a timer chip, for instance.

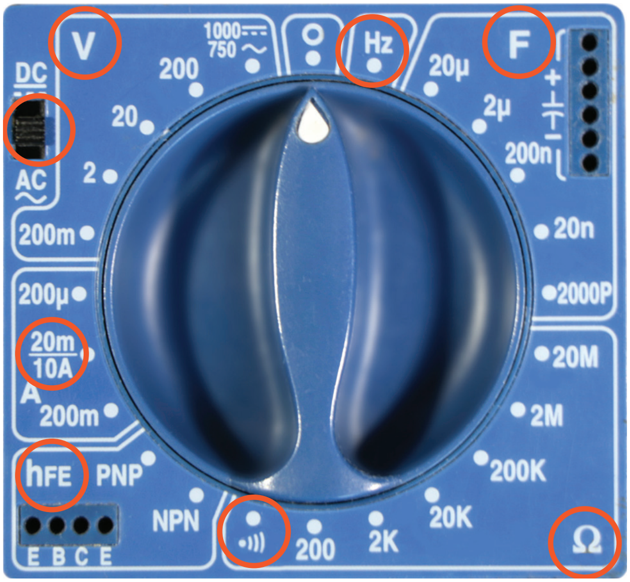


Figure 1-6. The dial of a meter that is able to perform all the functions which I think are desirable in this book.

I don't see any provision for measuring AC amps. There's a letter **A** followed by the symbol for DC, but no letter **A** followed by a wavy line for AC. That's a bit disappointing.

Another drawback of this meter is that it cannot measure capacitance in farads. Wait—what about that letter **F**, which I circled? No, it has a degree symbol beside it, so it means "degrees Fahrenheit." That's a bit misleading, especially as the meter is not shipped with a temperature probe, so you have no way to use this feature.

Lastly, I have circled **2M**, which is the upper limit for measuring electrical resistance. Really 20M would be better. Overall, I'm not impressed by this meter. You could still use it for the experiments in the book, but it costs more than the baseline model in Figure 1-1 and doesn't offer significant additional value for money.

Figure 1-7. Inspecting this meter dial reveals that some desirable features are missing. See text for details.

So how much money should you be willing to spend? Look online for a meter such as the baseline model in Figure 1-1, and whatever it costs, think of that amount as $B. If you spend between twice and four times $B, you should be able to get all the features that I have recommended. The meter in Figure 1-3, which I bought for testing while I was writing this book, cost about $B x 3, and has done well. Moving up the price scale, the autoranging meter in Figure 1-2 cost $B x 6.

In figure 1-8 you see my favorite meter at the time of writing. Notice that it displays four digits. Some cheaper meters have started to appear with four-digit displays, but an extra digit doesn't necessarily mean that the electronics inside the meter are ten times more accurate than in a 3-digit meter. You'd have to compare the manufacturer's specifications carefully to find out. For the purposes of this book, 4-digit accuracy is not necessary.

Figure 1-8. This model costs about 20 times as much as the one in Figure 1-1.

The only problem with the meter in Figure 1-8 is that it costs about $B x 20. I regard it as a long-term investment. I'm happy with its accuracy, and I'm hoping it will last for many years, but these considerations may not be important if you don't know, yet, how interested you are in electronics.

If you have read all the suggestions above, but you still feel unsure about which meter to buy, browse ahead a little to get an idea of how you will be using a meter in experiments 1, 2, 3, and 4. Then make your decision.

This concludes my dissertation on meters. Your other purchasing decisions will be simpler.

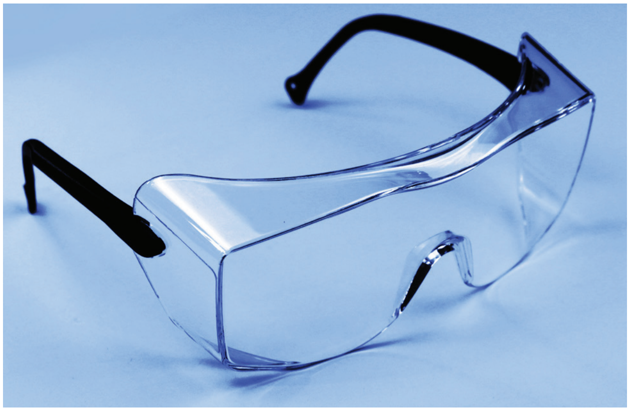


Figure 1-9. Safety glasses.

Safety Glasses

From time to time, there may be a slight risk to your eyes when you are working on electronics projects. For instance, when you are snipping a brittle piece of wire sticking out of a component such as an LED, a fragment could fly up toward your face.

Any cheap safety glasses will provide adequate protection, or regular eyeglasses are an acceptable substitute. Simple safety glasses are shown in Figure 1-9.

Test Leads

You will use *test leads* (pronounced "leeds") to connect components in the first few experiments. The type of leads I am referring to are *double-ended*.

Surely, any piece of wire has two ends? Yes, but in this case the term means that each end is fitted with an *alligator clip* as shown in Figure 1-10. Each spring-loaded clip can make an electrical connection by grabbing something and gripping it securely, freeing you to use your hands elsewhere. For the experiments in this book, very short leads are good, like the ones shown. Longer ones will work, but they tend to get tangled.

You don't want the kind of test leads that have a small single-pin plug at each end. Those are sometimes known as *jumper wires*.

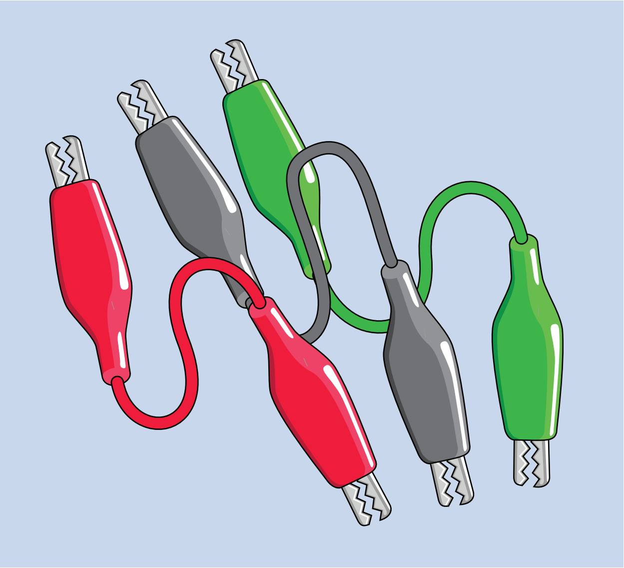


Figure 1-10. Test leads.

Power Supply

Almost all the experiments in this book will use a power source of 9 volts. You can obtain this from an everyday 9-volt alkaline battery of the type sold in supermarkets and convenience stores. It doesn't have to be a name brand. Later I'll suggest an upgrade to an *AC adapter*, but you don't need that right now.

A 9-volt battery has positive and negative terminals. Don't get them mixed up! If the positive terminal is not clearly identified, tag it with a red marker pen.

- Only use a 9-volt *alkaline battery* for experiments 1 through 4. Do not try to use a larger battery, or a battery that delivers more than 9 volts. Note that lithium batteries can be hazardous, and should not be used for any projects in this book.

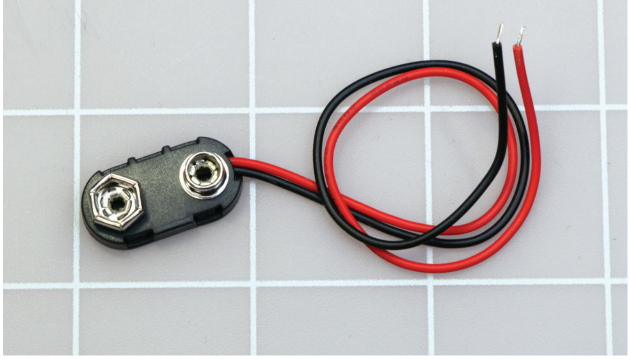


Figure 1-11. A connector for a 9V battery.

