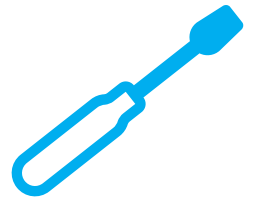


Burn things out, mess things up—that's how you learn.

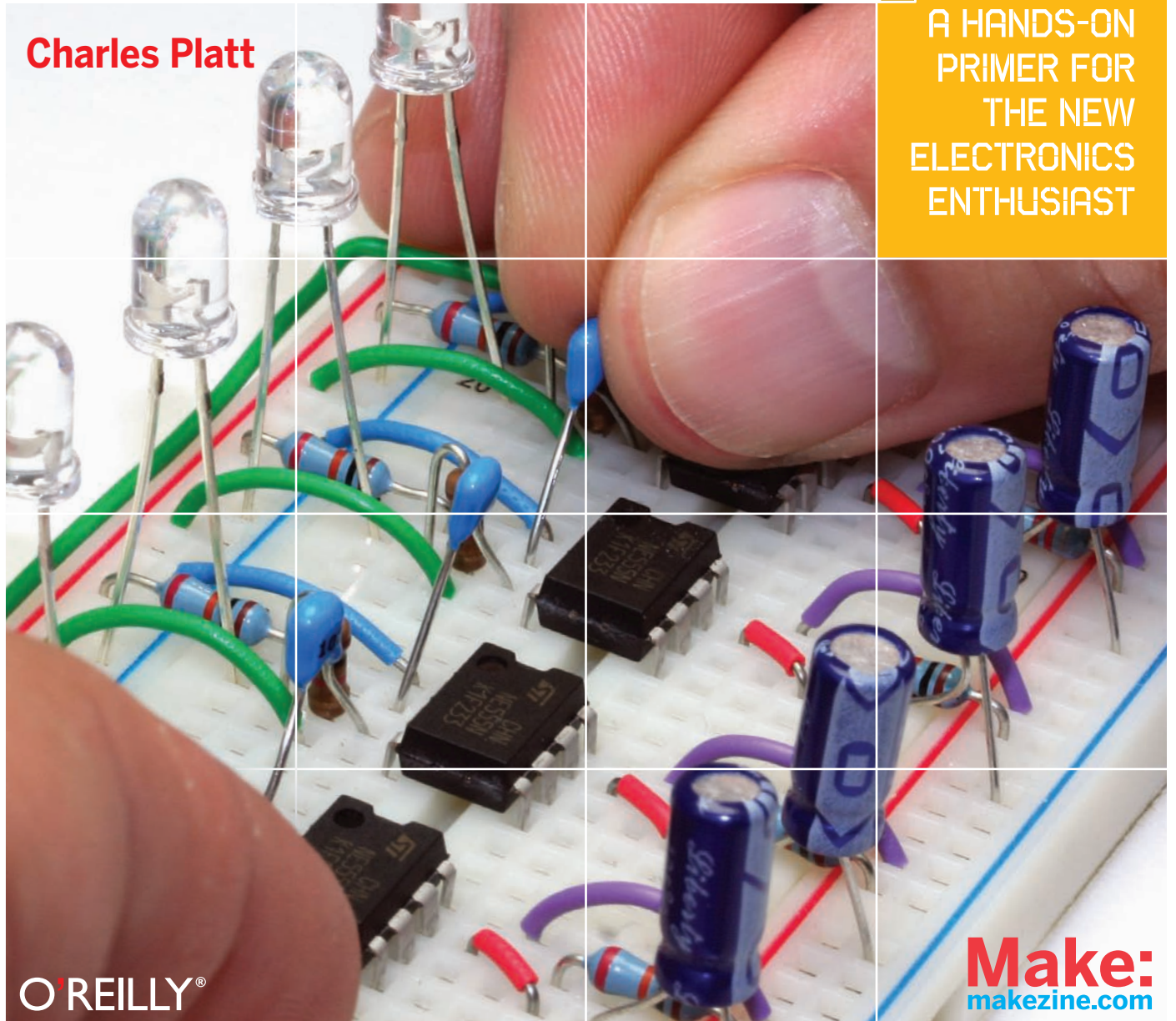


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Make: Electronics

Charles Platt

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[TI]

For my dearest Erico

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Preface

How to Have Fun with This Book

Everyone uses electronic devices, but most of us don't really know what goes on inside them.

Of course, you may feel that you don't need to know. If you can drive a car without understanding the workings of an internal combustion engine, presumably you can use an iPod without knowing anything about integrated circuits. However, understanding some basics about electricity and electronics can be worthwhile for 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. The tools are relatively cheap, you can do all the work on a tabletop, and it doesn't consume a lot of time (unless you want it to).
- Knowledge of electronics can enhance your value as an employee or perhaps even lead to a whole new career.

Learning by Discovery

Most introductory guides begin with definitions and facts, and gradually get to the point where you can follow instructions to build a simple circuit.

This book works the other way around. I want you to start putting components together right away. After you see what happens, you'll figure out what's going on. I believe this process of *learning by discovery* creates a more powerful and lasting experience.



Stay Within the Limits!

Although I believe that everything suggested in this book is safe, I'm assuming that you will stay within the limits that I suggest. Please always follow the instructions and pay attention to the warnings, denoted by the icon you see here. If you go beyond the limits, you will expose yourself to unnecessary risks.

Learning by discovery occurs in serious research, when scientists notice an unusual phenomenon that cannot be explained by current theory, and they start to investigate it in an effort to explain it. This may ultimately lead to a better understanding of the world.

We're going to be doing the same thing, although obviously on a much less ambitious level.

Along the way, you will make some mistakes. This is good. Mistakes are the best of all learning processes. I want you to burn things out and mess things up, because this is how you learn the limits of components and materials. Since we'll be using low voltages, there'll be no chance of electrocution, and so long as you limit the flow of current in the ways I'll describe, there will be no risk of burning your fingers or starting fires.



Figure P-1. Learning by discovery allows you to start building simple circuits right away, using a handful of cheap components, a few batteries, and some alligator clips.

How Hard Will It Be?

I assume that you're beginning with no prior knowledge of electronics. So, the first few experiments will be ultra-simple, and you won't even use solder or prototyping boards to build a circuit. You'll be holding wires together with alligator clips.

Very quickly, though, you'll be experimenting with transistors, and by the end of Chapter 2, you will have a working circuit that has useful applications.

I don't believe that hobby electronics has to be difficult to understand. Of course, if you want to study electronics more formally and do your own circuit design, this can be challenging. But in this book, the tools and supplies will be inexpensive, the objectives will be clearly defined, and the only math you'll need will be addition, subtraction, multiplication, division, and the ability to move decimal points from one position to another.

Moving Through This Book

Basically there are two ways to present information in a book of this kind: in tutorials and in reference sections. I'm going to use both of these methods. You'll find the tutorials in sections headed as follows:

- Shopping Lists
- Using Tools
- Experiments

You'll find reference sections under the following headings:

- Fundamentals
- Theory
- Background

How you use the sections is up to you. You can skip many of the reference sections and come back to them later. But if you skip many of the tutorials, this book won't be of much use to you. Learning by discovery means that you absolutely, positively have to do some hands-on work, and this in turn means that you have to buy some basic components and play with them. You will gain very little by merely imagining that you are doing this.

It's easy and inexpensive to buy what you need. In almost any urban or suburban area in the United States, chances are you live near a store that sells electronic components and some basic tools to work with them. I am referring, of course, to RadioShack franchises. Some Shacks have more components than others, but almost all of them have the basics that you'll need.

