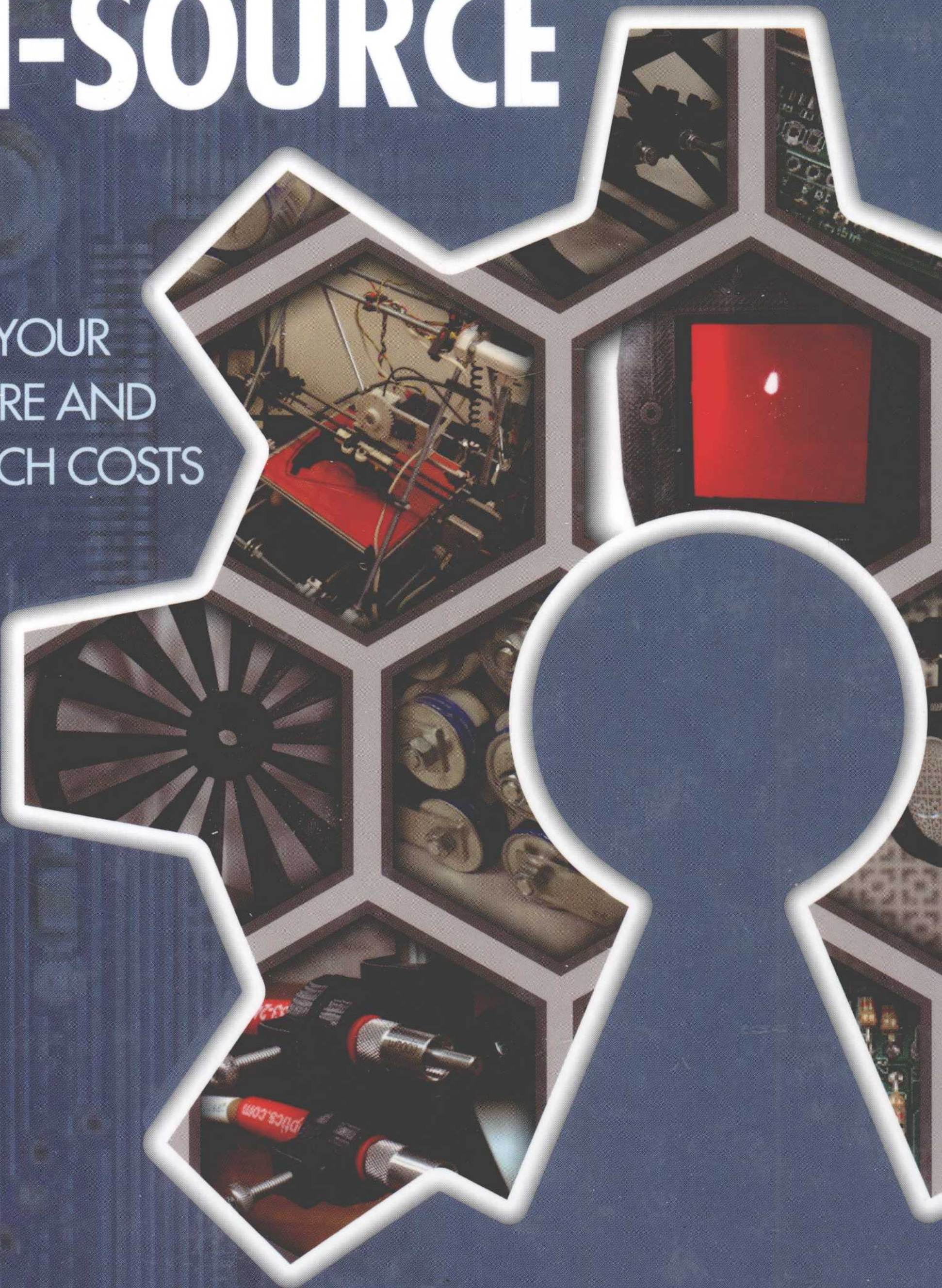
ELSEVIER

JOSHUA M. PEARCE

OPEN-SOURCE LAB

HOW TO BUILD YOUR OWN HARDWARE AND REDUCE RESEARCH COSTS



Open-Source Lab

How to Build Your Own Hardware and Reduce Research Costs

Joshua M. Pearce
Department of Materials Science & Engineering,
Department of Electrical & Computer Engineering,
Michigan Technological University,
Houghton, MI, USA