Battery Connector (optional)

My illustrations will show alligator test leads clipped onto the terminals of a 9-volt battery, but if you want to make a more secure connection, you can buy a connector which has snaps to fit your battery terminals and two wires with bare ends, as shown in Figure 1-11.

Fuse

A *fuse* interrupts a circuit if too much electric current passes through it. You will need a couple of glass cartridge fuses of the kind shown in Figure 1-12, or you can use automotive fuses available from auto parts stores. Either way, you will need one fuse rated for 1 amp and one rated for 3 amps (the cartridge type will have 1A and 3A engraved on their steel end caps, respectively). This illustration is a closeup view of a 2AG fuse that has a diameter of about 5mm.

Cartridge fuses are often rated for 250 volts, but any rating of 10 volts or higher will do. (The term "rating" means the maximum value the manufacturer thinks is appropriate for this product.)

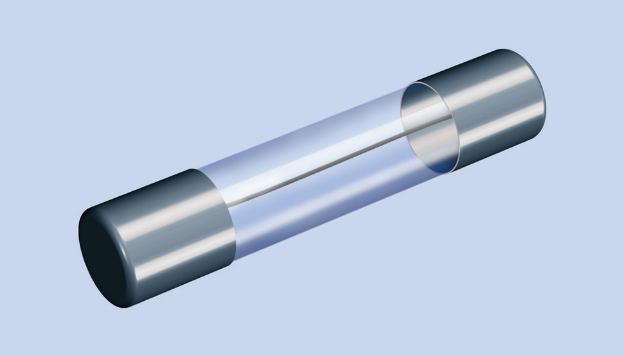


Figure 1-12. Closeup view of a 2AG fuse, 5mm in diameter.

Light-Emitting Diodes

More commonly known as ***LEDs***, they come in various shapes and forms. The ones we will be using are properly known as ***LED indicators***, and are often described as ***standard through-hole LEDs*** in catalogs. In the first two sections of this book, LEDs with a diameter of 5mm will be easier to handle, but I'm recommending 3mm LEDs for the remainder of the book, as they will be easier to fit into some of the circuits where components are crowded together. A typical red LED is shown in Figure 1-13.

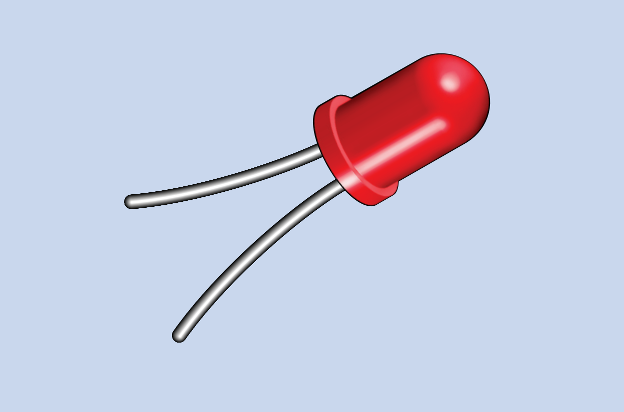


Figure 1-13. Closeup of a standard through-hole LED indicator.

Throughout this book I will often refer to ***generic red LEDs***. I want them to be red, because red LEDs will work with less current and a lower voltage than some other colors, which will be important in some experiments. By "generic" I mean the cheapest ones that are commonly available. They are used in so many applications, it's useful to keep at least a dozen.

Some generic LEDs are encapsulated in ***water clear*** plastic or resin, and may surprise you by emitting a color when power is applied. Other LEDs, such as the one in Figure 1-13, are known as ***diffuse***, as they are encapsulated in plastic or resin tinted with the same color that they will display. Water-clear LEDs are brighter, if all other aspects are the same, but I think diffuse LEDs are more pleasant to look at.

Resistors

You'll need a variety of ***resistors*** to control the voltage in various parts of a circuit. Two resistors are shown in closeup in Figure 1-14 (in real life, each of them would be less than 1/2" long). Later I will explain how the colored stripes tell you the value of each resistor. The color of the body of the resistor is not important for our purposes.

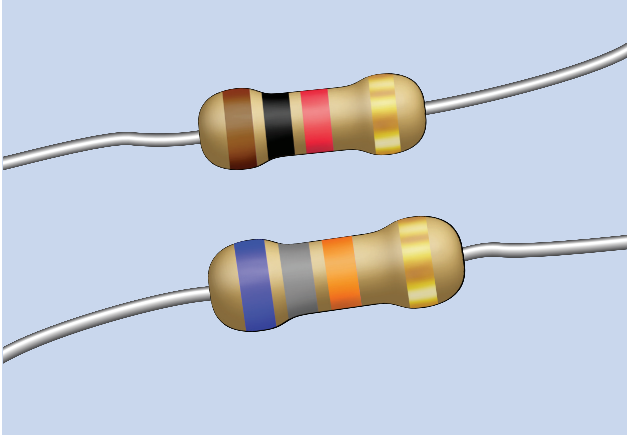


Figure 1-14. Two sample resistors.

If you are buying your own resistors, they are so small and cheap, you would be foolish to select just the two or three values listed in each experiment. Get a prepackaged selection in bulk from surplus or discount sources, or a site such as eBay. If you want to know exactly which values of resistors are required for each experiment in the book, check the tables in Appendix A.

Hardware

In Experiment 5, I'll be showing you how to make your own lemon-juice battery. You'll need some copper-plated pennies for this little project (or some other objects with a copper surface), and also some zinc-plated hardware such as mending plates about 1 inch long, like the one in Figure 1-15. Four will be sufficient, or small brackets will do instead. You can find them at any hardware store.

As for the pennies, new ones will work better than old ones, as they will be less tarnished. If you live in a part of the world where copper-plated coins don't exist anymore, I've suggested some other options in the buying guide in Appendix A.

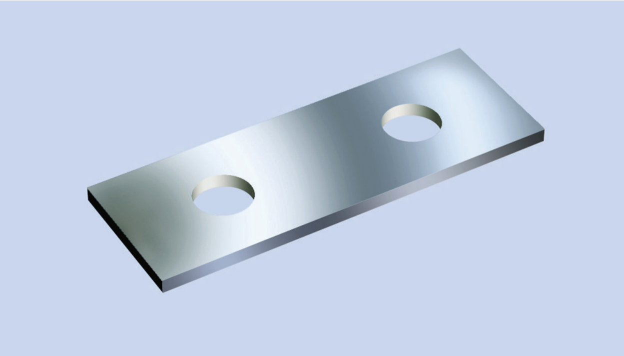


Figure 1-15. A zinc-plated mending plate. Try to find some that are about 1 inch long. Small brackets will do instead.

Experimenter's Notebook

Every time you conduct an experiment, you really need to keep a record of how you set it up and what happened. You can make your notes on a computer or using your phone, but an old-fashioned notebook with paper pages has some advantages. You don't have to open an application to update the entries, and it's safe from accidental data deletion. Keep it on the corner of your desk, and it may turn out to be more useful than you expect.

That's the last item on my list, so let's get started!

Experiment 1

Taste the Power!

Can you taste electricity? It feels as if you can. Using a battery-energized Tongue Test, this project will demonstrate electrical resistance.

You Will Need:

- 9V alkaline battery (1).
- Multimeter (1).

That's all!

Caution: No More than 9 Volts

A 9V alkaline battery won't hurt you. But ***do not*** try this experiment with a higher-voltage battery, and ***do not*** use a bigger battery that can deliver more current. Absolutely positively do not try to use a car battery or an alarm battery! Also, if you have metal braces on your teeth, be careful not to touch them with the battery.

Testing Your Tongue

Moisten your tongue and touch the tip of it to the metal terminals of a 9V battery, as shown in Figure 1-16. (Maybe your tongue isn't quite as big as the one in the picture. Mine isn't. But this experiment should work regardless of how big or small your tongue may be.)