You can also visit auto supply stores such as AutoZone and Pep Boys for basics such as hookup wire, fuses, and switches, while stores such as Ace Hardware, Home Depot, and Lowe's will sell you tools.

If you prefer to buy via mail order, you can easily find everything you need by searching online. In each section of the book, I'll include the URLs of the most popular supply sources, and you'll find a complete list of URLs in the appendix.

Fundamentals

Mail-ordering components and tools

Here are the primary mail-order sources that I use myself online:

<http://www.radioshack.com>

RadioShack, a.k.a. The Shack. For tools and components. Not always the cheapest, but the site is easy and convenient, and some of the tools are exactly what you need.

<http://www.mouser.com>

Mouser Electronics.

<http://www.digikey.com>

Digi-Key Corporation.

<http://www.newark.com>
Newark.

Mouser, Digi-Key, and Newark are all good sources for components, usually requiring no minimum quantities.

<http://www.allelectronics.com>
All Electronics Corporation. A narrower range of components, but specifically aimed at the hobbyist, with kits available.

<http://www.ebay.com>
You can find surplus parts and bargains here, but you may have to try several eBay Stores to get what you want. Those based in Hong Kong are often very cheap, and I've found that they are reliable.

<http://www.mcmaster.com>
McMaster-Carr. Especially useful for high-quality tools.
Lowe's and Home Depot also allow you to shop online.

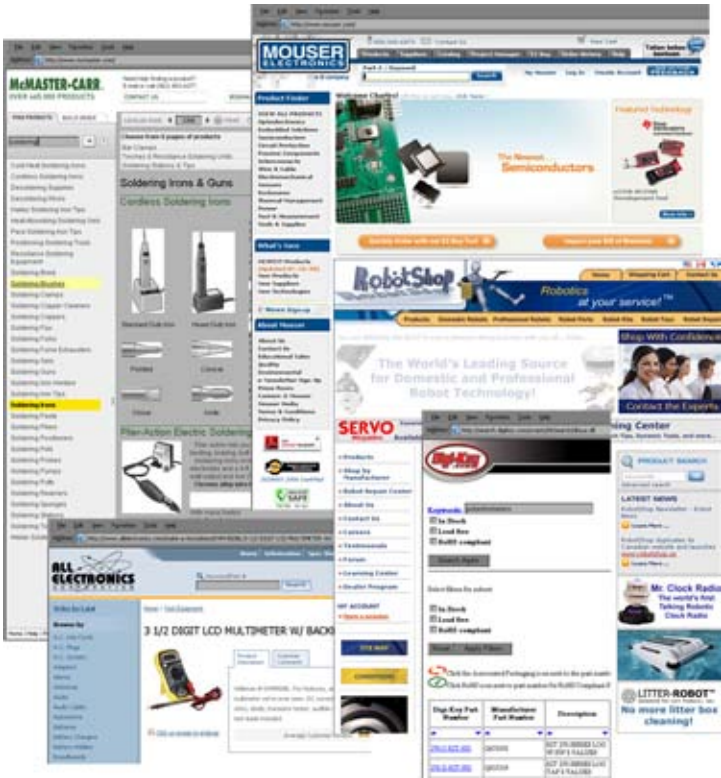


Figure P-2. You'll find no shortage of parts, tools, kits, and gadgets online.

Companion Kits



Maker Shed (www.makershed.com) offers a number of *Make: Electronics* companion kits, both toolkits and bundles of the various components used in the book's experiments. This is a simple, convenient, and cost-effective way of getting all the tools and materials you need to do the projects in this book.

Comments and Questions

Please address comments and questions concerning this book to the publisher:

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Experiment 4: Varying the Voltage

Potentiometers come in various shapes and sizes, but they all do the same thing: they allow you to vary voltage and current by varying resistance. This experiment will enable you to learn more about voltage, amperage, and the relationship between them. You'll also learn how to read a manufacturer's data sheet.

You will need the same batteries, battery carrier, alligator clips, and LED from the last experiment, plus:

- Potentiometer, 2K Ω linear. Quantity: 2. (See Figure 1-46.) Full-sized potentiometers that look like this are becoming less common, as miniature versions are taking their place. I'd like you to use a large one, though, because it's so much easier to work with.
- One extra LED.
- Multimeter.

Look Inside Your Potentiometer

The first thing I want you to do is find out how a potentiometer works. This means you'll have to open it, which is why your shopping list required you to buy two of them, in case you can't put the first one back together again.

Most potentiometers are held together with little metal tabs. You should be able to grab hold of the tabs with your wire cutters or pliers, and bend them up and outward. If you do this, the potentiometer should open up as shown in Figures 1-47 and 1-48.



Figure 1-46



Figure 1-47



Figure 1-48. To open the potentiometer, first pry up the four little metal tabs around the edge (you can see one sticking out at the left and another one sticking out at the right in Figure 1-47). Inside is a coil of wire around a flat plastic band, and a pair of springy contacts (the wiper), which conduct electricity to or from any point in the coil when you turn the shaft.

Depending whether you have a really cheap potentiometer or a slightly more high-class version, you may find a circular track of conductive plastic or a loop of coiled wire. Either way, the principle is the same. The wire or the plastic

possesses some resistance (a total of 2K in this instance), and as you turn the shaft of the potentiometer, a wiper rubs against the resistance, giving you a shortcut to any point from the center terminal.

You can try to put it back together, but if it doesn't work, use your backup potentiometer instead.

To test your potentiometer, set your meter to measure resistance (ohms) and touch the probes while turning the potentiometer shaft to and fro, as shown in Figure 1-49.

Dimming Your LED

Begin with the potentiometer turned all the way counterclockwise, otherwise you'll burn out the LED before we even get started. (A very, very small number of potentiometers increase and decrease resistance in the opposite way to which I'm describing here, but as long as your potentiometer looks like the one in Figure 1-48 after you open it up, my description should be accurate.)

Now connect everything as shown in Figures 1-50 and 1-51, taking care that you don't allow the metal parts of any of the alligator clips to touch each other. Now turn up the potentiometer *very* slowly. You'll notice the LED glowing brighter, and brighter, and brighter—until, oops, it goes dark. You see how easy it is to destroy modern electronics? Throw away that LED. It will never glow again. Substitute a new LED, and we'll be more careful this time.

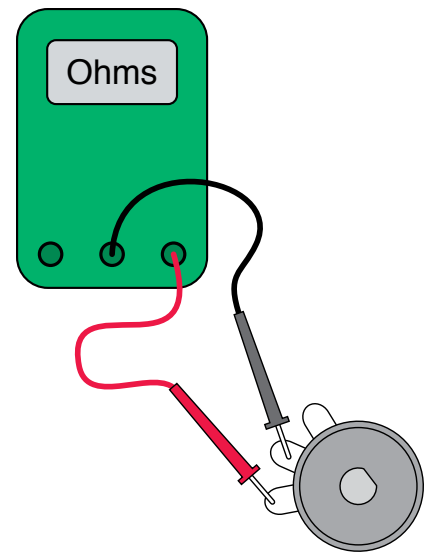


Figure 1-49. Measure the resistance between these two terminals of the potentiometer while you turn its shaft to and fro.

