SECOND EDITION

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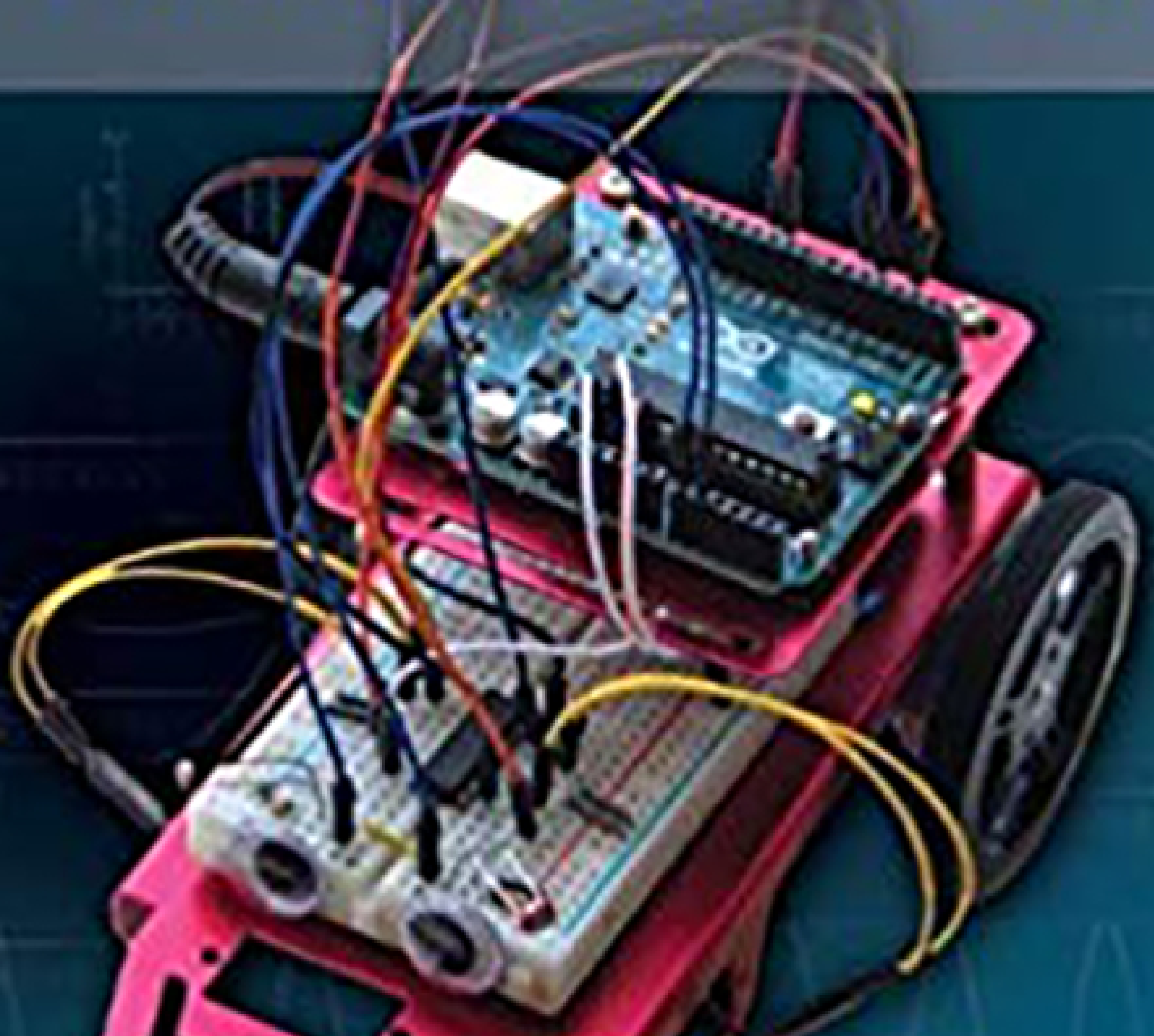
JEREMY BLUM

EXPLORING ARDUINO®

TOOLS AND TECHNIQUES FOR ENGINEERING WIZARDRY



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Tools and Techniques for Engineering Wizardry

Second Edition

Jeremy Blum

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*To Leah, for helping me to see every
challenge as an opportunity.*

About the Author

Jeremy Blum is currently the director of engineering at Shaper (shapertools.com), where he is using computer vision to reinvent the way people use handheld power tools. Prior to joining Shaper, Jeremy was a lead electrical architect/engineer for confidential products at Google [x], including Google Glass.