Do you feel that tingle? Now set aside the battery, stick out your tongue, and dry the tip of it very thoroughly with a tissue. Touch the battery to your tongue again, and you should feel less of a tingle.

- What if you don't feel anything? A very few people seem to have unusually thick skin, or dry tongues, or perhaps both. A few have emailed me over the years to report that they didn't feel any tingle at all. If you have this problem, dissolve a pinch of salt in a few ounces of water, and moisten your tongue with it. That should do the trick!

What's happening, here? You can use a meter to find out.

Figure 1-16. An intrepid Maker tests the characteristics of a 9V alkaline battery.

Setting Up Your Meter

If you have a new multimeter, does it have a battery preinstalled? Select any function with the dial, and wait to see if the display shows a number. If the display window is blank, you may have to open the meter and put in a battery before you can use it. I can't tell you how to do this, or what type of battery you need, because the requirements of meters vary a lot. You'll have to check the instructions that should have been supplied.

Meters are supplied with two leads, one red and one black. I'll refer to them as *meter leads* to distinguish them from the test leads that you will also be using. Actually, the word "lead" can refer to almost any piece of wire connecting with a device or a component.

Each meter lead has a plug on one end and a steel probe on the other end, as shown in Figure 1-17. You insert the plugs into the meter, then touch the probes at locations where you want to know what's going on. The probes can measure electrical flow, or can detect voltage. The projects in this book entail such low voltages and currents, the probes cannot hurt you (unless you poke yourself with their sharp ends).

You can buy other types of meter leads as accessories. Some are very short, and some terminate in alligator clips or little spring-loaded hooks known as *mini-grabbers*. I like short leads and mini-grabbers myself, but meters are supplied with probes by default.

Now, where should you plug the leads into your meter? This is not as simple as it sounds.

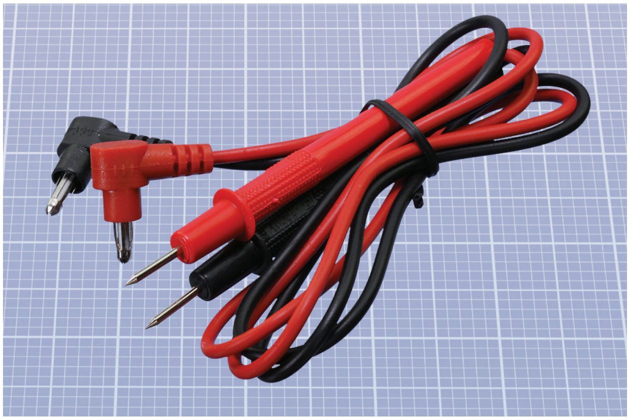


Figure 1-17. Typical meter leads. The large squares in the background are at intervals of 1 inch, divided into tenths.

First I'll deal with the black lead, which is easy. Its plug should go into the socket on your meter labeled **COM**, which is *common* to all your measurements. After you plug in the black lead, you will never have to unplug it again.

Another socket should have a letter **V** beside it, and also a Greek symbol named *omega*, which looks like the sample in Figure 1-18 and represents electrical resistance.

Ω

Figure 1-18. The Greek letter omega represents units of electrical resistance.

The socket may have some other symbols beside it as well, but V and the omega symbol will always be there, indicating that this socket can measure electrical resistance or voltage. Plug the red lead into it. See Figures 1-19 and 1-20.

You may see a third socket labeled **mA**, meaning *milliamps*. I'll get to that later. You should see a fourth socket labeled 10A or 20A, meaning 10 amps or 20 amps. This, too, I will deal with later. Don't use these sockets now.

Figure 1-19. Where to plug in the meter leads.

Figure 1-20. Different meter, same places to plug the leads.

Ohms	Kilohms	Megohms
1 Ω	0.001K	0.000001M
10 Ω	0.01K	0.00001M
100 Ω	0.1K	0.0001M
1,000 Ω	1K	0.001M
10,000 Ω	10K	0.01M
100,000 Ω	100K	0.1M
1,000,000 Ω	1,000K	1M

Figure 1-21. Conversion table for units of resistance.

What Is Resistance?

Electrical resistance reduces the flow of electric current. Almost every substance in the world has at least some resistance, even including your tongue.

We measure distance in miles or kilometers, and temperature in Fahrenheit or Celsius degrees. We measure electrical resistance in *ohms*, which is an international unit named after Georg Ohm, who was an electrical pioneer.

The Greek omega symbol that I showed in Figure 1-18 represents ohms.

For resistances above 999 ohms the uppercase letter K is used, which means *kilohm*, equivalent to 1,000 ohms. Sometimes K has an omega symbol printed after it, just to make things absolutely clear; but more often, it doesn't. For example, a resistance of 1,500 ohms will usually be referred to as 1.5K. Above 999,999 ohms, uppercase letter M is used, meaning *megohm*, which is a million ohms. In everyday speech, a megohm is often referred to as a "meg." If someone is using a "two-point-two meg resistor," its value will be 2.2M.

```
1K = 1,000 ohms

1M = 1,000K = 1,000,000 ohms
```

A table showing intermediate values is in Figure 1-21.

In Europe, you may find that a resistance value has a letter R, K, or M where you would expect a decimal point to be. This reduces the risk of errors, because sometimes a point can disappear when it is badly printed. Thus, 5K6 in a European circuit diagram means 5.6K, 6M8 means 6.8M, and 3R3 means 3.3 ohms. I won't be using the European style here, but you may run into it in some circuit diagrams elsewhere.

A material that has very high resistance to electricity is known as an *insulator*. Most (but not all) plastics, including the colored sheaths around wires, are insulators.

A material with very low resistance is a *conductor*. Metals such as copper, aluminum, silver, and gold are excellent conductors.

Is your tongue an insulator or a conductor?

Let's find out.

The Tongue Assessment

Inspect the dial on the front of your meter, and you'll find one position, or a set of values, identified with the omega symbol. On an auto-ranging meter, simply turn the dial to point to the symbol as shown in Figure 1-22. Then touch the probes to your tongue about an inch apart, and wait for the meter to choose a range automatically. Watch for letter **K** in the numeric display.

On a manual meter, you must choose a range. The way you do this is to select the *maximum* value that you expect. The meter will measure resistances up to that value, but not above it. For a tongue measurement, setting your meter to 200K or 400K (200,000 ohms or 400,000 ohms) should be about right. See the closeups of manual meters in figure 1-23 and figure 1-24.

What if your tongue has a resistance higher than 200K? A manual meter will display an error message, which usually looks like **OL**. It means "open leads," as if the meter leads are not connected to anything. What do you do? Simply turn the meter dial to the next higher value, such as 2M. Your tongue is unlikely to have a resistance higher than that.

- When you see **OL**, select a different range.

Whatever value you find for the resistance of your tongue, please write it in your experimenter notebook. I'm going to refer to it later.

Now put aside the probes, stick out your tongue, and use a tissue to dry it carefully and thoroughly, as you did before. Without allowing your tongue to become moist again, repeat the test, and the reading should be higher.

Here are two conclusions from your tongue tests.

- When you were touching your tongue with a battery, more moisture seemed to allow more electricity to flow, creating a bigger tingle.
- When you were using the meter, more moisture seemed to create a lower resistance.

I use the phrase "seemed to," because we haven't proved anything yet. All we have so far is a theory. Even if a lower resistance does allow more current to flow, I would like to know how much. And what exactly is "current," anyway? During the next few experiments, you'll discover the answers to these questions. By the end of Experiment 4, all the mysteries will be resolved.

What if you can't get any resistance value for your tongue, and you just see the **OL** error message? Try cleaning the probes, first with a detergent such as dish washing liquid, and then with something very slightly abrasive, such as toothpaste. Don't use a highly abrasive cleanser, such as a bath cleanser; it will damage the plating on the probes. Rinse and dry the probes after cleaning them.

If all else fails, add salty water to your tongue, as I suggested when you were using the battery.

