Make:

Wearable Electronics

Design, prototype, and wear your own interactive garments

Kate Hartman

Make: Wearable Electronics

Kate Hartman

MAKER MEDIA
SEBASTOPOL, CA

Make: Wearable Electronics

by Kate Hartman

Printed in Canada.

Published by Maker Media, Inc., 1005 Gravenstein Highway North, Sebastopol, CA 95472.

Maker Media books may be purchased for educational, business, or sales promotional use. Online editions are also available for most titles (*http://safaribooksonline.com*). For more information, contact O'Reilly Media's corporate/institutional sales department: 800-998-9938 or *corporate@oreilly.com*.

Editors: Brian Jepson and Emma Dvorak
Production Editor: Kara Ebrahim
Copyeditor: Jasmine Kwityn
Proofreader: Amanda Kersey
Indexer: Ellen Troutman
Cover Fashion Designer: Angella Mackey
Interior Designer: David Futato
Illustrator: Rebecca Demarest
Cover Photographer: Henrik Bengtsson
Cover Model: Jenny Andresson
Technical Editors: Rob Faludi, Erin Lewis, Pearl Chen, and Lynne Bruning
Custom Illustrator: Jen Liu
Research Assistant: Hillary Predko

August 2014: First Edition

Revision History for the First Edition:

2014-08-05: First release

2014-09-22: Second release

2015-10-16: Third release

See *http://oreilly.com/catalog/errata.csp?isbn=9781449336516* for release details.

ISBN: 978-1-449-33651-6

[TI]

To Red, for helping us see that our work with technology is ultimately about people.

Table of Contents

Preface

About The Book

Figure P-1. *"Monarch," a muscle-triggered kinetic textile created by the Social Body Lab*

Our bodies are our primary interface for the world. Interactive systems that live on the body can be intimate, upfront, and sometimes quite literally in your face. They sit close to your skin, inhabit your clothing, and sometimes even start to feel like part of you. This makes wearable electronics an exciting, challenging, and inspiring area to work in.

On one level this book is about how to make wearable electronics. It will introduce you to the tools, materials, and techniques necessary to create interactive electronic circuits and embed them in clothing and other things that can be worn.

On another level, this book is asking you: *"What's next?"*

We're living in a moment where wearable technologies are just starting to become a part of our everyday lives. They live on our wrists and in our glasses. They track our activities and transport us into virtual worlds. But this is just the beginning. There is still a lot that has yet to be revealed.

This book is inviting you to join the conversation about the future of wearable and body-centric technologies. What do we need? What do we want? And what should be avoided?

In the last 10–15 years, the technology that lives in our pockets has dramatically transformed. In the next decade, we can expect to see great strides in the development of the technology that lives on our bodies and in our clothes. It's a good time to ask questions and express opinions. This book will hopefully help you get started with that.

Who This Book Is For

This book is for people who want to roll up their sleeves and make some wearable electronics. This includes students, researchers, hackers, makers, fashion designers, engineers, industrial designers, developers, costume enthusiasts, artists, and textile mavens.

There are two perspectives from which you might be approaching this book.

The first: you know some stuff. There's a broad range to this. Maybe you're someone who has used an Arduino to blink an LED at a workshop once upon a time. Or maybe you run a design firm that produces massively robust interactive installations in museums and now you've got a client who wants you to generate a prototype that's wearable. Either way, you know enough to have a sense of what universe you're in. This book will help you build upon what you already know and might even lead you into some areas you didn't expect!

The second: when it comes to electronics and programming, you're a bit of a n00b. Maybe you're a fashion designer that realizes that interactivity in clothing is something you should wrap your head around. Or perhaps you're a sociologist who is developing a data-collection system that includes sensors that live on the body. Or maybe you're an artist with a newfound interest in self tracking. In any case, there are likely many things in this book that you may not have heard of before. If you're in this category, take this advice: be brave. It's OK if things are new to you or if you don't understand it on the first go. This book might be your gateway to a whole new list of things you didn't realize you wanted to learn. Stick with it—it's interesting stuff!

What You Need to Know

This book covers most of the basics, but it does assume that you understand soldering and basic hand sewing. If either of these things are new to you, check out Appendix C for resources where you can learn more. It is possible to complete most of the examples in the book with one or the other, but I do encourage you to learn both.

How This Book Is Organized

This book will take you on a journey that starts with circuit basics and ends with how to make interactive wireless wearables. In between, you'll learn about materials, microcontrollers, sensors, and actuators, and how these things fit into the world of wearable electronics. Here is what lies ahead:

Chapter 1, Circuits
: This chapter introduces you to circuit basics and then will show you six different ways to build the same circuit using different conductive materials.

Chapter 2, Conductive Materials
: Here you will take a deep dive into the range of conductive materials that we can use to construct circuits.

Chapter 3, Switches
: On, off, and beyond! This chapter provides an overview of switch basics and explains how to create your own.

Chapter 4, E-Textile Toolkits
: This chapter reviews the different electronic textile toolkits that are available for use in your wearable electronics projects.

Chapter 5, Making Electronics Wearable
: Making a circuit is one thing, but wearing it is another. This chapter goes through factors to consider when designing wearable electronics.

Chapter 6, Microcontrollers
: This is where the brains come in. This chapter provides an introduction to both the hardware and software aspects of getting up and running with microcontrollers.