Jeremy received his master's and bachelor's degrees in Electrical and Computer Engineering from Cornell University. At Cornell, he co-founded and led Cornell University Sustainable Design, he launched a first-of-its-kind entrepreneurial co-working space for students, and he conducted robotics and machine learning research.

Jeremy has designed prosthetic hands, fiber-optic LED lighting systems, home-automation systems, 3D printers and scanners, self-assembling robots, wearable computing platforms, augmented reality devices, and learning robots. His work has been featured in international conferences, peer-reviewed journals, and popular media outlets such as Discovery Channel, the *Wall Street Journal*, and *Popular Science* magazine. *Forbes* magazine named him to their annual "30 Under 30" list in recognition of his work that has "helped America make things and get stuff done." He is the co-author of several patents in the fields of wearable computing and augmented reality fabrication.

When not building products, Jeremy is teaching. His written and video tutorials have been utilized by millions of people to learn electrical engineering and embedded software design. His book, *Exploring Arduino*, has been translated into multiple languages and is used as an engineering textbook around the world, including at his alma mater, Cornell. Jeremy's passion is using engineering to improve people's lives, and giving people the tools they need to do the same. You can learn more about Jeremy at his website, jeremyblum.com.

About the Technical Editor

Dr. Derek Molloy is an associate professor in the Faculty of Engineering and Computing's School of Electronic Engineering at Dublin City University, Ireland. He lectures at undergraduate and postgraduate levels in object-oriented programming with embedded systems, digital and analog electronics, and connected embedded systems. His research contributions have largely been in the fields of computer and machine vision, embedded systems, 3D graphics/visualization, and e-learning. Derek produces a popular YouTube video series that has introduced millions of people to embedded Linux and digital electronics topics. In 2013, he launched a personal web/blog site that is visited by thousands of people every day and that integrates his YouTube videos with support materials, source code, and user discussion. He has published other books in this Wiley mini-series: *Exploring BeagleBone* in 2015, followed in 2016 by *Exploring Raspberry Pi*. The second edition of *Exploring BeagleBone* was released earlier this year. You can learn more about Derek, his work, and his other publications at his personal website, `derekmolloy.ie`.

Acknowledgments

In the several years since the first edition of this book was released, I've received so many notes from readers who have told me about the many ways that they've learned from *Exploring Arduino*. I've also received plenty of constructive criticism—little things that I can adjust to improve the book's utility. I've taken all these comments to heart and have tracked them carefully over the past few years. It is my intention to make this second edition even more useful than the first, while still maintaining the approachability that many readers told me that they appreciated. So, THANK YOU to everybody who has given me feedback about the first edition of *Exploring Arduino*!

Second, I must extend my thanks again to Wiley. They've been amazing partners through this journey, and I'm glad to have them to continue to see this book through to a second edition. In particular, I'd like to thank Jim Minatel, Adaobi Obi Tulton, Dr. Derek Molloy, Marylouise Wiack, and Athiyappan Lalith Kumar.

Thanks also to the wonderful folks at Adafruit, who have collaborated with me on ensuring that parts kits are easy to obtain for this book. Adafruit contributes heavily to the open source hardware and software communities, and I certainly would not be the engineer that I am today without their excellent products and guides.

Back when I wrote the first edition of *Exploring Arduino*, I was still getting my master's degree. I've long since graduated, but now I've got my work at Shaper to focus on. I owe a big thanks to all my co-workers both at Shaper and at Google (my previous employer) for always encouraging me, and for building awesome hardware with me!

I want to give a special shout-out to my professors at Cornell, especially Professor François Guimbretière, who taught the course where I was first introduced to Arduino. He has since used the first edition of this book as a textbook for that course, and it makes me so happy to know that I've been able to give back to Cornell in that capacity.

Finally, I want to thank my parents, my brother, my wife, and my friends for putting up with me, and for always encouraging me. I feel so fortunate to have such wonderful people in my life.