Figure 1-22. Selecting resistance in an auto-ranging meter.

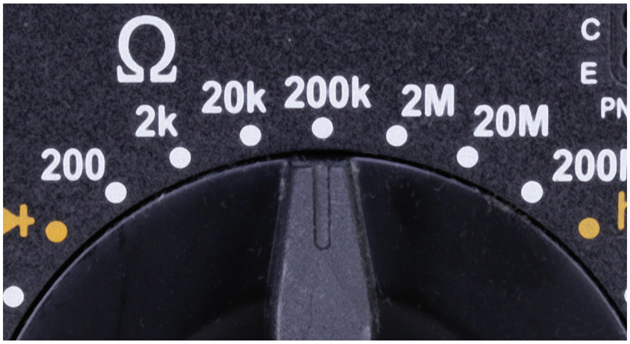


Figure 1-23. A manual meter requires you to select the range

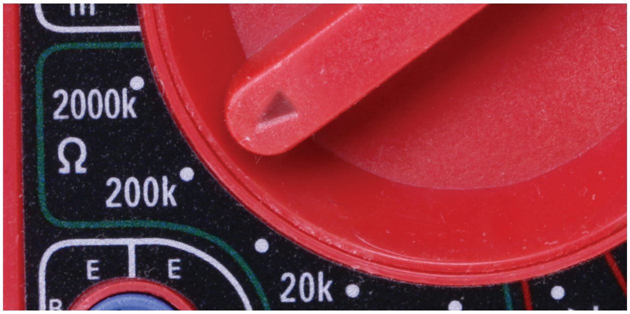


Figure 1-24. Different meter, same feature.

Other Resistances

A successful experiment should give you the same result every time, without any random factors interfering.

The tongue test is full of random factors, which are properly known as ***uncontrolled variables***. Moisture on your tongue was one variable. I suspect that another variable is the distance between the probes, and we can investigate that.

Hold the meter probes so that their tips are only 1/4" apart. Touch them to your moist tongue. Now separate the probes by 1" and try again. What readings do you get?

- When electricity travels through a shorter distance, it encounters less resistance, if all other factors remain the same.

Try a similar experiment on your arm, as shown in Figure 1-25. If you get no reading, moisten your skin. You can vary the distance between the probes in fixed steps, such as 1/4", and note the resistance shown by your meter. Do you think that doubling the distance between the probes doubles the resistance?

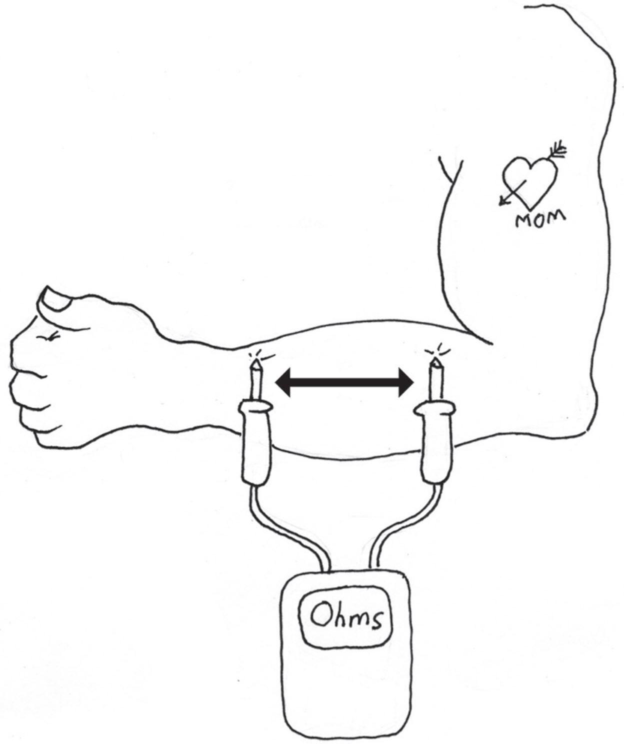


Figure 1-25. Vary the distance between the probes, and check the reading on your meter.

There is one more variable that I haven't discussed, which is the amount of pressure between each probe and the skin. If you press harder, I suspect that the resistance will diminish. Can you prove this? Why do you think it happens? How could you design an experiment to eliminate this variable?

If you get tired of measuring skin resistance, you can try dunking the probes into a glass of water. Then dissolve some salt in the water, and test it again. No doubt you've heard that water conducts electricity, but the full story is not so simple. Pure water has a relatively high resistance, as you can find out for yourself if you obtain some distilled water, which is usually sold cheaply in supermarkets. Salt, or some other impurities, will lower the resistance.

To get a better understanding of what is happening in these experiments, you need to know more about the flow of electricity, which is known as ***current***. (Sometimes it is referred to as ***amperage***.) I'll show you how to measure that in Experiment 2.

The Man Who Discovered Resistance

Georg Simon Ohm, pictured in Figure 1-26, was born in Bavaria in 1787 and worked in obscurity for much of his life, studying the nature of electricity using metal wire that he had to make for himself (you couldn't truck on down to Home Depot for 100 feet of doorbell wire back in the early 1800s).

Despite his limited resources and inadequate mathematical abilities, Ohm was able to demonstrate in 1827 that the electrical resistance of a conductor such as copper varied in inverse proportion with its area of cross-section, and the current flowing through it is proportional to the voltage applied to it, so long as temperature is held constant. Fourteen years later, the Royal Society in London finally recognized the significance of his contribution and awarded him the Copley Medal. Today, his discovery is known as ***Ohm's Law***. When you get to Experiment 4, you will be able to discover Ohm's Law for yourself (although really, you'll be rediscovering it).

Figure 1-26. Georg Simon Ohm, after being honored for his pioneering work, most of which he pursued in relative obscurity.

Cleanup and Recycling

Your battery should be almost as good as new. You can use it again.

Remember to switch off your meter before putting it away. Most meters will switch themselves off after a while, or will beep to remind you, but you can prolong the battery life if you switch off the meter more promptly.

Experiment 2

Go with the Flow

In this experiment you'll build your first circuit, in which you'll learn about electric current by taking an LED to its limits—and beyond.

You Will Need:

- 9V battery (1).
- Resistor, 15 ohms, brown-green-black (1).
- Resistor, 150 ohms, brown-green-brown (1).
- Resistor, 470 ohms, yellow-purple-brown (1).
- Resistor, 1.5K (1,500 ohms), brown-green-red (1).
- Generic red LED (2).
- Test leads (1 red, 1 black, 1 other color).
- Multimeter (1).

Rating a Resistor

Often we need to add electrical resistance to a circuit, for reasons that you will soon see. This can be done very easily by using components known as (guess what) *resistors*, which have their values measured in ohms.

Resistors that you acquire for the projects in this book may or may not be labeled—but that's okay, as you can find out what their values are. First I'll show you how to measure the values, and then I'll explain how to decode them.

Some resistors have a number clearly stated on them in tiny print that you can read with a magnifying glass, as shown in Figure 2-1, on the next page. Unfortunately, most manufacturers don't print numbers on resistors. They use a color code.

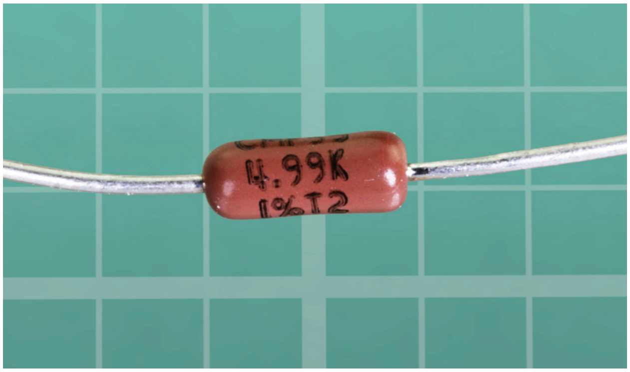


Figure 2-1. An unusual resistor that has its value printed on it.