Chapter 7, Sensors
: Sensors are what microcontrollers use to listen to the physical world. This chapter provides an introduction to the basics of working with sensor data and presents a variety of sensors that are useful in the wearable context.

Chapter 8, Actuators
: Actuators make things happen! From light to sound to motion, this chapter introduces you to actuators that can be employed in your wearable electronic designs.

Chapter 9, Wireless
: Time to bust out! This chapter introduces three approaches for wireless communication, meaning your project can send and receive data without being tied down.

Appendix A, Tools
: This provides an overview of the electronics and sewing tools that you might need for your studio, workshop, or lab.

Appendix B, Batteries
: Power it up! Here you'll find details of battery options for your wearable electronics projects.

Appendix C, Resources
: Want to learn more? Here's a list of resources that will take you above and beyond what's covered in this book.

Appendix D, Other Neat Things
: This is a selection of materials and processes that might help you make your wearables happen.

Appendix E, Microcontroller Options
: Here you'll find a more comprehensive list of microcontroller options to use in your wearable electronics projects.

About the Title

Make: Wearable Electronics does indeed cover how to make electronics that are wearable. More broadly, it provides a nontraditional approach to constructing electronic projects. The tools and techniques that are covered can also be applied to textiles, tapestries, toys, and more!

About Experiments and Projects

Throughout the book, we'll walk through *experiments* that will get you going and take a look at real-world *projects* that will serve as inspiration. A deliberate gap has been left between the two.

Some wearable electronics and e-textile books show you exactly how to build a particular project. This is not one of them. Instead, this book provides the building blocks that will help bring your own ideas to life.

About the Examples

Here are some technical notes about the examples presented in this book:

Connections

Most of the example circuits presented in this book can be created using alligator clips. Alligator clips can always be replaced by conductive thread, soldered wires, or other conductive materials as desired.

Power

All of the analog circuits can be powered using CR2032 batteries. Except where noted, the microcontroller circuits can be powered either by 1,000 mAh rechargeable lithium polymer batteries or via the microcontroller's USB connection. For alternative power options, see Appendix B.

Code

All code can be found here: *https://github.com/katehartman/Make-Wearable-Electronics*

About Part Numbers

Throughout the book, you will see part numbers that are preceded by a supplier code. These are the codes that will be used:

- AF: Adafruit Industries
- DK: Digi-Key
- IV: Inventables
- LE: Less EMF
- MS: Maker Shed
- RO: RobotShop
- RS: RadioShack
- SF: SparkFun Electronics

You can learn about these suppliers and more in Appendix C.

What Was Left Out

This book does not attempt to replicate existing resources. Take note of the references and project examples that are woven into each chapter, as well as the materials provided in Appendixes C and D. These breadcrumbs will lead you to a world of smart and talented thinkers, makers, and visionaries working in this and intersecting fields.

Experiment: Imagined Wearable

An experiment in the preface? That's right! The best time for you to start prototyping wearable electronics is right now. Sometimes it's easier to work through ideas before you even know what technologies you might use to create them.

Imagine something intended to be worn on your body (a garment or accessory) that would help you better relate to the world around you. It could be something practical, possible, or desirable. Or it could be something ridiculous, outlandish, annoying, or invasive. The technology that your garment utilizes does not have to actually exist and can be one of your own invention.

Once you've imagined your wearable, create a physical, wearable prototype or mock up that demonstrates what it might look like and how it would work. To make it, you can modify something that already exists (t-shirt, sneakers, top hat, etc.) or create something new from raw materials. It doesn't have to be fancy. Sometimes paper, duct tape, and Sharpies will do just fine.

This is a conceptual prototype—you do not need to implement any technology. Instead, focus on the design of the piece as well as the story behind it. Feel free to be creative, playful, and inventive. Try creating supporting materials such as instructions for use or user scenarios to help develop the story of your wearable. If you need some inspiration, check out the sidebar on this page.

Conventions Used in This Book

The following typographical conventions are used in this book:

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

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

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

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

This icon signifies a tip, suggestion, or general note.

This icon indicates a warning or caution.

Shape-Shifting Glasses

While I hate that I need to wear glasses, I love the glasses that I own. I interchange two pairs of prescription glasses, and my choice of glasses before I leave the house is influenced by what I happen to be wearing, where I am going, who I will be seeing, and how I am feeling. These factors actually create a wide variety of potential glasses, but sadly, I only have two pairs.

The Shape-Shifting Glasses would be the product of an advanced form of nanotechnology (I think?) and would be moldable to any shape, while maintaining accurate prescription. A button in one of the arms (think of the size of a inset reset button on a small electronic, the kind you have to press with a pin) would activate the moldability/solidification of the glasses. When activated, you would simply squish and stretch the lenses to the preferred size and shape, set the button again, and they would then remain in the desired fashion.

-Elijah Montgomery

Figure P-2. *Elijah Montgomery's Shape-Shifting Glasses, an imagined wearable*

Using Code Examples

This book is here to help you get your job done. In general, you may use the code in this book in your programs and documentation. You do not need to contact us for permission unless you're reproducing a significant portion of the code. For example, writing a program that uses several chunks of code from this book does not require permission. Selling or distributing a CD-ROM of examples from Make: books does require permission. Answering a question by citing this book and quoting example code does not require permission. Incorporating a significant amount of example code from this book into your product's documentation does require permission.