ELSEVIER
AMSTERDAM • BOSTON • HEIDELBERG • LONDON • NEW YORK • OXFORD
PARIS • SAN DIEGO • SAN FRANCISCO • SYDNEY • TOKYO

Elsevier
225 Wyman Street, Waltham, MA 02451, USA
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK
Radarweg 29, PO Box 211, 1000 AE Amsterdam, The Netherlands

Library of Congress Cataloging-in-Publication Data
Pearce, Joshua, author.
Open-source lab : how to build your own hardware and reduce research costs / Joshua Pearce.
pages cm
Includes bibliographical references and index.
1. Laboratories--Equipment and supplies. 2. Open source software. I. Title.
Q185.P43 2013
681'.750285--dc23
2013035658

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN: 978-0-12-410462-4

Note: For color version of the figure, the reader is referred to the online version of this book.

For information on all **Elsevier** publications
visit our web site at store.eslevier.com

Printed and bound in USA
14 15 16 17   10 9 8 7 6 5 4 3 2 1

Open-Source Lab

Foreword

At the heart of open-source hardware is the freedom of information. We are inherently free to open our devices as we wish and poke around. There are no laws inhibiting a consumer to unscrew their household items and take the lid off—though it most likely voids the warranty. But the freedom to repair, freedom to study, and freedom to understand needs to be accompanied with a freedom of accessible information: schematics, diagrams, code, and in short source files. Open-source hardware includes the previous freedoms and also grants the freedom to remix, remanufacture and resell an item, provided that the hardware remains open source.

History points to a multitude of repair manuals from cars to washing machines; patterns to follow from model airplanes to dresses; and recipes shared through friends and families for generations. Historically DIY (Do-It-Yourself) was not a fad but a way of life. Access to information coupled with a basic knowledge of tinkering has given consumers the power to fix more, waste less, and understand the physical world around them. But technologies are becoming more opaque, as their size gets smaller, making them more difficult to open and tinker. Historically, an important factor for understanding the physical world was that items were built on a human scale. Human scale is the one that humans can relate to and can visibly see with the naked eye. The scale of most objects previous to computing has been on the human scale. Items in our daily lives now include miniscule chip sets and tiny form factors that require schematics and code to diagnose, repair, or even understand. Perhaps no one understands this better than researchers themselves. With closed source and patented devices, there is no requirement to include source files so that people may understand the hardware. In many cases, steps are taken to obfuscate information from the consumer. In addition to documentation, many new inventions require special equipment and tools, such as laser cutters, PCR machines for DNA sequencing, environmental chambers and other lab equipment described in Pearce's work. These tools are beginning to see open-source versions so that consumers may build their own, often at a lower cost. Even more standard tools, such as tractors and

CNC machines are being open sourced so that others may have the benefit of access to these basic tools.

If history has favored open source, why are we entering a new movement of open-source hardware? Patents have become problematic to innovation. Basic building blocks of new technologies are being closed off with patents, causing further innovation to become increasingly expensive or halt altogether. While patenting the building blocks of technology may benefit one company, it fails to advance society. Today Intellectual Property can be sold as a good. The *idea* is the commodity rather than the physical object itself. Selling ideas rather than goods does not create a sustainable market for the common consumer. Patents were created to incentivize inventors and spur innovation in exchange for 20 years of exclusive rights in the form of a monopoly. The patentee had to submit a prototype and disclose how their innovation was created to the public. But the rules on patents have changed over time and there are many schools of thought that the patent system is broken and no longer reflects the reasons why the patent system was created in the first place. In today's patent system, prototypes are no longer required, money made from patents is going to lawyers rather than the inventor, and a 20 years monopoly is not a rational timeframe for the pace of technology in the digital era. Inventors are finding different incentives to innovate. The barriers and frustrations the patent system, has created are turning inventors toward a new alternative to patents: open-source hardware.