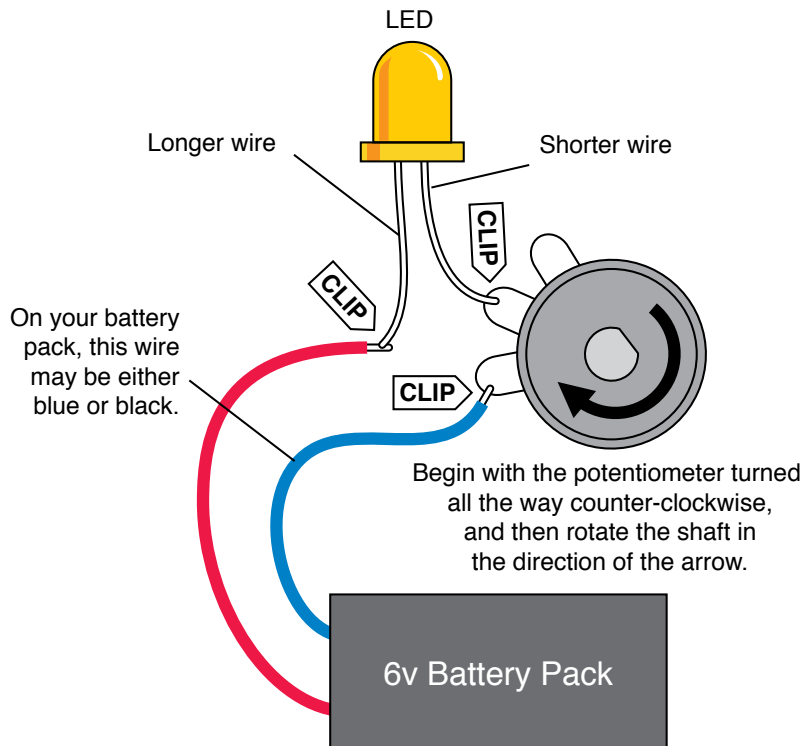


Figure 1-50. The setup for Experiment 4. Rotating the shaft of the 2K potentiometer varies its resistance from 0 to 2,000Ω. This resistance protects the LED from the full 6 volts of the battery.



Figure 1-51. The LED in this photo is dark because I turned the potentiometer up just a little bit too far.



Figure 1-52



Figure 1-53



Figure 1-54. Each meter has a different way to measure volts DC. The manually adjusted meter (top) requires you to move a slider switch to “DC” and then choose the highest voltage you want to measure: In this case, the selected voltage is 20 (because 2 would be too low). Using the autoranging RadioShack meter, you set it to “V” and the meter will figure out which range to use.

While the batteries are connected to the circuit, set your meter to measure *volts DC* as shown in Figures 1-52 through 1-54. Now touch the probes either side of the LED. Try to hold the probes in place while you turn the potentiometer up a little, and down a little. You should see the voltage pressure around the LED changing accordingly. We call this the *potential difference* between the two wires of the LED.

If you were using a miniature old-fashioned lightbulb instead of an LED, you’d see the potential difference varying much more, because a lightbulb behaves like a “pure” resistor, whereas an LED self-adjusts to some extent, modifying its resistance as the voltage pressure changes.

Now touch the probes to the two terminals of the potentiometer that we’re using, so that you can measure the potential difference between them. The potentiometer and the LED share the total available voltage, so when the potential difference (the voltage drop) around the potentiometer goes up, the potential difference around the LED goes down, and vice versa. See Figures 1-55 through 1-57. A few things to keep in mind:

- If you add the voltage drops across the devices in the circuit, the total is the same as the voltage supplied by the batteries.
- You measure voltage relatively, between two points in a circuit.
- Apply your meter like a stethoscope, without disturbing or breaking the connections in the circuit.

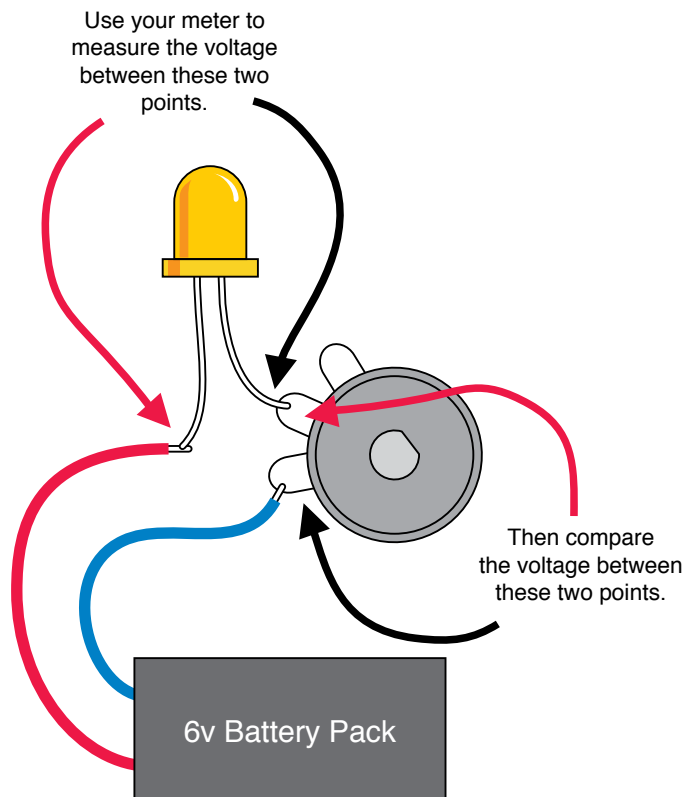


Figure 1-55. How to measure voltage in a simple circuit.

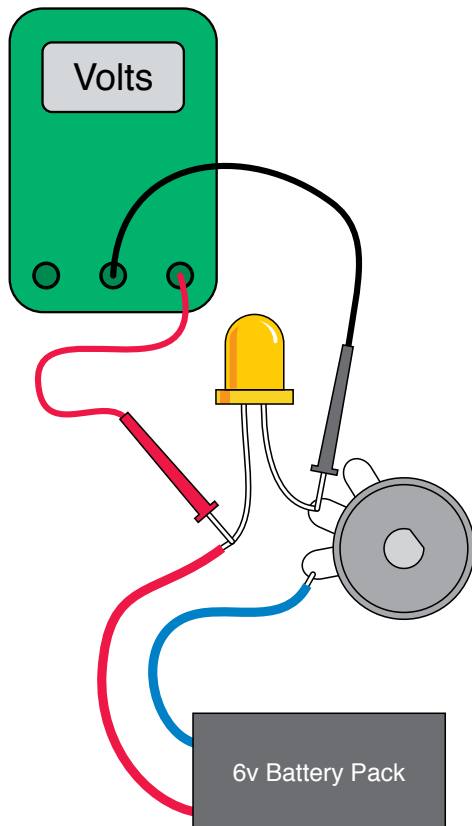


Figure 1-58. The meter shows how much voltage the LED takes.

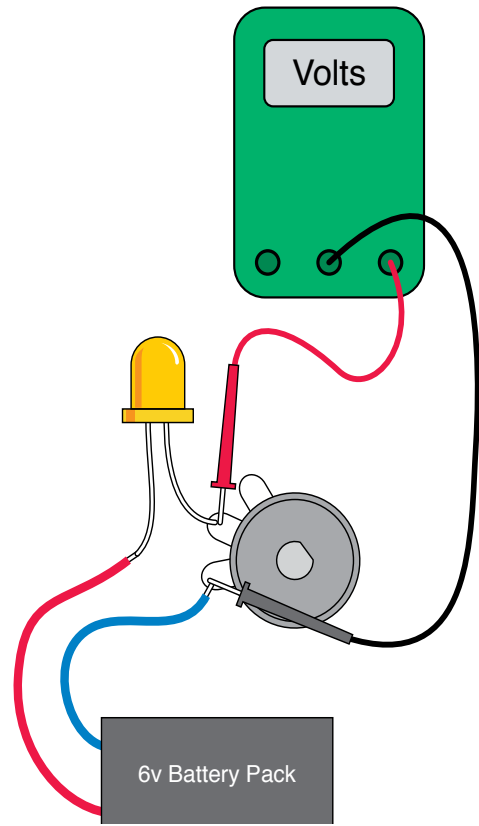


Figure 1-57. The meter shows how much voltage the potentiometer takes.