We appreciate, but do not require, attribution. An attribution usually includes the title, author, publisher, and ISBN. For example: "*Make: Wearable Electronics* by Kate Hartman (Make). Copyright 2014 Kate Hartman, 978-1-4493-3651-6."

If you feel your use of code examples falls outside fair use or the permission given here, feel free to contact us at *bookpermissions@makermedia.com*.

Safari® Books Online

Safari Books Online is an on-demand digital library that delivers expert content in both book and video form from the world's leading authors in technology and business.

Technology professionals, software developers, web designers, and business and creative professionals use Safari Books Online as their primary resource for research, problem solving, learning, and certification training.

Safari Books Online offers a range of product mixes and pricing programs for organizations, government agencies, and individuals. Subscribers have access to thousands of books, training videos, and prepublication manuscripts in one fully searchable database from publishers like Maker Media, O'Reilly Media, Prentice Hall Professional, Addison-Wesley Professional, Microsoft Press, Sams, Que, Peachpit Press, Focal Press, Cisco Press, John Wiley & Sons, Syngress, Morgan Kaufmann, IBM Redbooks, Packt, Adobe Press, FT Press, Apress, Manning, New Riders, McGraw-Hill, Jones & Bartlett, Course Technology, and dozens more. For more information about Safari Books Online, please visit us online.

How to Contact Us

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

Make:
1005 Gravenstein Highway North
Sebastopol, CA 95472
800-998-9938 (in the United States or Canada)
707-829-0515 (international or local)
707-829-0104 (fax)

Make: unites, inspires, informs, and entertains a growing community of resourceful people who undertake amazing projects in their backyards, basements, and garages. Make: celebrates your right to tweak, hack, and bend any technology to your will. The Make: audience continues to be a growing culture and community that believes in bettering ourselves, our environment, our educational system—our entire world. This is much more than an audience, it's a worldwide movement that Make is leading—we call it the Maker Movement.

For more information about Make:, visit us online:

> Make: magazine: *http://makezine.com/magazine/*
> Maker Faire: *http://makerfaire.com*
> Makezine.com: *http://makezine.com*
> Maker Shed: *http://makershed.com/*

We have a web page for this book, where we list errata, examples, and any additional information. You can access this page at:

> *http://bit.ly/wearable-electronics*

To comment or ask technical questions about this book, send email to:

> *bookquestions@oreilly.com*

Acknowledgments

In 2004, I attended an information session about the Interactive Telecommunications graduate program at New York University. Red Burns (who was the long-standing chair of the program at the time) candidly told us, "If you think you know what you're going to do here, you're wrong." She was, as always, right.

I never expected to become a wearable technologist, nor did I anticipate I would write a book about such things. But here we are. My opportunity to participate in all of this would never have happened without the support, hard work, and enthusiasm of some truly fabulous individuals.

To the following people I would like to offer my most heartfelt thanks:

To Brian Jepson, who first put this ball in my court and has been integral to this process from beginning to end.

To my editors, Meghan Blanchette, Shawn Wallace, and Emma Dvorak, who provided the guidance needed to sculpt these pages into something printworthy.

To my technical editors, Rob Faludi, Erin Lewis, Pearl Chen, and Lynne Bruning, who lent their attentiveness and depth of knowledge.

To Rob Faludi, also, for telling me I should write this thing.

To my research assistant, Hillary Predko, for her skill, zest, and speed.

To Jen Liu, whose delightful illustrations ignite the imagination.

To Angella Mackey, whose work is featured on the cover, for showing us that electronics can possess mystery, allure, and sass.

To the constellation of brilliant artists, designers, and makers whose projects are featured throughout this book for challenging our expectations and showing us what's possible.

To Leah Buechley for boldly challenging the way we think about designing electronics.

To the folks at SparkFun Electronics and Adafruit Industries for leading the way in making e-textile gear available to the masses.

To Becky Stern, Hannah Perner-Wilson, and Mika Satomi for setting the bar for ninja documentation skills.

To Syuzi Pakhchyan for nuturing our community.

To Despina Papadapoulous for the inspiration and the on-ramp.

To Dan O'Sullivan for telling me to just make the hats.

To Tom Igoe for helping me to become a teacher.

To OCAD University for taking a leap of faith and making me an assistant professor.

To the Digital Futures crew, especially to Suzanne Stein, Emma Westecott, Barbara Rauch, Paula Gardner, Caroline Langill, Tom Barker, Adam Tindale, Nick Puckett, Simone Jones, and Jeff Watson, for the collegiality and the camaraderie.

To my students for being brave and making beautiful things.

To Sara Diamond, Monica Contreras, and Helmut Reichenbächer for developing and sustaining a foundation upon which I could build.

To the rockstar research assistants who helped transform the Social Body Lab from an empty room to a vibrant ecosystem: Boris Kourtoukov, Borzu Talaie, Calliope Gazetas, Erin Lewis, Gabe Sawhney, Hazel Meyer, Hillary Predko, Izzie Colpitts-Campbell, Jackson McConnell, Julian Higuerey-Nuñez, Ken Leung, Oldouz Moslemian, Rachael Kess, Rickee Charbonneau, Rob King, Ryan Maksymic, and Stewart Shum. The pages of this book are painted with your talent and effort.

To the nice folks at the White Squirrel Coffee Shop for keeping me caffeinated and giving me a place to think.

To Gabe Sawhney for listening to my rants.