The parts list that I provided for this experiment mentions the colors of bands printed on each resistor. You can see them in Figure 2-2. The wires coming out of them are *leads*, even though they look unlike the leads for your meter or the test leads with alligator clips on each end. The wires coming out of your LED are leads, too.

Your resistors may have silver bands instead of the gold bands that I have shown, but that's okay. I'll explain the difference in a moment.

First, I want you to check the values of the resistors. Make sure the red meter lead is still in the volts-ohms socket of your meter, as in Experiment 1. The 15-ohm resistor has a value that is much lower than that of your tongue, so you need to select a different resistance range. A value of 200 ohms is often the lowest available, so try that.

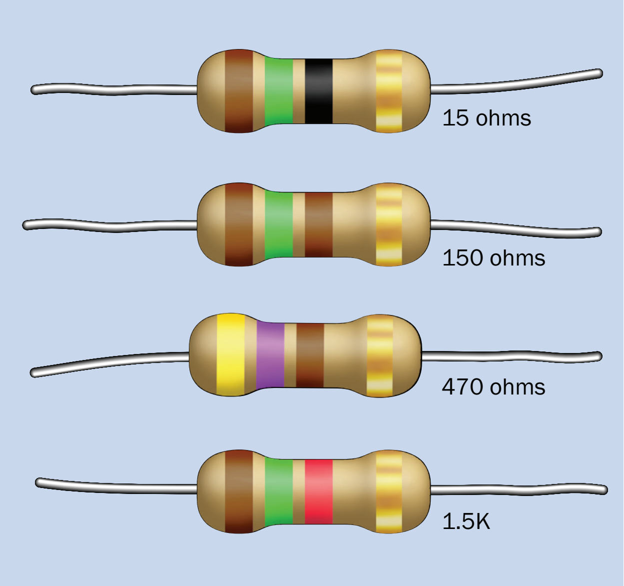


Figure 2-2. The resistors that you need in this experiment.

The resistor can be either way around; it makes no difference. Place it on a surface such as wood or plastic, which doesn't conduct electricity, and hold the probes by their plastic handles. If you touch the metal ends of the probes while trying to measure the resistor, you'll also be measuring the resistance of yourself, which is not what you want. See Figure 2-3.

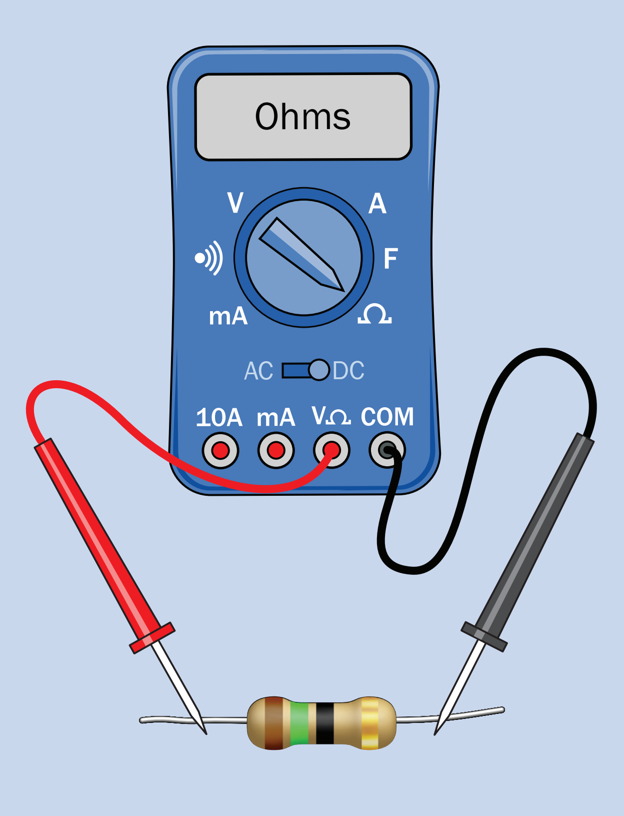


Figure 2-3. Checking the value of a 15-ohm resistor.

Press hard to make a good connection. If this seems awkward, you can try adding a couple of test leads, as in Figure 2-4. Now you can do hands-free resistor testing, and the results should be very nearly the same.

Write the value of your measured resistance in your notebook. Remove the 15-ohm resistor, and substitute the 150-ohm resistor. After you measure that, try the 470-ohm resistor—although, you'll get an OL error mes-

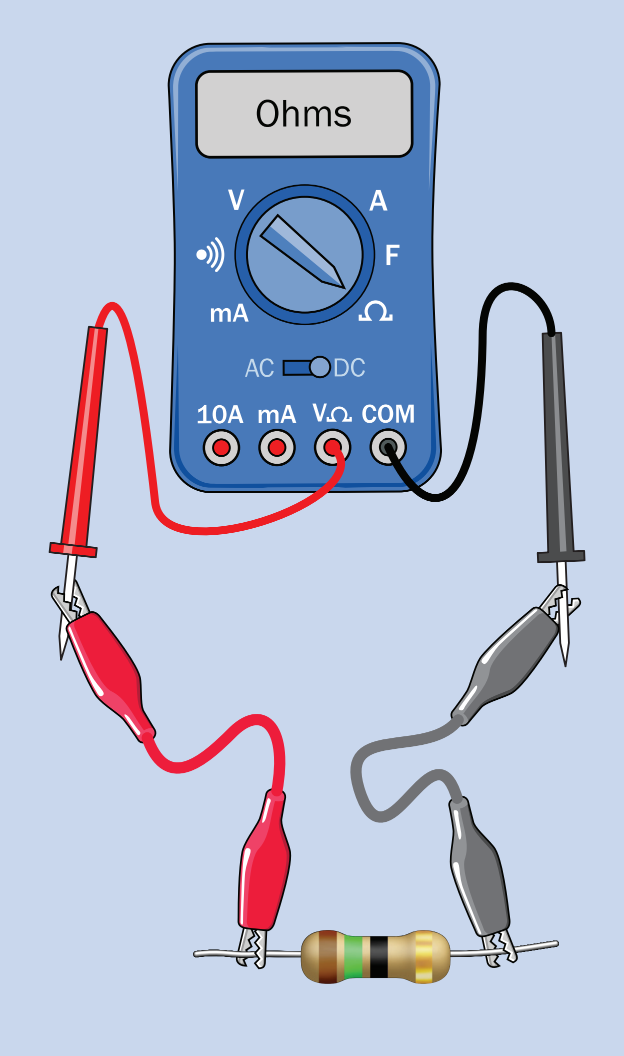


Figure 2-4. Using test leads to grab the resistor.

sage until you change the range on your meter dial from 200 ohms to 2K. Finish by checking the 1.5K resistor.

I'm betting that the values which you measure will not be exactly what you expect. The values I found when I tried this were 15.1 ohms, 148 ohms, 467 ohms, and 1,520 ohms.

You have just encountered a basic truth in electronics:

- Measurements are never precise.

Your meter isn't absolutely precise, and nor are the values of the resistors. Other factors can interfere, such as room temperature, which affects electrical resistance. There is also a tiny amount of resistance between the probes of the meter and the leads of the resistor. Your goal is to get as close as possible to accurate measurements, but total precision is impossible. That's just the way things are when you deal with electronic hardware.

Decoding a Resistor

Now that you've verified your resistor values—more or less—I'll explain their coding. The system is shown in Figure 2-5, and the procedure goes like this.