Checking the Flow

Now I want you to make a different measurement. I want you to measure the flow, or current, in the circuit, using your meter set to mA (milliamps). Remember, to measure current:

- You can only measure current when it passes *through* the meter.
- You have to insert your meter into the circuit.
- Too much current will blow the fuse inside your meter.

Make sure you set your meter to measure mA, not volts, before you try this. Some meters require you to move one of your leads to a different socket on the meter, to measure mA. See Figures 1-58 through 1-61.



Figure 1-58. Any meter will blow its internal fuse if you try to make it measure too high an amperage. In our circuit, this is not a risk as long as you keep the potentiometer in the middle of its range. Choose “mA” for milliamps and remember that the meter displays numbers that mean thousandths of an amp.



Figure 1-59



Figure 1-60



Figure 1-61. A manual meter such as the one here may require you to shift the red lead to a different socket, to measure milliamps. Most modern meters don’t require this until you are measuring higher currents.

Insert your meter into the circuit, as shown in Figure 1-62. Don’t turn the potentiometer more than halfway up. The resistance in the potentiometer will protect your meter, as well as the LED. If the meter gets too much current, you’ll find yourself replacing its internal fuse.

As you adjust the potentiometer up and down a little, you should find that the varying resistance in the circuit changes the flow of current—the amperage. This is why the LED burned out in the previous experiment: too much current made it hot, and the heat melts it inside, just like the fuse in the previous experiment. *A higher resistance limits the flow of current, or amperage.*

Now insert the meter in another part of the circuit, as shown in Figure 1-63. As you turn the potentiometer up and down, you should get exactly the same results as with the configuration in Figure 1-64. This is because the current is the same at all points in a similar circuit. *It has to be, because the flow of electrons has no place else to go.*

It's time now to nail this down with some numbers. Here's one last thing to try. Set aside the LED and substitute a $1\text{k}\Omega$ resistor, as shown in Figure 1-64. The total resistance in the circuit is now $1\text{k}\Omega$ plus whatever the resistance the potentiometer provides, depending how you set it. (The meter also has some resistance, but it's so low, we can ignore it.)

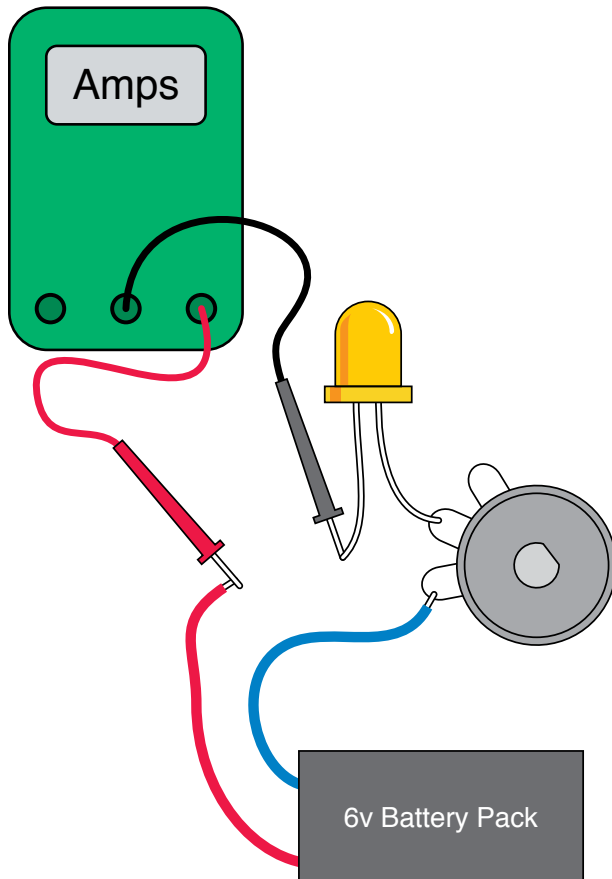


Figure 1-62. To measure amps, as illustrated here and in Figure 1-63, the current has to pass through the meter. When you increase the resistance, you restrict the current flow, and the lower flow makes the LED glow less brightly.

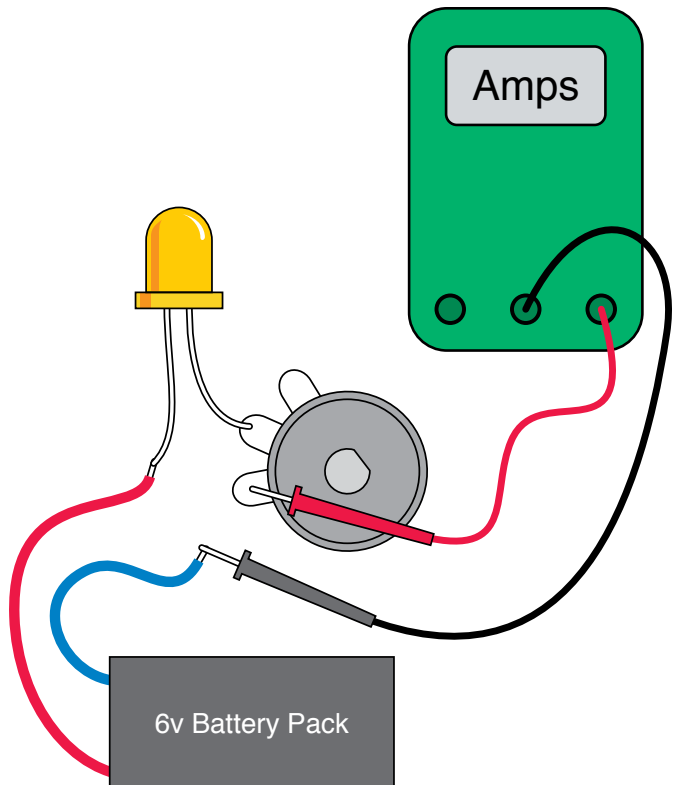


Figure 1-63

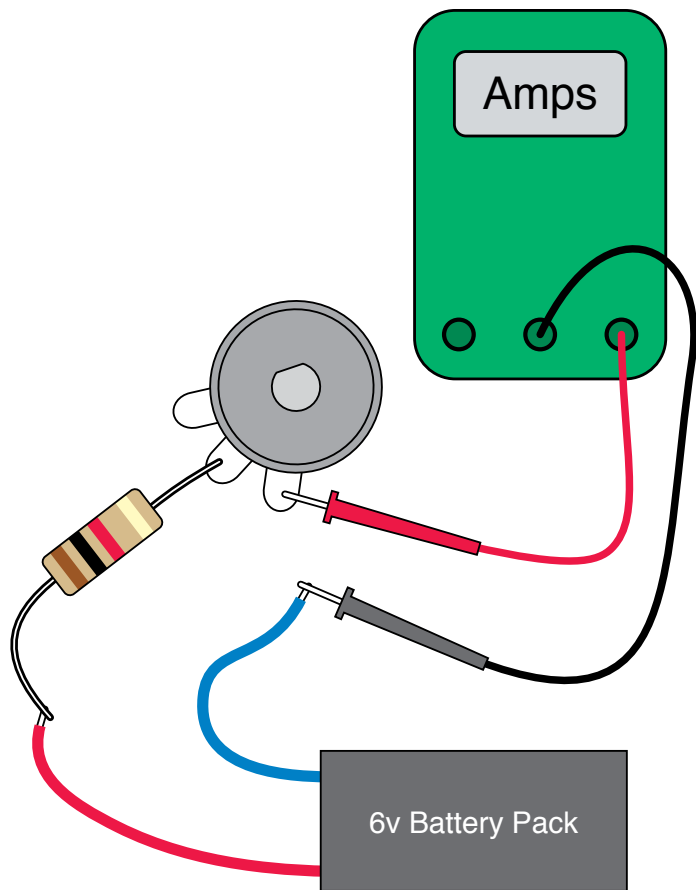


Figure 1-64. If you substitute a resistor instead of the LED, you can confirm that the current flowing through the circuit varies with the total resistance in the circuit, if the voltage stays the same.