Contents at a Glance

Contents

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Introduction

When the first edition of this book came out in 2013, I opened it with the following greeting:

> *You have excellent timing. As I often like to say, "We're living in the future."*

I think I backed myself into a corner with that introduction, because if 2013 was "the future," then I'm not quite sure what to call the present! The *far future*? The *future-future*? My point is, the march of progress has been swift, and the possibilities for what you can do with even a cursory knowledge of embedded electronics and software continue to expand every day.

Since the first edition of this book was released, electronics and software have continued to become increasingly accessible with every passing day. In 2013, I was hesitant to include a chapter about connecting your hardware projects to the internet because the process for doing so was still quite fussy. The "Internet of Things" (IoT) was just an emerging nerdy buzzword in 2013. Now, it's a key part of the global vernacular. It seems like every product for sale nowadays contains a microcontroller. Everything is "smart" and most of those things also feature phone or web connectivity. I bet you didn't think you'd be buying a Bluetooth-enabled toothbrush back when "Bluetooth" just referred to people talking to themselves through their wireless cellphone headsets.

Considering all this, I felt it was time to release a new edition of *Exploring Arduino*. This second edition expands upon everything that was covered in the first edition. It updates all the projects with new challenges and details, clarifies questions that people had from the first edition, and adds a plethora of new content, including a lot more details on wireless connectivity, new Arduino hardware, changes to the Arduino ecosystem and software, and more.

Why Arduino?

With the tools available to you today, many of which you'll learn about in this book, you have the opportunity and the ability to bend the physical world to your whim. Until very recently, it has not been possible for someone to pick up a microcontroller and use it to control their world within minutes. A *microcontroller* is a programmable integrated circuit (IC) that gives you the power to define the operation of complex mechanical, electrical, and software systems using relatively simple commands. The possibilities are endless, and the Arduino microcontroller platform will become your new favorite tool as you explore the world of electronics, programming, human-computer interaction, art, control systems, and more. Throughout the course of this book, you'll use the Arduino to do everything from detecting motion to creating wireless control systems to communicating over the internet.

Whether you are completely new to any kind of engineering or are a seasoned veteran looking to get started with embedded systems design, the Arduino is a great place to start. Are you looking for a general reference for Arduino development? This book is perfect for you, too. It walks you through a number of separate projects, but you'll also find it easy to return to the book for code snippets, best practices, system schematics, and more. The electrical engineering, systems design, and programming practices that you'll learn while reading this book are widely applicable beyond the Arduino platform and will prepare you to take on an array of engineering projects, whether they use the Arduino or some other platform.

Who This Book Is For

This book is for Arduino enthusiasts of all experience levels. Chapters build upon each other, utilizing concepts and project components from previous chapters to develop more complex ideas. But don't worry. Whenever you face new, complex ideas, a cross-reference reminds you where you first encountered any relevant building-block concepts so that you can easily refresh your memory.

This book assumes that you have little or no previous experience working with programming or electrical engineering. Using feedback from readers of the first edition of this book, I've taken special care to be very detailed in my explanation of the more confusing topics you may encounter. To effectively support readers of various experience levels, the book features several optional sections and *sidebars*, or short excerpts, that explain a particular concept in greater detail. Although these sidebars are not necessary for you to gain a good understanding of how to use the Arduino, they do provide a closer look at technical topics for the more curious reader.

What You'll Learn in This Book

This book is not a recipe book. If you want to follow step-by-step instructions that tell you exactly how to build a particular project without actually explaining why you are doing what you are doing, this book is not for you. You can think of this book as an introduction to electrical engineering, computer science, product design, and high-level thinking using the Arduino as a vehicle to help you experience these concepts in a hands-on manner.

When building hardware components of the Arduino projects demonstrated in this book, you'll learn not just how to wire things together, but also how to read schematics, why particular parts are used for particular functions, and how to read datasheets that will allow you to choose appropriate parts to build your own projects. When writing software, I provide complete program code, but you will first be stepped through several iterative processes to create the final program. This will help to reinforce specific program functions, good code-formatting practices, and algorithmic understanding.

This book will teach physics concepts, algorithms, digital design principles, and Arduino-specific programming concepts. It is my hope that working through the projects in this book will not just make you a well-versed Arduino developer, but also give you the skills you need to develop more-complex electrical systems, and to pursue engineering endeavors in other fields, and with different platforms.

Features Used in This Book

The following features and icons are used in this book to help draw your attention to some of the most important or useful information in the book:

WARNING Be sure to take heed when you see one of these asides. They appear when particular steps could cause damage to your electronics if performed incorrectly.