To Kati London for the candor.

To Tony Wong, Ted Redelmeier, and John Rose for holding the rope when I need to muster my courage.

To Carrie Schulz for being a stellar fellow cartographer.

To Jason Bellenger for the patience and for the adventures.

And finally…

To my parents, who though they also never anticipated that I would become a wearable technologist, somehow still knew how to support me every step of the way.

Circuits 1

Welcome to the world of wearable electronics! Before diving into designing complex, body-based, interactive projects, it is important that you have an understanding of basic circuits. In this chapter, you will learn about both how circuits work as well as how to construct them using a variety of tools and materials.

Figure 1-1. *"Connection and Motion" by Izzie Colpitts-Campbell; this wearable circuit uses stainless-steel-coated brass chain to connect LEDs to a battery pack*

Circuit Basics

There are some essential concepts that everyone should know when constructing circuits. These concepts will help guide circuit design and choice of components.

A *circuit* is a closed loop of electricity that contains a power source and a load. Conductors provide pathways for the electricity to travel between components in the loop.

A *power source* provides electricity. You will use a battery or battery pack as the power source for all of the circuits you create in this book. Batteries are a sensible power source for wearable electronics because they are relatively portable and compact.

A *load* is something that makes use of the electricity in the circuit. For the examples in this chapter, you will use light-emitting diodes (LEDs) as the load in your circuits.

A *conductor* is a material that permits the flow of electricity. In this chapter, you will use a variety of conductors to create electrical connections in your circuits.

A *circuit diagram* is a clear, concise representation of the components and connections in a circuit. It helps you understand the electrical connections being made within a circuit. It is not an image of an actual circuit.

In a circuit diagram, each component is represented as a symbol. Figure 1-2 shows an example of a few.

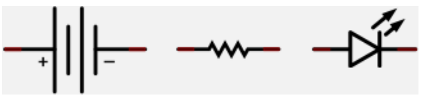

Figure 1-2. *Circuit symbols (left to right) for a battery, resistor, and LED*

Using these symbols, you can draw a diagram of a simple circuit, as shown in Figure 1-3.

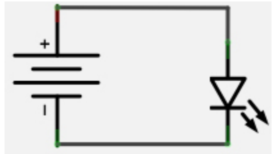

Figure 1-3. *Basic circuit with battery and LED*

Electricity is thought of as traveling from the point of highest electrical potential (*power* or "+") to the lowest (*ground* or "–"). So in this circuit, it flows from the positive terminal of the battery (marked with "+") to the positive terminal of the LED, through the LED, out the negative terminal of the LED to the negative terminal of the battery (marked with "–"), thus completing the loop (see Figure 1-4). Along the way, it will travel through the LED and (assuming it provides the correct power requirements) cause the LED to light.

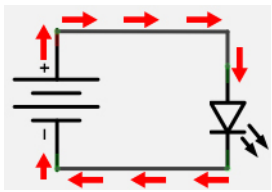

Figure 1-4. *The current (indicated by the red arrows) travels from power (+) to ground (-)*

Electricity likes to follow the path of least resistance. You can think of it as being a bit lazy. If electricity has the option of working to light up an LED or to take a path through a nonresistive material back to the battery, it's going to take the easy road. You can see this in Figure 1-5.

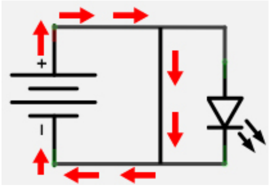

Figure 1-5. *When presented with the opportunity, electricity will always follow the path of least resistance; in this circuit, the electricity does not reach the LED, so the LED will not light up*

The problem with this alternative path is that it creates a *short circuit*. A short circuit is a closed loop of electricity that has a power source but no load.

If electricity is fed from the positive end of the battery directly into the negative, depending on the duration of the short, it will likely drain the battery. In some situations, the results can be more severe, including smoke, melted wires, and damaged components. At minimum, your project won't function properly. No matter what the circumstance, shorts are not good, so it's best to make sure they don't happen in your circuit.

Insulators are materials that do not conduct electricity. They can be used to prevent short circuits.

To see how this circuit might look in real life, you can use components like a 3V battery (CR2032) and a 5mm through-hole LED (see Figure 1-6).

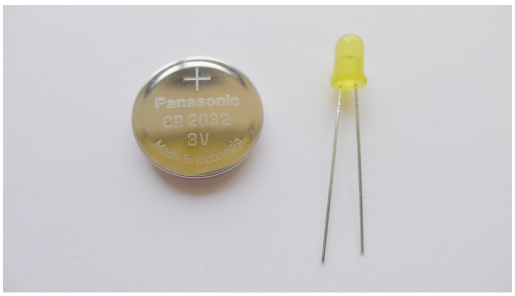

Figure 1-6. *CR2032 3V battery and 5mm LED*

In order to implement the circuit depicted in the circuit diagram, all you need to do is press the positive end of the LED to the positive end of the battery and the same with the negative end of each component, as shown in Figure 1-7.