Turn the potentiometer all the way counterclockwise, and you have a total of 3K resistance in the circuit. Your meter should show about 2 mA flowing. Now turn the potentiometer halfway, and you have about 2K total resistance. You should see about 3 mA flowing. Turn the potentiometer all the way clockwise, so there’s a total of 1K, and you should see 6 mA flowing. You may notice that if we multiply the resistance by the amperage, we get 6 each time—which just happens to be the voltage being applied to the circuit. See the following table.

Total resistance	Current	Voltage
(KΩ)	(mA)	(Volts)
3	2	6
2	3	6
1	6	6

In fact, we could say:

$$\text{voltage} = \text{kilohms} \times \text{milliamps}$$

But wait a minute: 1K is 1,000 ohms, and 1mA is 1/1,000 of an amp. Therefore, our formula should really look like this:

$$\text{voltage} = (\text{ohms} \times 1,000) \times (\text{amps}/1,000)$$

The two factors of 1,000 cancel out, so we get this:

$$\text{volts} = \text{ohms} \times \text{amps}$$

This is known as Ohm's Law. See the section, "Fundamentals: Ohm's Law," on the following page.

FUNDAMENTALS

Series and parallel

Before we go any further, you should know how resistance in a circuit increases when you put resistors in series or in parallel. Figures 1-65 through 1-67 illustrate this. Remember:

- Resistors in series are oriented so that one follows the other.
- Resistors in parallel are oriented side by side.

When you put two equal-valued resistors in series, you double the total resistance, because electricity has to pass through two barriers in succession.

When you put two equal-valued resistors in parallel, you divide the total resistance by two, because you're giving the electricity two paths which it can take, instead of one.

In reality we don't normally need to put resistors in parallel, but we often put other types of components in parallel. Lightbulbs in your house, for instance, are all wired that way. So, it's useful to understand that resistance in a circuit goes down if you keep adding components in parallel.

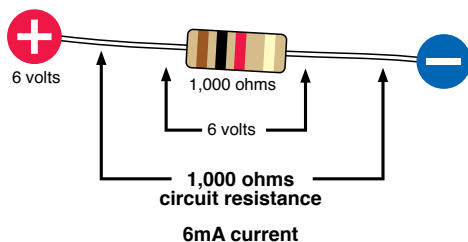


Figure 1-65. One resistor takes the entire voltage, and according to Ohm's Law, it draws $v/R = 6/1,000 = 0.006 \text{ amps} = 6\text{mA}$ of current.

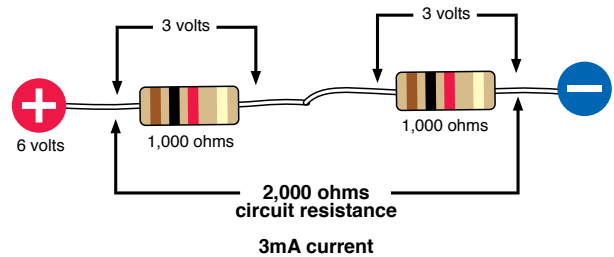


Figure 1-66. When two resistors are in series, the electricity has to pass through one to reach the other, and therefore each of them takes half the voltage. Total resistance is now 2,000 ohms, and according to Ohm's Law, the circuit draws $v/R = 6/2,000 = 0.003 \text{ amps} = 3\text{mA}$ of current.

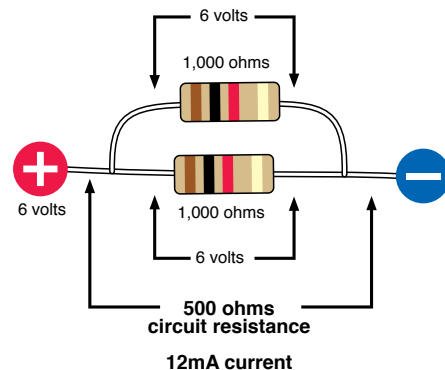


Figure 1-67. When two resistors are in parallel, each is exposed to the full voltage, so each of them takes 6 volts. The electricity can now flow through both at once, so the total resistance of the circuit is half as much as before. According to Ohm's Law, the circuit draws $v/R = 6/500 = 0.012 \text{ amps} = 12\text{mA}$ of current.

FUNDAMENTALS

Ohm's Law

For reasons I'll explain in a moment, amps are normally abbreviated with the letter I. V stands for volts and R stands for resistance in ohms (because the omega symbol, Ω , is not easily generated from most keyboards). Using these symbols, you can write Ohm's Law in three different ways:

$$V = I \times R$$

$$I = V/R$$

$$R = V/I$$

Remember, V is a *difference* in voltage between two points in a simple circuit, R is the resistance in ohms *between* the same two points, and I is the current in amps flowing *through* the circuit between the two points.

Letter I is used because originally current was measured by its *inductance*, meaning the ability to induce magnetic effects. It would be much less confusing to use A for amps, but unfortunately it's too late for that to happen.

Using Ohm's Law

Ohm's Law is extremely useful. For example, it helps us to figure out whether a component can be used safely in a circuit. Instead of stressing the component until we burn it out, we can predict whether it will work.

For instance, the first time you turned the potentiometer, you didn't really know how far you could go until the LED burned out. Wouldn't it be useful to know precisely what resistance to put in series with an LED, to protect it adequately while providing as much light as possible?

How to Read a Data Sheet

Like most information, the answer to this question is available online.

Here's how you find a manufacturer's data sheet (Figure 1-68). First, find the component that you're interested in from a mail-order source. Next, Google the part number and manufacturer's name. Usually the data sheet will pop up as the first hit. A source such as *Mouser.com* makes it even easier by giving you a direct link to manufacturers' data sheets for many products.



TLHG / R / Y540.
Vishay Semiconductors

High Efficiency LED in 5 mm Tinted Diffused Package

Description
The TLH.54.. series was developed for standard applications like general indicating and lighting purposes.
It is housed in a 5 mm tinted diffused plastic package. The wide viewing angle of these devices provides a high on-off contrast.
Several selection types with different luminous intensities are offered. All LEDs are categorized in luminous intensity groups. The green and yellow LEDs are categorized additionally in wavelength groups.



18223
e2
Pb-free

That allows users to assemble LEDs with uniform appearance.

Features

- Choice of three bright colors
- Standard T-1 package
- Small mechanical tolerances
- Suitable for DC and high peak current
- Wide viewing angle
- Luminous intensity categorized
- Yellow and green color categorized
- TLH.54.. with stand-offs
- Lead-free device

Applications

- Status lights
- OFF / ON indicator
- Background illumination
- Readout lights
- Maintenance lights
- Legend light

Figure 1-68. The beginning of a typical data sheet, which includes all relevant specifications for the product, freely available online.

BACKGROUND

How much voltage does a wire consume?

Normally, we can ignore the resistance in electric wires, such as the little leads of wire that stick out of resistors, because it's trivial. However, if you try to force large amounts of current through long lengths of thin wire, the resistance of the wire can become important.

How important? Once again, we can use Ohm's Law to find out.

Suppose that a very long piece of wire has a resistance of 0.2Ω . And we want to run 15 amps through it. How much voltage will the wire steal from the circuit, because of its resistance?