- Ignore the color of the body of the resistor.
- If there is a silver or gold stripe, turn the resistor so the stripe is on the right-hand side. Silver means that the value of the resistor is accurate within plus-or-minus 10%, while gold means that the value is accurate within plus-or-minus 5%. These percentages are known as the ***tolerance*** of the resistor. Some resistors have a 1% tolerance, or even better—in which case,

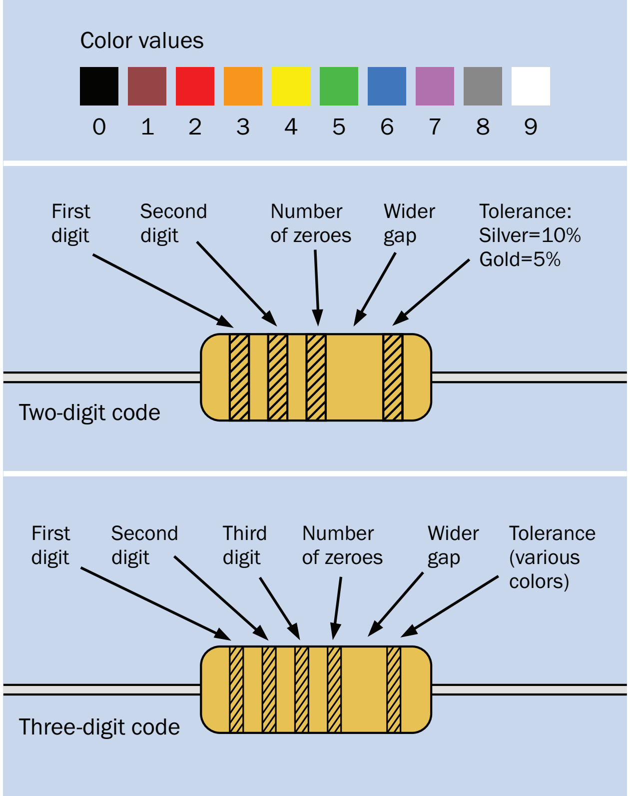


Figure 2-5. The color-coding system for resistors.

they won't have a silver or gold stripe, and some other color will be used. Whatever it is, you will find a gap between it and the other stripes, this gap being wider than the gaps among the other stripes.

- At the left end of the resistor will be three or four colored stripes. If the group consists of three stripes, the colors of the first two tell you the first two digits in the value of the resistor. If the group consists of four stripes, the colors of the first three tell you the first three digits in the value of the resistor.
- The last stripe in the group tells you how many zeroes follow the digits in the value of the resistor.

For example, look at your 1.5K resistor. Its colors are brown (1), green (5), and red (two zeroes). In other words, 1500, which is 1.5K.

A resistor with a group of four colored stripes is likely to have a better tolerance than 5%. The exact tolerance is not important for the projects in this book.

Mysterious Numbers

If you check a few resistors (or shop for them online) you'll notice that the same pairs of digits keep turning up. In hundreds of ohms, we often find 100, 150, 220, 330, 470, and 680. In thousands of ohms, the typical sequence is 1.0K, 1.5K, 2.2K, 3.3K, 4.7K, and 6.8K. In tens of ohms, we find 10, 15, 22, 33, 47, and 68. Why is this?

Long ago, manufacturing resistors accurately was a challenge, so the tolerance was 20%. In other words, the actual value could be a full 20% higher or lower than it was supposed to be. In the case of a 15K resistor, its actual resistance could be as low as 12K, because:

`15K - 20%   =  12K`

On the other hand, a 10K resistor could have a value 20% higher, like this:

`10K + 20%  =  12K`

So, a 15K resistor and a 10K resistor might both have the same value, and there was no point in manufacturing resistors with intermediate values.

Figure 2-6 illustrates this. The white numerals are the *nominal values* to create resistors, meaning the values that manufacturers are trying to achieve. You can see how cleverly they were chosen so that the range of possible values, 20% above and below, allowed hardly any overlap.

Resistors are manufactured much more accurately today, but everyone got into the habit of using the old range of values, and these are still the ones that you are most likely to find. Bearing this in mind, I have used them throughout this book.

20% less than nominal	0.8	1.2	1.76	2.64	3.76	5.44
Nominal Value	**1.0**	**1.5**	**2.2**	**3.3**	**4.7**	**6.8**
20% more than nominal	1.2	1.8	2.64	3.96	5.64	8.16

Figure 2-6. The original range of multipliers for resistor values, and the range of values plus-or-minus 20%.

The First Circuit

Take a look at one of your red LEDs. Old-fashioned light bulbs wasted a lot of power by converting electricity into heat, but LEDs are smarter: They convert almost all their power into light, and they last almost indefinitely—if you don't mistreat them.

What if you do mistreat them? This may be the time to find out.

Start with your 1.5K resistor. That's the one with brown-green-red colored bands. Grip it in a test lead connected with the negative side of your 9V battery. The resistor can be either way around; it doesn't care.

Now use another test lead to grip your LED, as in Figure 2-7. You *do* need to be careful to connect the LED the right way around, as shown.

- When you pass electric current through an LED, its longer lead must always be more positive than its shorter lead, as if the long lead had some extra length added (+) to it.

Touch the loose leads of the LED and the resistor together. Your LED lights up! Amazing. You have your first circuit.

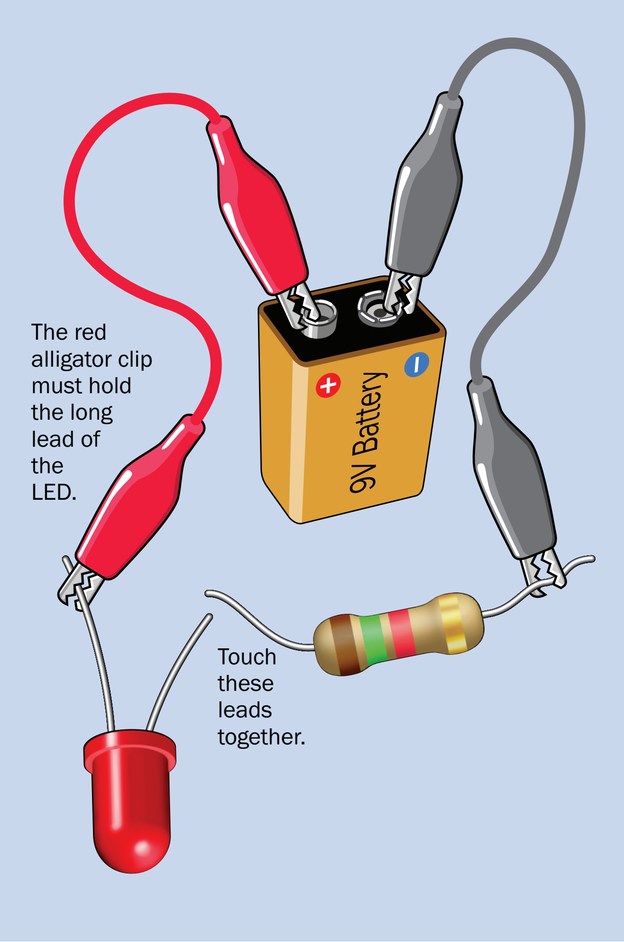


Figure 2-7. Testing an LED.

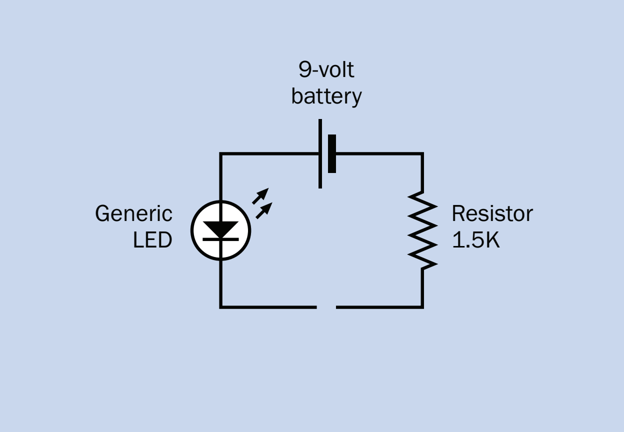


Figure 2-8. Schematic version of the LED circuit.

Polarity

When dealing with a power source such as a battery, remember:

- The "plus" symbol always means "positive."
- The "minus" symbol always means "negative."
- The distinction between positive and negative is called *polarity*.