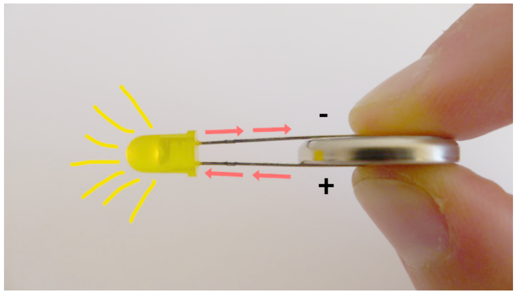

Figure 1-7. *A simple circuit*

And bam! You have a circuit. This configuration allows electricity to flow from the battery, through the LED, and back to the battery giving the LED the power it needs to light up. This technique was used by James Powderly and Evan Roth (Graffiti Research Lab) to create magnetic modules (see Figure 1-8) that could act as light graffiti on buildings and other urban structures.

Figure 1-8. *LED "throwies" (image courtesy of James Powderly and Evan Roth)*

Ohm's Law

The circuit you just created is a quick-and-dirty way to light up an LED, but there are a few more things to learn before you can construct a technically correct and long-lasting circuit.

There are three key pieces of information to pay attention to when designing a circuit:

Voltage
: The difference in electrical energy between two points. It is measured in volts (V).

Current
: The quantity or amount of electrical energy passing a particular point. It is measured in amps (A) or milliamps (mA).

Resistance
: The measure of a material's ability to prevent the flow of electricity. Resistance is measured in *ohms*, which is represented by the ohm symbol (Ω).

Ohm's law states that voltage (V) is equal to current (I) times resistance (R). As with any equation, if you know two of the three variables, you are able to determine the third. All three variations of this equation can be helpful to you as you're learning to construct circuits:

- $V = I \times R$
- $I = V \div R$
- $R = V \div I$

As it turns out, in the circuit you just created with the LED and battery, the LED is actually receiving a bit more than the desirable amount of current. Excessive current can shorten the LED's life or even burn it out. Because this battery supplies a relatively low amount of current, and an LED is not a particularly sensitive or expensive component, you can get away with more of a hacky approach. But ideally you should create a circuit that respects the needs of its components. To do this, you can use Ohm's law to determine how much resistance is needed.

To determine the voltage that needs to be used up, you will need to find the difference between the source voltage (Vs) and the forward voltage (Vf), which is the voltage used up by the LED. So the equation is actually as follows:

- $R = (Vs - Vf) \div I$

The source voltage (Vs) is that which is supplied by the battery. In this case, the CR2032 battery supplies 3V.

You can find the forward voltage (Vf) and the current required by the LED on the LED's datasheet (Figure 1-9). A *datasheet* is a document supplied by a component's manufacturer. This document provides information about the component, including the component's electrical needs and tolerances, mechanical diagrams of its physical packaging, diagrams of any pins or connections, and details on intended use and expected performance.

Absolute Maximum Ratings: (Ta=25℃) .

ITEMS	Symbol	Absolute Maximum Rating	Unit
Forward Current	I_F	20	mA
Peak Forward Current	I_{FP}	30	mA
Suggestion Using Current	I_{SU}	16-18	mA
Reverse Voltage (V_R=5V)	I_R	10	uA
Power Dissipation	P_D	105	mW
Operation Temperature	T_{OPR}	-40 ~ 85	℃
Storage Temperature	T_{STG}	-40 ~ 100	℃
Lead Soldering Temperature	T_{SOL}	Max. 260℃ for 3 Sec. Max. (3mm from the base of the expoxy bulb)	

Absolute Maximum Ratings: (Ta=25℃)

ITEMS	Symbol	Test condition	Min.	Typ.	Max.	Unit
Forward Voltage	V_F	I_F=20mA	1.8	---	2.2	V
Wavelenength (nm) or TC(k)	Δ λ	I_F=20mA	587	---	591	nm
*Luminous Intensity	I_V	I_F=20mA	150	---	200	mcd
50% Viewing Angle	2 θ 1/2	I_F=20mA	40	---	60	deg

Figure 1-9. *A detail from the LED's datasheet*

According to the datasheet, the forward voltage of this LED is rated as 1.8 to 2.2V. So let's say 2V. The LED requires 16–18mA of current, with a maximum of 20mA. Let's use 17mA or 0.017A for the calculations.

Now that you have all of the necessary information, the equation will play out as follows:

- R = (Vs – Vf) ÷ I
- R = (3V-2V) ÷ 0.017A
- R = 58.82Ω

These calculations tell you that you should ideally add 58.82 ohms of resistance to the circuit.

Finding Datasheets

If you order a component online, there will usually be a link to the datasheet on the web catalog page that you ordered the component from. In rare cases, datasheets will be included in the packaging when you purchase a component. If not, the easiest place to start is the Internet. Open your favorite search engine and type in the part number and the word "datasheet" to find it. You will likely find a PDF of the datasheet on the manufacturer's website, the distributor's website, or in a datasheet database, of which there are many on the Web. If you don't know the part number, you can even try a description such as "5mm yellow LED."

The added bonus is that these days many distributors provide an abundance of additional resources on their parts pages. Not only do they include links to datasheets, but also to tutorials, circuit diagrams, circuit board design files, sample code, and sometimes even example projects.

Understanding Resistors

Now you know how much resistance you need. But how do you add resistance to the circuit?

A *resistor* is a component that resists the flow of electricity. It can be implemented in a circuit to use up extra electricity that is not needed by the load.

You know from the Ohm's law equations that you need approximately 58.82Ω resistance for the circuit. However, resistors come in set values, so there may not always be the exact resistor that meets your needs.