Once again, you begin by writing down what you know:

$$R = 0.2$$

$$I = 15$$

We want to know V , the potential difference, for the wire, so we use the version of Ohm's Law that places V on the left side:

$$V = I \times R$$

Now plug in the values:

$$V = 15 \times 0.2 = 3 \text{ volts}$$

Three volts is not a big deal if you have a high-voltage power supply, but if you are using a 12-volt car battery, this length of wire will take one-quarter of the available voltage.

Now you know why the wiring in automobiles is relatively thick—to reduce its resistance well below 0.2Ω . See Figure 1-69.

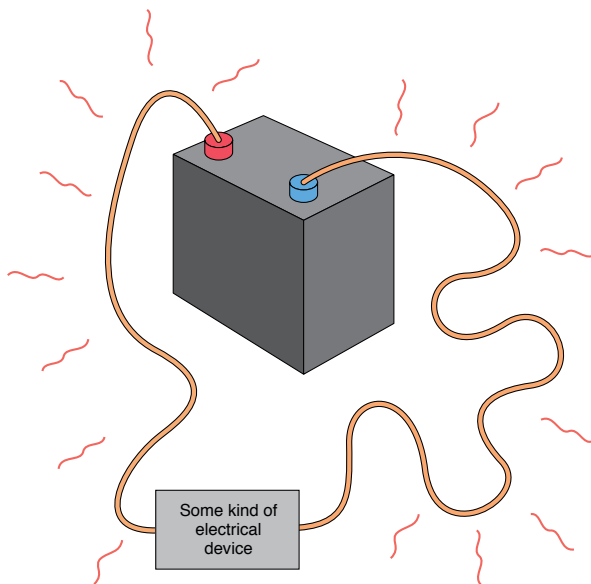


Figure 1-69. When a 12-volt car battery runs some kind of electrical device through a long piece of thin wire, the resistance of the wire steals some of the voltage and dissipates it as heat.

BACKGROUND

The origins of wattage

James Watt (Figure 1-70) is known as the inventor of the steam engine. Born in 1736 in Scotland, he set up a small workshop in the University of Glasgow, where he struggled to perfect an efficient design for using steam to move a piston in a cylinder. Financial problems and the primitive state of the art of metal working delayed practical applications until 1776.

Despite difficulties in obtaining patents (which could only be granted by an act of parliament in those times), Watt and his business partner eventually made a lot of money from his innovations. Although he predated the pioneers in electricity, in 1889 (70 years after his death), his name was assigned to the basic unit of electric power that can be defined by multiplying amperes by volts. See the Fundamentals section, “Watt Basics,” on page 31.



Figure 1-70. James Watt's development of steam power enabled the industrial revolution. After his death, he was honored by having his name applied to the basic unit of power in electricity.

Here's an example. Suppose I want a red LED, such as the Vishay part TLHR5400, which has become such a common item that I can buy them individually for 9 cents apiece. I click the link to the data sheet maintained by the manufacturer, Vishay Semiconductor. Almost immediately I have a PDF page on my screen. This data sheet is for TLHR, TLHG, and TLHY types of LED, which are red, green, and yellow respectively, as suggested by the R, G, and Y in the product codes. I scroll down and look at the “Optical and Electrical Characteristics” section. It tells me that under conditions of drawing a current of 20 mA, the LED will enjoy a “Typ,” meaning, typical, “forward voltage” of 2 volts. The “Max,” meaning maximum, is 3 volts.

Let's look at one other data sheet, as not all of them are written the same way. I'll choose a different LED, the Kingbright part WP7113SGC. Click on the link to the manufacturer's site, and I find on the second page of the data sheet a typical forward voltage of 2.2, maximum 2.5, and a maximum forward current of 25 mA. I also find some additional information: a maximum reverse voltage of 5 and maximum reverse current of 10 μ A (that's microamps, which are 1,000 times smaller than milliamps). This tells us that you should avoid applying excessive voltage to the LED the wrong way around. If you exceed the reverse voltage, you risk burning out the LED. Always observe polarity!

Kingbright also warns us how much heat the LED can stand: 260° C (500° F) for a few seconds. This is useful information, as we'll be putting aside our alligator clips and using hot molten solder to connect electrical parts in the near future. Because we have already destroyed a battery, a fuse, and an LED in just four experiments, maybe you won't be surprised when I tell you that we will destroy at least a couple more components as we test their limits with a soldering iron.

Anyway, now we know what an LED wants, we can figure out how to supply it. If you have any difficulties dealing with decimals, check the Fundamentals section “Decimals,” on the next page, before continuing.

How Big a Resistor Does an LED Need?

Suppose that we're use the Vishay LED. Remember its requirements from the data sheet? Maximum of 3 volts, and a safe current of 20mA.

I'm going to limit it to 2.5 volts, to be on the safe side. We have 6 volts of battery power. Subtract 2.5 from 6 and we get 3.5. So we need a resistor that will take 3.5 volts from the circuit, leaving 2.5 for the LED.

The current flow is the same at all places in a simple circuit. If we want a maximum of 20mA to flow through the LED, the same amount of current will be flowing through the resistor.

Now we can write down what we know about the resistor in the circuit. Note that we have to convert all units to volts, amps, and ohms, so that 20mA should be written as 0.02 amps:

$$V = 3.5 \text{ (the potential drop across the resistor)}$$

$$I = 0.02 \text{ (the current flowing through the resistor)}$$

We want to know R , the resistance. So, we use the version of Ohm's Law that puts R on the left side:

$$R = V/I$$

Now plug in the values:

$$R = 3.5/0.02$$

Run this through your pocket calculator if you find decimals confusing. The answer is:

$$R = 175\Omega$$

It so happens that 175Ω isn't a standard value. You may have to settle for 180Ω or 220Ω , but that's close enough.

Evidently the 470Ω resistor that you used in Experiment 3 was a very conservative choice. I suggested it because I said originally that you could use any LED at all. I figured that no matter which one you picked, it should be safe with 470Ω to protect it.

Cleanup and Recycling

The dead LED can be thrown away. Everything else is reusable.

FUNDAMENTALS

Decimals

Legendary British politician Sir Winston Churchill is famous for complaining about "those damned dots." He was referring to decimal points. Because Churchill was Chancellor of the Exchequer at the time, and thus in charge of all government expenditures, his difficulty with decimals was a bit of a problem. Still, he muddled through in time-honored British fashion, and so can you.

You can also use a pocket calculator—or follow two basic rules.

Doing multiplication: combine the zeros

Suppose you need to multiply 0.04 by 0.005 :

1. Count the total number of zeros following both of the decimal points. In this case, three zeros.
2. Multiply the numbers which follow the zeros. In this case, $4 \times 5 = 20$.
3. Write down the result as 0 followed by a decimal point, followed by the number of zeros, followed by the multiplication result. Like this: 0.00020 , which is the same as 0.0002 .

Doing division: cancel the zeros

Suppose you need to divide 0.006 by 0.0002 :

1. Shift the decimal points to the right, in both the numbers, by the same number of steps, until both the numbers are greater than 1. In this case, shift the point four steps in each number, so you get 60 divided by 2 .
2. Do the division. The result in this case is 30 .

THEORY

Doing the math on your tongue

I'm going to go back to the question I asked in the previous experiment: why didn't your tongue get hot?

Now that you know Ohm's Law, you can figure out the answer in numbers. Let's suppose the battery delivered its rated 9 volts, and your tongue had a resistance of 50K, which is 50,000 ohms. Write down what you know:

$$V = 9$$

$$R = 50,000$$

We want to know the current, I , so we use the version of Ohm's Law that puts this on the left:

$$I = V/R$$

Plug in the numbers:

$$I = 9/50,000 = 0.00018 \text{ amps}$$

Move the decimal point three places to convert to milliamps:

$$I = 0.18 \text{ mA}$$

That's a tiny current that will not produce much heat at 9 volts.