Open-source hardware creates products driven by capitalism rather than monopolies, an open environment for sharing information, and a powerful opportunity for companies and individuals to learn from each other. Open-source hardware is a growing movement with a lucrative business model. It has spread into many areas of innovation, as Pearce has done with his work in scientific hardware, others do in electronics, mechanical designs, space programs, farm equipment, fashion, and materials science to name a few. We are at a crucial point in the history of technology which will determine if we hoard information or share it with others; sell information or sell goods; educate with open documentation or let everyone reinvent the wheel for themselves.

—Alicia Gibb
Founder, Open Source Hardware Association

Preface

As the process of development that has succeeded in free and open-source software is now being applied to hardware, an opportunity has arisen to radically reduce the cost of experimental research in the sciences while improving the tools that we use. Specifically, the combination of open-source 3-D printing and open-source microcontrollers running on free software enables the development of powerful research tools at unprecedented low costs. In this book, these developments are illustrated with numerous examples to lay out a path for reinforcing and accelerating free and open-source scientific hardware development for the benefit of science and society. Wise scientists will join the open-source science hardware revolution to see the costs of their research equipment drop as their work becomes easier to replicate and cite.

Most scientists who do experimental work are familiar with and somewhat acclimated to the often extreme prices we pay for scientific equipment. For example, last year, I received a quote for a $1000 lab jack. A lab jack is not an overly special or sophisticated research tool; it simply moves things up and down like a jack for a car, only more precisely and the "things" it has to move are much smaller. That price for the application I was planning on using it for (moving millimeter-scale solar photovoltaic cells into a beam of light) was absurd, but as many researchers in academia know, the prices are effectively multiplied because of institutional overheads. Thus, at my institution for example, where we pay 71% overhead for industry-sponsored research, purchasing that lab jack would demand that I raise $1710 from sponsors! Historically, you, I and the rest of the scientific community had no choice—we had to buy proprietary tools to participate in state-of-the-art research or develop everything from scratch. Thus, we had to choose between paying exorbitant fees or investing a lot of our own time as even the simplest research tools like a lab jack are time-consuming to fabricate from scratch. No more! Now the combination of open-source microcontrollers and 3-D printers enables all of us to fabricate low-cost scientific equipment with far less-time investment than ever possible in the history of science. If you want the complete digital designs

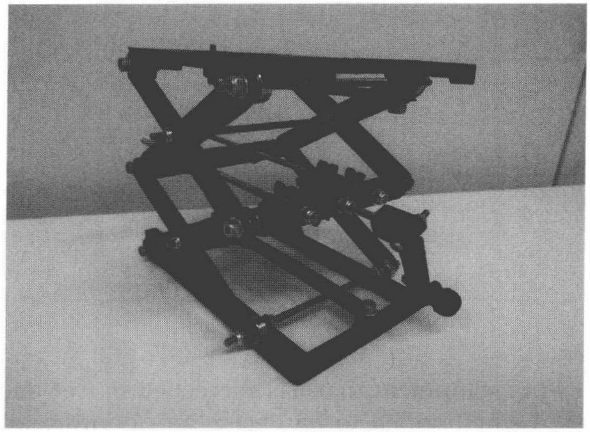


FIGURE 1

An open-source lab jack. A lab jack is a height-adjustable platform ideal for mounting optomechanical subassemblies that require height adjustment. This lab jack was developed by the Michigan Tech Open Sustainability Technology Lab group primarily by Nick Anzalone and the gears were developed by Thingiverse user: GregFrost. The OpenSCAD files (raw source code), STL files (for printing) and instructions can be found at http://www.thingiverse.com/thing:28298.

of a lab jack, you can print for a few dollars (Figure 1).[1] In fact, for $1710, you could buy yourself a nice 3-D printer and print hundreds of lab jacks and other high-value equipment for your friends, colleagues and family! Scientists have been catching on and the files for the lab jack have already been downloaded thousands of times.