If you don't have the exact resistor you're looking for on hand (or if it doesn't exist), you do one of two things:

- Use the next largest value. In your circuit, this will be a 62Ω resistor.
- Combine two resistors in a row that add up to the correct value (e.g., 56Ω + 3Ω = 59Ω).

For your purposes, go with a 62Ω resistor to reduce the amount of wiring. After adding the correct resistor to your circuit, the circuit diagram will look like Figure 1-10.

If you don't have a 62Ω resistor handy, you can use the more common 68Ω value, or even 100Ω.

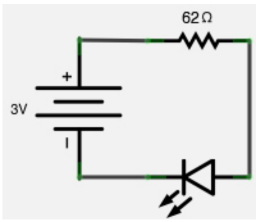

Figure 1-10. *Circuit diagram with 3V battery, LED, and 62Ω resistor*

When looking at the actual component, the value of a through-hole resistor can be determined by the color bands displayed on it. Each color indicates a value. A 62Ω resistor is marked with the colors blue(6), red(2), black(1), and gold(±5%), as shown in Figure 1-11.

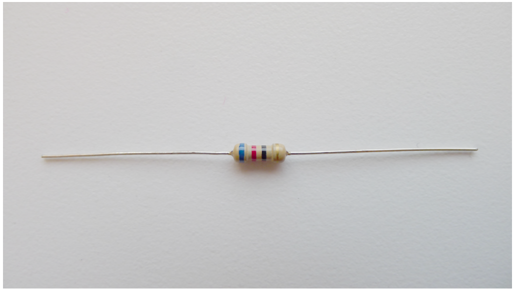

Figure 1-11. *A 62Ω resistor*

You can decode these bands by consulting a resistor color chart, going to a resistor calculator website, or downloading a resistor application for your smartphone. Table 1-1 shows a table you can use to decode a resistor's color codes. Figure 1-12 shows the ResistorCode iPhone app.

When reading the color bands on the resistor, orient it so that the silver or gold band is on the right. Then read the colors from left to right. The first two bands will indicate the first two digits of the number. The third band indicates the multiplier for that digit. The fourth band indicates the tolerance.

Table 1-1. Resistor chart

Color	Value	Multiplier	Tolerance
Black	0	1	-
Brown	1	10	±1%
Red	2	100	±2%
Orange	3	1K	-
Yellow	4	10K	-
Green	5	100K	±0.5%
Blue	6	1M	±0.25%
Purple	7	10M	±0.1%
Gray	8	100M	±0.05%
White	9	1000M	-
Gold	-	1/10	±5%
Silver	-	1/100	±10%
None	-	-	±20%

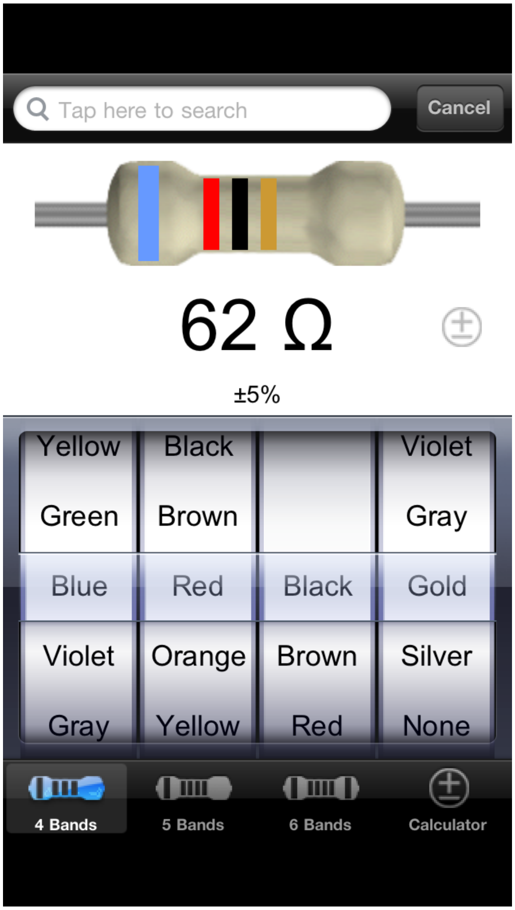

Figure 1-12. *Using a resistor app to decode the colors of a resistor*

Series and Parallel

OK, so you know how to create a circuit with one LED, but how about three? When adding additional components to the circuit, you need to understand the difference between *series* and *parallel*.

Series

In a series, components, like LEDs, are connected in a row. Electricity flows through one, into the next, and then into the next.

Parallel
: In a parallel configuration, components are connected side by side, each with an independent connection to power and ground.

LEDs can be connected in series (Figure 1-13). But the power source must supply adequate voltage. The factor that needs to be considered is called *voltage drop*. When electricity passes through and gets used up by a component, the voltage drops before it moves on to the next component.

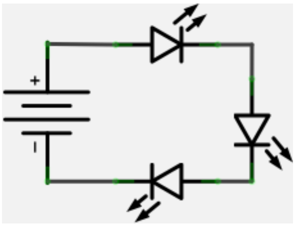

Figure 1-13. *Three LEDs in series*

The LEDs you have been working with in this chapter are rated for a forward voltage drop of 1.8–2.2 volts. This means that if you used a 3V battery as your power source that the first LED would get 2V, the second 1V, and the last no voltage. This obviously won't work. The way to fix this is to use a power source whose voltage could accommodate this voltage drop. Because each of the three LEDs has a voltage drop of around 2V, you would want a battery pack that provided at least 6V.