What about when you shorted out the battery? How much current made the wires get hot? Well, suppose the wires had a resistance of 0.1 ohms (probably it's less, but I'll start with 0.1 as a guess). Write down what we know:

$$V = 1.5$$

$$R = 0.1$$

Once again we're trying to find I , the current, so we use:

$$I = V/R$$

Plug in the numbers:

$$I = 1.5/0.1 = 15 \text{ amps}$$

That's 100,000 times the current that may have passed through your tongue, which would have generated much more heat, even though the voltage was lower.

Could that tiny little battery really pump out 15 amps? Remember that the battery got hot, as well as the wire. This tells us that the electrons may have met some resistance inside the battery, as well as in the wire. (Otherwise, where else did the heat come from?) Normally we can forget about the internal resistance of a battery, because it's so low. But at high currents, it becomes a factor.

I was reluctant to short-circuit the battery through a meter, to try to measure the current. My meter will fry if the current is greater than 10A. However I did try putting other fuses into the circuit, to see whether they would blow. When I tried a 10A fuse, it did not melt. Therefore, for the brand of battery I used, I'm fairly sure that the current in the short circuit was under 10A, but I know it was over 3A, because the 3A fuse blew right away.

The internal resistance of the 1.5-volt battery prevented the current in the short circuit from getting too high. This is why I cautioned against using a larger battery (especially a car battery). Larger batteries have a much lower internal resistance, allowing dangerously high currents which generate explosive amounts of heat. A car battery is designed to deliver literally hundreds of amps when it turns a starter motor. That's quite enough current to melt wires and cause nasty burns. In fact, you can weld metal using a car battery.

Lithium batteries also have low internal resistance, making them very dangerous when they're shorted out. High current can be just as dangerous as high voltage.

FUNDAMENTALS

Watt basics

So far I haven't mentioned a unit that everyone is familiar with: watts.

A watt is a unit of work. Engineers have their own definition of work—they say that work is done when a person, an animal, or a machine pushes something to overcome mechanical resistance. Examples would be a steam engine pulling a train on a level track (overcoming friction and air resistance) or a person walking upstairs (overcoming the force of gravity).

When electrons push their way through a circuit, they are overcoming a kind of resistance, and so they are doing work, which can be measured in watts. The definition is easy:

$$\text{watts} = \text{volts} \times \text{amps}$$

Or, using the symbols customarily assigned, these three formulas all mean the same thing:

$$W = V \times I$$

$$V = W/I$$

$$I = W/V$$

Watts can be preceded with an "m," for "milli," just like volts:

Number of watts	Usually expressed as	Abbreviated as
0.001 watts	1 milliwatt	1mW
0.01 watts	10 milliwatts	10 mW
0.1 watts	100 milliwatts	100 mW
1 watt	1,000 milliwatts	1W

Because power stations, solar installations, and wind farms deal with much larger numbers, you may also see references to kilowatts (using letter K) and megawatts (with a capital M, not to be confused with the lowercase m used to define milliwatts):

Number of watts	Usually expressed as	Abbreviated as
1,000 watts	1 kilowatt	1 KW
1,000,000 watts	1 megawatt	1 MW

Lightbulbs are calibrated in watts. So are stereo systems. The watt is named after James Watt, inventor of the steam engine. Incidentally, watts can be converted to horsepower, and vice versa.

THEORY

Power assessments

I mentioned earlier than resistors are commonly rated as being capable of dealing with 1/4 watt, 1/2 watt, 1 watt, and so on. I suggested that you should buy resistors of 1/4 watt or higher. How did I know this?

Go back to the LED circuit. Remember we wanted the resistor to drop the voltage by 3.5 volts, at a current of 20 mA. How many watts of power would this impose on the resistor?

Write down what you know:

$$V = 3.5 \text{ (the voltage drop imposed by the resistor)}$$

$$I = 20\text{mA} = 0.02 \text{ amps (the current flowing through the resistor)}$$

We want to know W, so we use this version of the formula:

$$W = V \times I$$

Plug in the values:

$$W = 3.5 \times 0.02 = 0.07 \text{ watts (the power being dissipated by the resistor)}$$

Because 1/4 watt is 0.25 watts, obviously a 1/4 watt resistor will have about four times the necessary capacity. In fact you could have used a 1/8 watt resistor, but in future experiments we may need resistors that can handle 1/4 watt, and there's no penalty for using a resistor that is rated for more watts than will actually pass through it.

Experiment 26: Tabletop Power Generation

If you have just three components, you can see magnetism generating electricity right in front of you, right now.

You will need:

- Cylindrical neodymium magnet, 3/4-inch diameter, axially magnetized. Quantity: 1. (Obtainable online at sites such as <http://www.kjmagnetics.com>.)
- Spool of hookup wire, 26-gauge, 100 feet. Quantity: 1.
- Spool of magnet wire, quarter-pound, 26-gauge, about 350 feet. Quantity: 1. (Search online for sources for “magnet wire.”)
- Generic LED. Quantity: 1.
- 100 μ F electrolytic capacitor. Quantity: 1.
- Signal diode, 2N4001 or similar. Quantity: 1.
- Jumper wires with alligator clips on the ends. Quantity: 2.

Procedure

You may be able to make this experiment work with the spool of hookup wire, depending on the size of the spool relative to the size of your magnet, but as the results are more likely to be better with the magnet wire, I’ll assume that you’re using that—initially, at least. The advantage of the magnet wire is that its very thin insulation allows the coils to be closely packed, increasing their inductance.

First peek into the hollow center of the spool to see if the inner end of the wire has been left accessible, as is visible in Figures 5-18 and 5-19. If it hasn’t, you have to unwind the wire onto any large-diameter cylindrical object, then rewind it back onto the spool, this time taking care to leave the inner end sticking out.

Scrape the transparent insulation off each end of the magnet wire with a utility knife or sandpaper, until bare copper is revealed. To check, attach your meter, set to measure ohms, to the free ends of the wire. If you make a good contact, you should measure a resistance of 30 ohms or less.

Place the spool on a nonmagnetic, nonconductive surface such as a wooden, plastic, or glass-topped table. Attach the LED between the ends of the wire using jumper wires. The polarity is not important. Now take a cylindrical neodymium magnet of the type shown in Figure 5-20 and push it quickly down into the hollow core, then pull it quickly back out. See Figure 5-21. You should see the LED blink, either on the down stroke or the up stroke.

The same thing may or may not happen if you use 100 feet of 26-gauge hookup wire. Ideally, your cylindrical magnet should fit fairly closely in the hollow center of the spool. If there’s a big air gap, this will greatly reduce the effect of the magnet. Note that if you use a weaker, old-fashioned iron magnet instead of a neodymium magnet, you may get no result at all.



Figure 5-18. An everyday 100-foot spool of hookup wire is capable of demonstrating the inductive power of a coil.



Figure 5-19. Magnet wire has thinner insulation than hookup wire, allowing the turns to be more densely packed, inducing a more powerful magnetic field.



Blood Blisters and Dead Media

Neodymium magnets can be hazardous. They're brittle and can shatter if they slam against a piece of magnetic metal (or another magnet). For this reason, many manufacturers advise you to wear eye protection.

Because a magnet pulls with increasing force as the distance between it and another object gets smaller, it closes the final gap very suddenly and powerfully. You can easily pinch your skin and get blood blisters.