TIP These asides contain quick hints about how to perform the task at hand more easily and effectively.

NOTE These asides contain additional information that may be of importance to you, including links to videos and online material that will make it easier to follow along with the development of a particular project.

SAMPLE HEADING

These asides go into additional depth about the current topic or a related topic.

Getting the Parts

In preparing the projects outlined in this book, I've taken special care to use components that are readily available through a variety of retailers, both in the United States and internationally. I've also partnered with Adafruit (`adafruit.com`), a popular retailer of hobbyist electrical components. You can purchase all the components required for completing the projects in this book from Adafruit. A convenient listing of Adafruit parts for each chapter is available at `exploringarduino.com/kits`.

At the beginning of each chapter, you'll find a detailed list of parts that you need to complete that chapter—all of these parts are available from many sources. The companion website for this book, `www.wiley.com/go/exploringarduino2e`, also provides links to multiple sources where you can find the parts for each chapter.

What You'll Need

In addition to the actual parts that you'll use to build your Arduino projects, there are a few other tools and materials that you'll need on your Arduino adventures. Most importantly, you'll need a computer that is compatible with the Arduino integrated development environment (IDE) (Mac OS X 10.7 Lion or newer, Windows XP or later, or a Linux distro). I will provide instructions for all operating systems when warranted.

Arduino now also has an entirely web-based editor, but this book will generally focus on the desktop IDE. All the instructions for the desktop software generally apply to the online IDE as well. The first version of this book was read by people all over the world, representing a wide range of internet speeds and reliability. To ensure that Arduino remains easily accessible to all, I'll mostly provide instructions that use the offline IDE, as constant internet access isn't always an option for everybody.

You may also want some additional tools that will be used throughout the book to debug and assemble hardware. These tools are not only necessary to complete the projects in this book. As you develop your electrical engineering skillset, they will come in handy for other projects, too. I recommend the following:

- A soldering iron and solder (Note: A few shields and microcontroller boards used in the final chapters of this book may be sold with some soldering required—this usually involves easy soldering of thru-hole pins to a circuit board.)
- A multimeter (This will be useful for debugging concepts within this book, but is not required.)
- A set of small screwdrivers
- Tweezers
- Wire cutters and wire strippers
- A hot glue gun
- A magnifying glass (Electronics are small, and sometimes it's necessary to read the tiny, laser-etched markings on integrated circuits in order to look up their datasheets online.)

Source Code and Digital Content

The primary companion site for this book is exploringarduino.com, and it is maintained by the author. You will find code downloads for each chapter on this site (along with videos, links, and other useful materials). Note that both 1st edition and 2nd edition content is available at this URL—ensure that you are visiting the pages for this edition of the book. Digital content for the first edition is located at exploringarduino.com/content1/ . . . and digital content for the second edition of this book is located at exploringarduino.com/content2/ . . . . The website clearly differentiates between content for the two editions of the book and is easy to navigate.

Wiley also maintains a repository of digital content that accompanies this book at wiley.com/go/exploringarduino2e. You can also search for the book at wiley.com by ISBN (the ISBN for this book is 9781119405375) to find links to book resources.

The code for this book is hosted on GitHub.com (a popular platform for sharing open source software). Throughout each chapter, you can find references to the names of code files as needed in listing titles and text. Each chapter's code packages will be linked from exploringarduino.com and wiley.com. You can download the code as a compressed ZIP archive from either source. After you download the code, just decompress it with an appropriate decompression tool—all operating systems have one built in. You can also pull code directly from this book's GitHub repository (which is linked from exploringarduino.com) if you are comfortable working with Git-based version control.

NOTE Because many books have similar titles, you may find it easiest to search by ISBN; this book's ISBN is 9781119405375.

NOTE Some URLs (especially the ones that I don't control) may change or be very long. To make it easier to type in long URLs that I may reference throughout the book, I will list a "shortened URL" using my personal domain name shortener: blum.fyi. For example, blum.fyi/jarvis redirects to a longer URL on my website about a project called "JARVIS."

Errata

We make every effort to ensure that there are no errors in the text or in the code. However, no one is perfect, and mistakes do occur. If you find an error in this book, such as a spelling mistake or faulty piece of code, we would be grateful for your feedback. By sending in errata, you may save another reader hours of frustration, and at the same time, you can help us provide even higher-quality information.