But there is also another way to connect multiple LEDs to a power source. Figure 1-14 shows three LEDs in parallel.

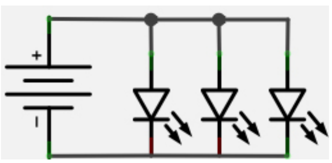

Figure 1-14. *Three LEDs in parallel*

In this situation, each LED receives the same amount of voltage, but the current is divided between them. The only thing missing from this circuit is the resistors. With resistors, the circuit will look like Figure 1-15.

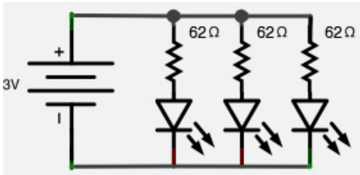

Figure 1-15. *Three LEDs in parallel with resistors*

If all the LEDs are the same, then they will each use the same resistors. However, if you add an LED that requires a different amount of voltage or current, you can use Ohm's law (see "Ohm's Law" on page 3) to calculate which resistor it needs.

Batteries can also be placed in series or in parallel. When batteries are connected in series, the voltage of the two batteries is added together. When they are connected in parallel, the voltage stays the same but their available current is added together.

For instance, AAA batteries usually supply around 1.5V. If two AAA batteries were placed in series (Figure 1-16), their voltage would be added together and the resulting battery pack would provide 3V and the same amount of current as a single AAA battery. If two AAA batteries were placed in parallel (Figure 1-17), the battery pack would supply 1.5V but twice as much current.

Figure 1-16. *AAA batteries in series*

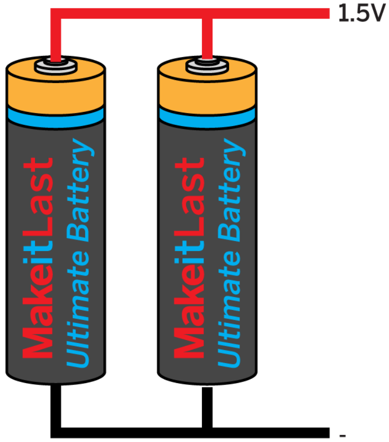

Figure 1-17. *AAA batteries in parallel*

Determining Polarity

Certain electronic components have a predetermined *polarity*. This means that it matters which way the component is connected in the context of a circuit. An LED is a good example.

LED stands for *light-emitting diode*. A *diode* is a component that only allows electricity to pass through it in one direction. If you connect an LED backward, electricity will not be able to pass through it, which means it will not light up.

Depending on the LED, there are four possible ways in which you might determine its polarity (Figure 1-18):

1. With through-hole LEDs, the leg of the anode (positive) side of the LED is usually longer than the cathode (negative).
2. Some manufacturers put a flat spot on the base of the lens of the LED by the cathode leg.
3. If you take a look inside the lens of the LED, you can see that there are two pieces that extend up from the legs. The piece that attaches to the cathode leg is the one with the wider top that slants over the shorter portion of the anode.
4. If all else fails, you can always give it a try on a breadboard or with alligator clips. If it is otherwise properly connected to a power source and doesn't light up, it probably means you have it in the wrong way. Flip it and give it another try.

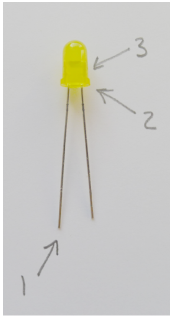

Figure 1-18. *Three places to look when determining the polarity of an LED*

Determining polarity of other components tends to vary, but be on the lookout for a + or – sign, which will indicate the positive or negative side of the component. Red (positive) and black (negative) wires can also be a clue.

Using a Multimeter

Because you cannot see, smell, or hear electricity, you'll need a special tool to detect it. A multimeter, shown in Figure 1-19, can be used to check *continuity* (whether current flows unimpeded through two points) as well as to measure voltage, resistance, and current.

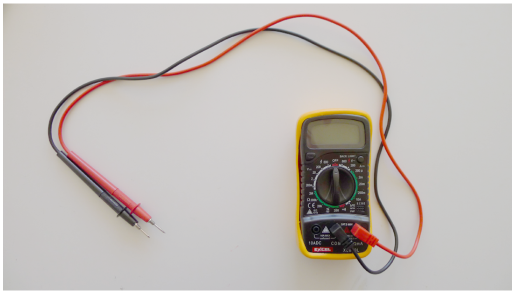

Figure 1-19. *A multimeter*

They usually have a dial (or buttons), shown in Figure 1-20, that are used to select a particular function, and probes (see Figure 1-21) that are used to make connections with whatever it is you are measuring.

Figure 1-20. *The dial of a multimeter is used to select the function*

Figure 1-21. *The connection for the probes; on this meter, you will need to move the red probe to the left if you are measuring current higher than 200mA*

There are a variety of multimeter tutorials available in basic electronics books as well as on the Internet. Check out Appendix C for some references. Here we will just cover the basic concept of what a multimeter does and when you might use it when creating circuits.

Continuity

The simplest but perhaps most useful function of a multimeter is the continuity or conductivity test. This is most often marked on the dial with a speaker or audio symbol (see Figure 1-22) because meters will beep when the test is positive. Once the dial is in position, simply place the probes at two locations across which you'd like to test the continuity or conductivity.