When information from a manufacturer or a book tells you that a component such as an LED has polarity, make sure to connect it the right way around.

If you connect positive voltage to the short lead of the LED instead of to the long lead, you are applying *reverse polarity*, and the LED won't work. You may also shorten its life.

What if you trim the leads on an LED to make it fit into a circuit that you're building, and you can't remember which lead is the long one anymore? Not a problem! An LED of the type you are using has a flat spot in its round base, marking the *shorter* lead (the more-negative one).

Schematics

Take a look at Figure 2-8 and notice the similarity with Figure 2-7. The circuit is the same, but I redrew it using symbols. This is known as a *schematic*. I will be using schematics throughout the book, because they're easy to understand and they don't take too much space. You'll find more examples of schematic symbols when you get to Experiment 6.

Notice the two instances of polarity in Figure 2-8:

- The long line in the battery symbol indicates the positive side of the battery.
- The big triangle inside the LED symbol always points from positive to negative.
- The small arrows are just there to remind you that this is a light-emitting diode. (Other types of diodes exist, which don't emit light.)

In Europe, the symbol for a resistor is just a rectangle with its value printed in it. I'm using the zigzag American symbol here, and some people in Europe still use it, too.

Overloading an LED

Now disconnect the 1.5K resistor and substitute the one rated for 150 ohms: brown-green-brown. What happens? The LED is much brighter.

Moistening your tongue reduced the resistance between the probes of your meter, so that when you applied the 9V battery, you got more of a tingle. Reducing the resistance in your circuit gives your LED more of a tingle.

Do you think you can make it even brighter? Maybe you can guess what will happen—but guessing isn't good enough. Remove the 150-ohm resistor, substitute the 15-ohm resistor, but don't touch the wires together yet.

Anyone who knows anything about electronics will be saying, at this point, "No, no, don't do that!" But when someone tells me not to do something, I always want to see what will happen when I do it.

One thing, though. The wires may get a bit hot if you hold them together for long. If you want to be super-cautious, use a glove.

When the lead from the LED touches the lead of the 15-ohm resistor, for a short moment the LED gets really bright. But—no, that was too good to last. The LED fades away until there's just a dim glow.

Some LEDs fail more dramatically than others. I'm not sure why. A couple of readers have told me that their LEDs split in half when they were overloaded. I haven't been able to make this happen myself, although I've tried. I do know that 3mm LEDs self-destruct more quickly than 5mm LEDs.

Anyway—now you see how easy it is to destroy electronic components. Throw away the LED that you overloaded, because it will never work properly again. Its life has been sacrificed in the interests of providing you with a learning experience. Fortunately, although LEDs are an amazing achievement in electronics, they don't cost much.

The question is, why exactly did the LED burn out? You might guess that too much electric current flowed through it—but again, I don't like guessing. I think you need a way to measure current, and your meter will do it. First, though, I will give you a definition.

Defining Current

Electric current is the flow of electricity, per second, usually measured in ***amperes***, which are abbreviated as ***amps***. The flow consists of ***electrons***, each of which is a tiny particle carrying an electrical charge. If your human senses were fast enough to count electrons as they zip through a wire, you could measure 1 amp as 6.25 quintillion electrons per second, in American quintillions.

Ampere Basics

The ampere is an international unit, abbreviated with letter A. One milliamp (usually written mA) is 1/1,000 of an ampere. A microamp (usually written μA) is 1/1,000 of a milliamp.

```
1mA = 1,000μA
1A = 1,000 mA = 1,000,000μA
```

In Figure 2-9, you'll see a table showing intermediate values.

Microamps	Milliamps	Amps
1μA	0.001mA	0.000001A
10μA	0.01mA	0.00001A
100μA	0.1mA	0.0001A
1,000μA	1mA	0.001A
10,000μA	10mA	0.01A
100,000μA	100mA	0.1A
1,000,000μA	1,000mA	1A

Figure 2-9. Conversion table for units of current.

Measuring Current

Every meter I have ever seen has a socket for measuring current labeled either **10A** or **20A**, telling you the maximum number of amps that it can deal with. You won't be measuring a high current like that right now.

Your meter will also have a socket labeled **mA**, meaning milliamps, for measuring smaller currents. The maximum for this socket is usually printed beside it. Often it's 200mA, but sometimes 400mA. Look carefully at your meter and make a mental note of how many mA it will stand.

The **mA** socket is often separate from all the others—but not always! Some meters combine the measurement of volts, ohms, and mA all in one socket. An example is shown in Figure 2-10. This meter is unusual in that it locates the **COM** socket in the middle, but it still functions the same way, and the right-hand socket is clearly labeled for volts, ohms, microamps, and milliamps.

Figure 2-10. This meter allows you to measure volts, ohms, μA, and mA all from one socket.

This is a nice feature, because you can leave the red lead plugged into the same socket almost all the time. But your meter may have a separate socket for mA, as many do. The meters that I showed in Figures 1-19 and 1-20, in the previous experiment, have this arrangement.

To measure current, it has to flow through your meter. This requires some caution, because too much current can blow a fuse inside the meter, in which case you have to open the meter to remove the fuse, and then you must find a replacement fuse online that is exactly the right type, and while you're waiting for it to come in the mail, you can't measure current with your meter. In a cheap meter, the fuse may not be socketed, which makes it difficult to remove, and—well, you get the idea, it's a hassle! So, don't push too much current through your meter. If you take just a couple of simple precautions, it shouldn't happen. Personally it's been about five years since I last blew a fuse in my meter, and at that time I bought a couple of spare fuses, just in case I got careless again.

For the circuit that you're using in this experiment, you can safely use the **mA** socket on any meter, because I happen to know that you won't be measuring more than 25mA. Turn the dial to the next-highest value in the range, which is usually 200mA.

What if you didn't have me telling you how much current you would be measuring? You could do a calculation, which I'll explain in Chapter 4, or you could start by using the socket labeled **10A** (or **20A**) and work downward.

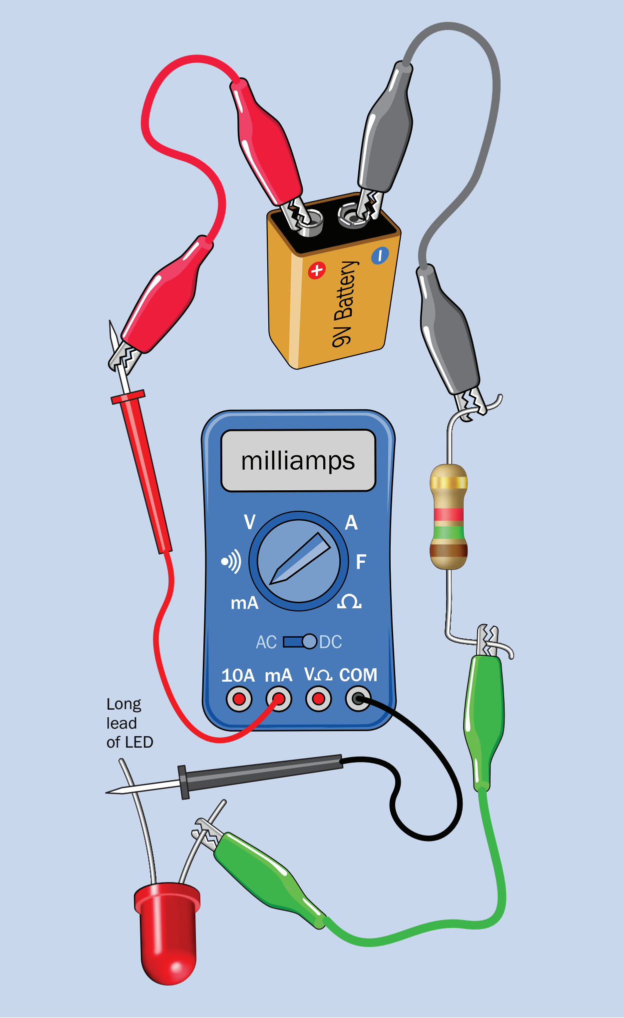


Figure 2-11. Measuring current with your meter.