Lower cost and less-time investment are actually only secondary benefits of using open-source hardware in your lab. The main advantages of the "open-source way" in science is customization and control. Rather than buy what is on the shelf or available from vendors online, you can create scientific instruments that meet your exact needs and specifications. This really is priceless (Figure 2). The ability to customize research tools is particularly helpful to those on the bleeding edge of science, which need custom, never-seen-before equipment to make the next great discovery. If the tools and software you use to run your experiments are open source, you and your lab group have complete control over your lab. If you hold the code, your lab will never be left empty handed (or stuck with extremely expensive paper weights) when commercial vendors go out of business, drop a product line, or lose key technical staff. Every research university in the world is sitting on millions of dollars of broken scientific equipment that is too expensive or time-consuming to repair. With open-source hardware, these problems largely evaporate. Similarly, if you only

[1]http://www.thingiverse.com/thing:28298

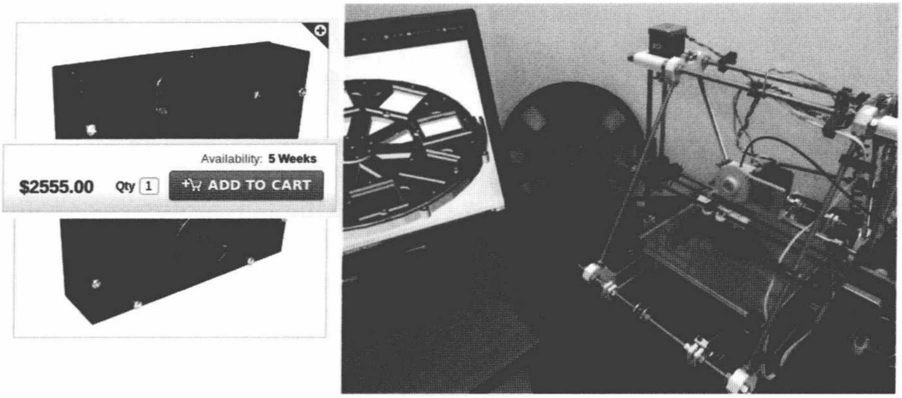


FIGURE 2

The ability to customize high-quality research-grade scientific equipment is priceless, yet it often costs orders of magnitude less than conventional proprietary tools.

use open-source hardware rather than locked-down proprietary tools, your lab cannot be held for ransom by dishonest hardware vendors. It is perhaps important to note here that "open source" does not necessarily mean "free" as we will discuss in Chapter 1. Making open-source hardware following the process outlined in this book almost always results in much lower costs. However, the open-source scientific hardware movement is still developing and all the research tools you need may not have been developed yet. For scientific hardware that we do not fabricate in our own lab, we will pay a premium for open-source equipment and free software because of the access to the control or simply because it is superior (as discussed in Chapter 2). I am far from alone in thinking this way. One of the computers I am typing this book on is running a version of Linux[2] developed by Red Hat. Although Red Hat's software is freely available for download on the Internet, they make over US$1 billion per year essentially selling service to help people maintain it and optimize it for their applications.

---

[2]Linux is a free and open-source computer operating system, which comes in many varieties. The majority of the rest of the book was written on a laptop running Ubuntu Linux (http://www.ubuntu.com/) and my lab is currently making the transition to Debian (http://www.debian.org/).

In our lab, whenever possible, we want control over our own equipment, thus we use open-source hardware and software as much as possible. We now develop the majority of our tools in at least some way using the open-source paradigm. Now we have joined a virtuous cycle—as our research group shares our designs for research equipment with others, they make them better and share their improvements back with us. I should be clear here; this goes far beyond simple benevolent sharing or charity. **Our lab equipment quality improves because we actively share.** In this way, we all benefit.