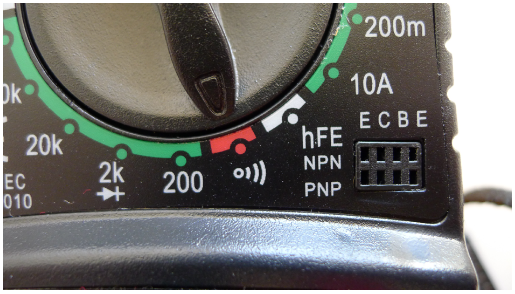

Figure 1-22. *The knob set for a continuity test*

This can be used to check the continuity of a questionable connection. Place the probes on either side of the questionable connection and if the meter beeps, you're good to go.

It can also be used to check for short circuits by placing the probes in two places that are *not* supposed to be connected. If the meter beeps, then you know you've got a short circuit somewhere.

Finally, it can be used to check the conductivity of a material. Place the probes at two points on a material and see if you're able to establish a connection across it (see Figure 1-23). This can be especially useful if you're shopping for conductive materials in unusual places like a fabric store. I recommend investing in a pocket multimeter for just these occasions.

If you are testing a material that you *think* is conductive but the meter doesn't beep, the next step is to measure resistance in ohms, just in case it conducts "well enough" for your needs.

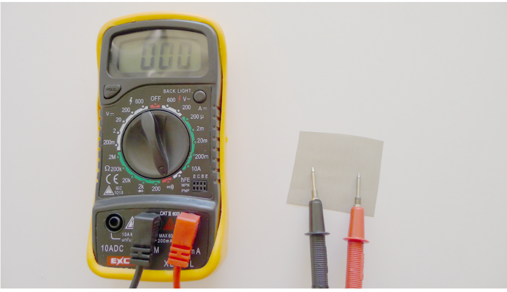

Figure 1-23. *Using a multimeter to test the conductivity of conductive fabric*

Resistance

To measure resistance, turn the knob to the portion of the dial marked with the ohm sign (Ω) and place the probes on either side of the component or material you would like to measure. You can use alligator clips to securely hold the component as shown in Figure 1-24.

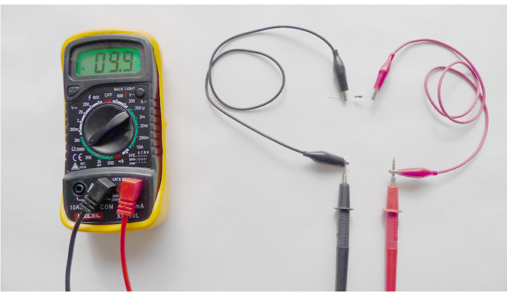

Figure 1-24. *Measuring the resistance of a fixed resistor*

With this setting, you can check the value of a fixed resistor, monitor the changing resistance of a variable resistor, or determine the resistance of a material like conductive thread. If your multimeter is not autoranging, you will have to select a resistance setting that's in the range of what you expect the component to be.

Voltage

Multimeters can also measure voltage. This is helpful for checking the state of a battery or determining if components of a circuit are receiving the voltage that they need. Turn the dial on the multimeter to the "V-" setting, set it to the range of voltage you expect to read, and place the probes on either end of whatever you want to measure (Figure 1-25).

Figure 1-25. *The knob set to measure voltage*

Figure 1-26 shows a battery that is at full strength, and Figure 1-27 shows one that's fading in power.

Figure 1-26. *Reading voltage of a fresh CR2032 battery*

Figure 1-27. *Reading voltage of a CR2032 battery that is fading*

Current

The process for measuring current with a multimeter is a bit different. The meter actually needs to be *in series* with the circuit in order to determine how much current is being pulled. Turn the dial to the "A" or "mA" section and select the appropriate range. With some meters, you may need to move the probe to another terminal at the bottom of the meter. Check your multimeter manual for details. Once you're set up, find a location where you can insert the meter into the circuit and take a reading. Knowing how much current a circuit draws at its peak usage and over time can be extremely helpful in terms of determining which battery to select for your project. More on this in Appendix B.

More About Circuits

The world of circuits is wide and wonderful. This chapter only covers the details that you needed to know in order to build the examples that follow in this book. To learn more, be sure to check out books like *Make: Electronics* by Charles Platt (O'Reilly), *Practical Electronics for Inventors* by Paul Scherz and Simon Monk (McGraw-Hill/TAB Electronics), and *Getting Started in Electronics* by Forrest Mims (Master). Details about these resources and others can be found in Appendix C.

Constructing Circuits

As you learned earlier, conductors or conductive materials are materials through which electricity can pass. When constructing a circuit, conductive materials provide the pathway for electricity to flow from one component to another.

Now that you have some understanding of how circuits work and how to measure different aspects of them, you can start to think about how to physically construct them. This section will illustrate a variety of ways to bring this basic LED circuit to life.

As you move through different iterations of this circuit, you'll see that through the use of different conductive materials it can take on many shapes and sizes. The core electronic components that you work with will be the same in each circuit. What will differ is the materials and tools you use to create the connections between the components.

Figure 1-28 shows the circuit you will create.

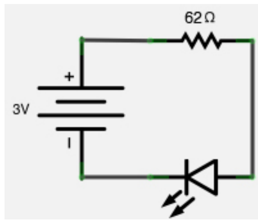

Figure 1-28. *A circuit with a 3V battery, LED, and resistor*