If there's an object made of iron or steel anywhere near a neodymium magnet, the magnet will find it and grab it, with results that may be unpleasant, especially if the object has sharp edges and your hands are in the vicinity. When using a magnet, create a clear area on a nonmagnetic surface, and watch out for magnetic objects underneath the surface. My magnet sensed a steel screw embedded in the underside of a kitchen countertop, and slammed itself into contact with the countertop unexpectedly.

Be aware that magnets create magnets. When a magnetic field passes across an iron or steel object, the object picks up some magnetism of its own. Be careful not to magnetize your watch!

Don't use magnets anywhere near a computer, a disk drive, credit cards with magnetic stripes, cassettes of any type, and other media. Also keep magnets well away from TV screens and video monitors (especially cathode-ray tubes). Last but not least, powerful magnets can interfere with the normal operation of cardiac pacemakers.



Figure 5-20. Three neodymium magnets, 1/4-, 1/2-, and 3/4-inch in diameter. I would have preferred to photograph them standing half-an-inch apart, but they refused to permit it.



Figure 5-21. By moving a magnet vigorously up and down through the center of a coil, you generate enough power to make the LED flash brightly.

Here's another thing to try. Disconnect the LED and connect a 100 μF electrolytic capacitor in series with signal diode, as shown in Figure 5-23. Attach your meter, measuring volts, across the capacitor. If your meter has a manual setting for its range, set it to 20V DC. Make sure the positive (unmarked) side of the diode is attached to the negative (marked) side of the capacitor, so that positive voltage will pass through the capacitor and then through the diode.

Now move the magnet vigorously up and down in the coil. The meter should show that the capacitor is accumulating charge, up to about 10 volts. When you stop moving the magnet, the voltage reading will gradually decline, mostly because the capacitor discharges itself through the internal resistance of your meter.

This experiment is more important than it looks. Bear in mind that when you push the magnet into the coil, it induces current in one direction, and when you pull it back out again, it induces current in the opposite direction. You are actually generating alternating current.

The diode only allows current to flow one way through the circuit. It blocks the opposite flow, which is how the capacitor accumulates its charge. If you jump to the conclusion that diodes can be used to change alternating current to direct current, you're absolutely correct. We say that the diode is "rectifying" the AC power.

Experiment 24 showed that voltage can create a magnet. Experiment 25 has shown that a magnet can create voltage. We're now ready to apply these concepts to the detection and reproduction of sound.

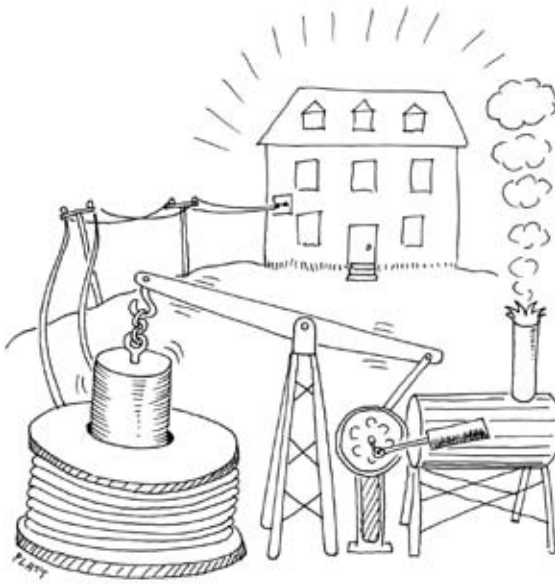


Figure 5-22. Because inductance increases with the diameter of a coil and with the square of the number of turns, your power output from moving a magnet through the coil can increase dramatically with scale. Those wishing to live “off the grid” may consider this steam-powered configuration, suitable for powering a three-bedroom home.

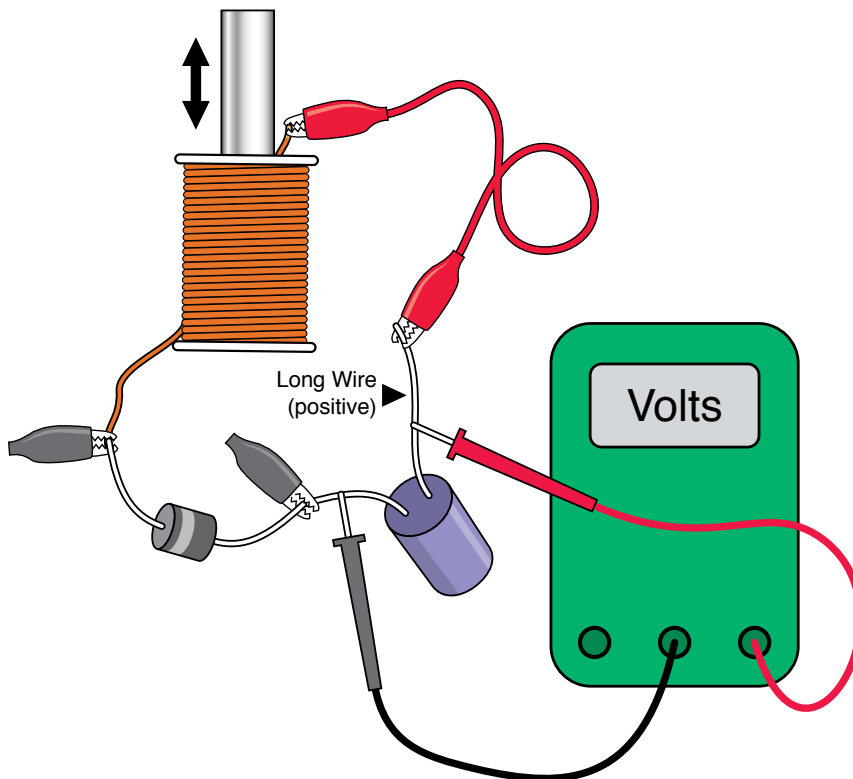


Figure 5-23. Using a diode in series with a capacitor, you can charge the capacitor with the pulses of current that you generate by moving the magnet through the center of the coil. This demo illustrates the principle of rectifying alternating current.

Acknowledgments

My association with MAKE magazine began when its editor, Mark Frauenfelder, asked me to write for it. I have always been very grateful to Mark for his support of my work. Through him I became acquainted with the exceptionally capable and motivated production staff at MAKE. Gareth Branwyn eventually suggested that I might like to write an introductory guide to electronics, so I am indebted to Gareth for initiating this project and supervising it as my editor. After I wrote an outline in which I described my idea for “Learning by Discovery” and the associated concept that cutting open components or burning them up can be an educational activity, MAKE’s publisher, Dale Dougherty, uttered the memorable phrase, “I want this book!” Therefore I offer special thanks to Dale for his belief in my abilities. Dan Woods, the associate publisher, was also extremely supportive.

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No free samples or other favors were received from any of the vendors mentioned herein, with the exception of two sample books from MAKE, which I read to ensure that I was not duplicating anything that had already been published.

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Colophon

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About the Author

Charles Platt became interested in computers when he acquired an Ohio Scientific C4P in 1979. After writing and selling software by mail order, he taught classes in BASIC programming, MS-DOS, and subsequently Adobe Illustrator and Photoshop. He wrote five computer books during the 1980s.

He has also written science-fiction novels such as *The Silicon Man* (published originally by Bantam and later by Wired Books) and *Protektor* (from Avon Books). He stopped writing science fiction when he started contributing to *Wired* in 1993, and became one of its three senior writers a couple of years later.

Charles began contributing to MAKE magazine in its third issue and is currently a contributing editor. *Make: Electronics* is his first title for Make Books. Currently he is designing and building prototypes of medical equipment in his workshop in the northern Arizona wilderness.

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