Current in the LED Circuit

I want you to rebuild your circuit with a new LED. Make sure you use the 1.5K resistor, this time—not the 150-ohm resistor, and definitely not the 15-ohm resistor. You don't want to mistreat more LEDs than necessary.

Insert the meter into the circuit, as shown in Figure 2-11, and make sure the red lead is in the **mA** socket, not the volts-ohms socket (assuming your meter has a separate socket for mA).

- Remember, when you are measuring current, the meter is inserted into the circuit, with current passing through it.

From the positive battery terminal, current goes through the meter, through the LED, through the resistor, and back into the negative side of the battery.

You might be concerned that the black lead of the meter connects with the long lead of the LED. But this is quite okay. The logic goes like this:

- The red lead of the meter must be more positive than the black lead, so it connects with the positive side of the battery.

- The black lead of the meter connects via the LED and the resistor to the negative side of the battery.

What value do you see on your meter? Whatever it is, make a note of it. I obtained 5.1mA in my circuit. Actually it was 5.08, but I rounded it to 5.1, because this kind of measurement isn't very accurate, for reasons that I will explain shortly. It's not good practice to include extra decimal places when the measurement does not support them.

- When you remove a decimal place, if the digit that you omit was 5, 6, 7, 8, or 9, add 1 to the preceding value. So, 5.08 becomes 5.1. This is known as *rounding up*.

- When you remove 1, 2, 3, or 4, you don't have to change the value of the preceding digit. This is known as *rounding down*.

Now remove your meter from the left side of your circuit, and insert it into the right side. The two meter positions are suggested in Figure 2-12. Make sure the black lead of the meter connects with the negative side of the battery. When I did this, my meter reading was exactly the same as before. Is that what you find, in your circuit? I hope so, because in a simple circuit like this, the current has nowhere else to flow. Therefore, it has to be the same all the way through.

- The current is the same at all points throughout a simple circuit.

Is 5.1mA an acceptable current for the LED? Well—it seems okay. The LED doesn't burn out. But would it still be okay if you ran 5.1mA through it for a day or two? Um—I guess so.

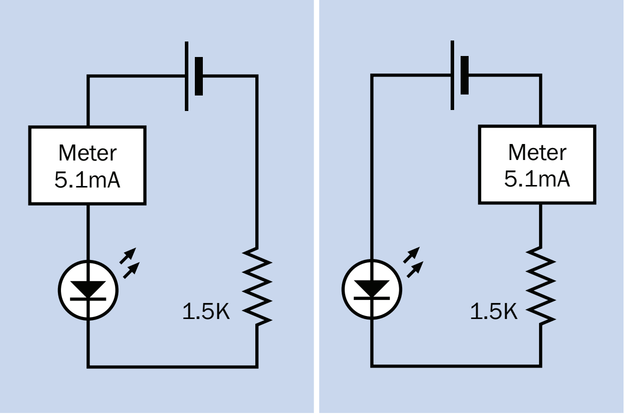


Figure 2-12. Two ways to measure current through a circuit.

Alternatively, do you think maybe you could get just a little more light out of the LED, without damaging it, if you reduced the resistance a teeny bit? There's an easy way to eliminate the guesswork. You ask the manufacturer.

Getting the Data

Almost any component has a datasheet published online by the manufacturer. Finding it is really easy, so long as you know the part number of the component. When you're buying components yourself, you will see the part number. When you are using a component from a kit, the supplier will usually show the part number.

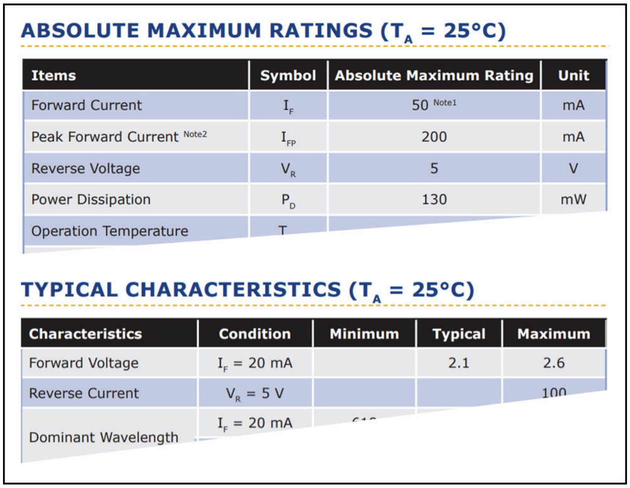
Suppose my red LED is a Cree C503B-RAN. I simply go to my usual search engine and type in:

```
cree C503B-RAN datasheet
```

A moment later, all the information I could possibly want is on the screen. In fact there's more than I need, and some of it is quite technical, so I've snipped just the relevant parts from the datasheet in Figure 2-13.

When you look at a datasheet and see the phrase "Absolute Maximum Ratings," think of it as being like a sign telling you the headroom on a low bridge. The numbers are serious! They really mean it! If you exceed these limits, the component will be damaged. Always stay *well below* the maximum.

For this LED, you can see 50 mA is the absolute maximum, so my value of 5.1mA is just a fraction of that. Incidentally, *forward current* means that it is flowing in



ABSOLUTE MAXIMUM RATINGS (T_A = 25°C)

Items	Symbol	Absolute Maximum Rating	Unit
Forward Current	I_F	50 Note1	mA
Peak Forward Current Note2	I_{FP}	200	mA
Reverse Voltage	V_R	5	V
Power Dissipation	P_D	130	mW
Operation Temperature	T		

TYPICAL CHARACTERISTICS (T_A = 25°C)

Characteristics	Condition	Minimum	Typical	Maximum
Forward Voltage	I_F = 20 mA		2.1	2.6
Reverse Current	V_R = 5 V			100
Dominant Wavelength	I_F = 20 mA	[illegible]		

Figure 2-13. Sections clipped from an LED datasheet.

the correct direction through the component. As for *peak* forward current, that would be just for a fraction of a second, if your power supply is fluctuating for some reason. It shouldn't normally happen.

Now check the "Typical Characteristics" in the datasheet. The word "Typical" is sometimes abbreviated as "Typ." These are the realistic values that you should use on a routine basis. Notice in the "Condition" column, it says "IF = 20mA." I'll explain that weird term "IF" a bit later, when I deal more with datasheets, but right now, 20mA is what you need to know. That is what you should really be using on a "typical" basis.

So, putting the 1.5K resistor in the circuit was a very safe bet. You could try substituting lower-value resistors and measuring the current till it was closer to 20mA, but I'll just give you the quick answer: 470 ohms will be a conservative option with a 9V battery, for a generic red LED. You can check this yourself.

Of course, if you wanted your LED to be dimmer for some reason—perhaps to extend the life of your battery—there's nothing stopping you from using a higher-value resistor.

Now you have a circuit which should keep the LED happy on an indefinite basis. So the lesson is: Always read a manufacturer's datasheet!

Keep the 470-ohm resistor in your circuit for now, but remove the alligator clip from the battery so that you don't run it down.

Father of Electromagnetism

Born in 1775 in France, André-Marie Ampère (shown in Figure 2-14) was a mathematical prodigy who became a science teacher, despite being largely self-educated in his father's library. His best-known work was to derive a theory of electromagnetism in 1820, describing the way that an electric current generates a magnetic field. He used this principle to make the first reliable measurements of what came to be known as *amperage*.

Figure 2-14. André-Marie Ampère.

He also built the first instrument to measure the flow of electricity (now known as a *galvanometer*). And, since he seems to have had some spare time, he discovered the element fluorine. People weren't distracted by text messages and cat videos in those days.

Direct and Alternating Current

The flow of current that you get from a battery is known as *direct current*, or *DC*. You can think of it as a steady stream of electrons in one direction, like the flow of water from a faucet.