To find the errata page for this book, go to `wiley.com/go/exploringarduino2e` and click the Errata link. On this page, you can view all errata that has been submitted for this book and posted by Wiley editors. I also review all errata reports and post errata notes to `exploringarduino.com` on each chapter page.

Supplementary Material and Support

During your adventures with your Arduino, you'll inevitably have questions and perhaps run into problems. One of the best aspects of using the Arduino is the excellent support community that you can find on the web. This extremely active base of Arduino users will readily help you along your journey. I maintain a list of updated resources for getting help with Arduino, electrical engineering, and embedded software on the Exploring Arduino Resources page:

`exploringarduino.com/resources`

I used to try to answer people's individual Arduino questions directly, but that's unfortunately no longer possible due to the sheer volume of questions that I receive through my website, Twitter, Facebook, YouTube, and other channels. I highly encourage you to seek help through the forums linked from the Resources page listed here. I can almost guarantee that their response times will be faster than mine.

What Is an Arduino?

The best part about the Arduino prototyping platform is that it's whatever you want it to be. The Arduino could be an automatic plant-watering control system. It could be a web server. It could even be a quadcopter autopilot.

The Arduino is a microcontroller development platform paired with an intuitive programming language that you develop using the Arduino integrated development environment. By equipping the Arduino with sensors, actuators, lights, speakers, add-on modules (called *shields*), and other integrated circuits, you can turn the Arduino into a programmable "brain" for just about any control system.

It's impossible to cover everything that the Arduino is capable of, because the possibilities are limited only by your imagination. Hence, this book serves as a guide to get you acquainted with the Arduino's functionality by executing several projects that will give you the skills you need to develop your own projects.

You'll learn more about the Arduino and the available variations of the board in Chapter 1, "Getting Started and Understanding the Arduino Landscape." If you're eager to know all the inner workings of the Arduino, you're in luck: It is completely open source, and all the schematics and documentation are freely available on the Arduino website. Appendix A, "Deciphering Datasheets and Schematics," covers some of the Arduino's technical specifications.

An Open Source Platform

If you're new to the world of open source, you are in for a treat. This book does not go into detail about the open source hardware movement, but it is worth knowing a bit about the ideologies that make working with the Arduino so wonderful. If you want a full rundown of what open source hardware is, check out the official definitions on the Open Source Hardware Association website (`blum.fyi/OSHW-Definition`).

Because the Arduino is open source hardware, all the design files, schematics, and source code are freely available to everybody. This means that you can more easily hack the Arduino to serve a very particular function, and also integrate the Arduino platform into your designs, make and sell Arduino clones, and use the Arduino software libraries in other projects. There are hundreds of Arduino derivative boards available (often with specialized functions added on to them).

The Arduino open source license also permits commercial reuse of their designs (so long as you don't utilize the Arduino trademark on your designs). So, if you use an Arduino to prototype an exciting project and you want to turn it into a commercial product, you can do that.

Be sure to respect the licenses of the source code and hardware that you use throughout this book. Some licenses require that you provide attribution to the original author when you publish a design based on their previous work. Others require that you always share improvements that you make under an equivalent license. This sharing helps the community grow, and leads to all the amazing online documentation and support that you'll often refer to during your Arduino adventures. All code examples that I've written for this book (unless otherwise specified) are licensed under the MIT License, enabling you to use them for anything you want.

Beyond This Book

You may already be familiar with my popular series of YouTube Arduino and electronics tutorials (`youtube.com/sciguy14`). I refer to them throughout this book as a way to see more-detailed walkthroughs of the topics covered here. If you're curious about some of the remarkable things that you can do with clever combinations of electronics, microcontrollers, computer science, and creativity, check out my portfolio (`jeremyblum.com/portfolio`) for a sampling of projects. Like Arduino, most of what I do is released via open source licenses that allow you to easily duplicate my work for your own needs.

I'm anxious to hear about what you do with the skills you acquire from this book. I encourage you to share them with me and with the rest of the world (use the tag *#ExploringArduino* on social media). Good luck on your Arduino adventures!

Arduino Engineering Basics

Exploring Arduino®: Tools and Techniques for Engineering Wizardry, Second Edition.
Jeremy Blum.