For those working at academic, government and industry laboratories, this book is meant to be an introductory guide on how to join and take advantage of all the benefits of open-source hardware for science. Chapter 1 covers the basics of open source, a brief overview of the history and etiquette of open-source communities. The theoretical argument for why this method of technological development is superior to the standard models is laid out in Chapter 2, which describes why nice guys finish first both in research and at the industrial scale. Chapter 3 covers the nitty-gritty of open-source licensing. Chapters 4 and 5 describe the two most useful tools for fabricating open-source scientific equipment, the Arduino microcontroller and RepRap 3-D printer, respectively. Chapter 6 is the heart of the book and describes digital designs for open-source scientific hardware in physics, engineering, biology, environmental science and chemistry. Finally, in Chapter 7, we take a peek at the future and possible ramifications of large-scale adoption of open-source hardware and software for science.

A note to readers: This book is not necessarily the kind of text you read from cover to cover. If you are already "at one with the force of open source" and just want to get your hands dirty—start building by skipping to Chapter 4. Similarly, only a few of the examples in Chapter 6 will be relevant to your work—no need to learn about PCR if you are a physicist researching new nanoscale solid-state detector technologies—just go right to the tools that will be most helpful to you... share and enjoy.

1.1. STANDARD DISCLAIMER

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or safety may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, equipment, compounds, or experiments described herein. In using such information or methods, they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the author, contributors, or editors assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

Joshua M. Pearce, Ph.D.

Associate Professor
Department of Materials Science & Engineering Department of Electrical &
Computer Engineering Michigan
Technological University Houghton, MI USA

Acknowledgments

First and foremost, and on a personal note, I would like to thank my wonderful wife, Jen, for putting up with the long hours of writing this text, turning various parts of our house into electronics, 3-D printing and scientific labs as the need arose, her support and also for reading and critiquing the manuscript.

I would like to thank my children, Emily and Jerome, who actually helped with some of the making of my first 3-D printer and with various experiments throughout the years.

I would also like to thank the rest of my family: Mom and Dad, Solomon, Mary Rachel and Elijah for their support and encouragement. A special thanks to Mary Rachel for giving me a copy of *Makers* by Cory Doctorow, which laid some of the ground work for this book.

I would like to thank Elsevier for having the foresight and courage for both publishing this book and also ensuring that it is maintained in the open-source ethos by making it available to the widest possible scientific audience. For this, I especially thank Beth Campbell, Jill Cetel, Paula Callaghan, Cathleen Sether, and Laura Colantoni for making this book a reality.

This book was truly a massive international and asynchronous collaboration that extends back years and contains the genius and insights of people I have worked closely with, but also many whom I have never met (or may only know of through their esoteric Internet handles).

First, from the past and present members of my own research group at Michigan Tech—the Michigan Tech Open Sustainability Technology Lab, I would like to thank for fruitful collaboration: Nick Anzalone, Megan Kreiger, Chenlong Zhang, Ben Wittbrodt, Allie Glover, Brennan Tymrak, Meredith Mulder, Ankit Vora, John Laureto, Joseph Rozario, Jephias Gwamuri, Alicia Steele, Thad Waterman, and Paulo Seixas Epifani Veloso. Special thanks goes to Rodrigo Periera Faria, Bas Wijnen and Jerry Anzalone for collaboration and contributions to major sections of this book and for reading drafts of portions of the manuscript. I would also like to thank other Michigan Tech collaborators and supporters: Doug Oppliger, John Irwin, Allison Hein, and the support and leadership of both of my department heads, Steve Kampe in Materials Science and Engineering and Dan Fuhrmann in Electrical and Computer Engineering.

In addition, my former students at Queen's University helped me get started with the wondrous RepRap and on the train of thought that led to this book: Christine Morris Blair, Kristen Laciak, Steven Keating, Christian Baechler, Matthew DeVuono, Amir Nosrat, Ivana Zelenika, and Rob Andrews.

I would also like to acknowledge the funders, supporters and corporate sponsors for some of this and related work, including the McArthur Internship at Michigan Tech, the National Science Foundation, Natural Sciences and Engineering Research Council of Canada, Superior Ideas (and supporters through it), the Appropedia Foundation, Re:3D, Tech for Trade, Ocean Optics, Type A Machines, MatterHackers, Ultimachine, and the Square One Education Network.

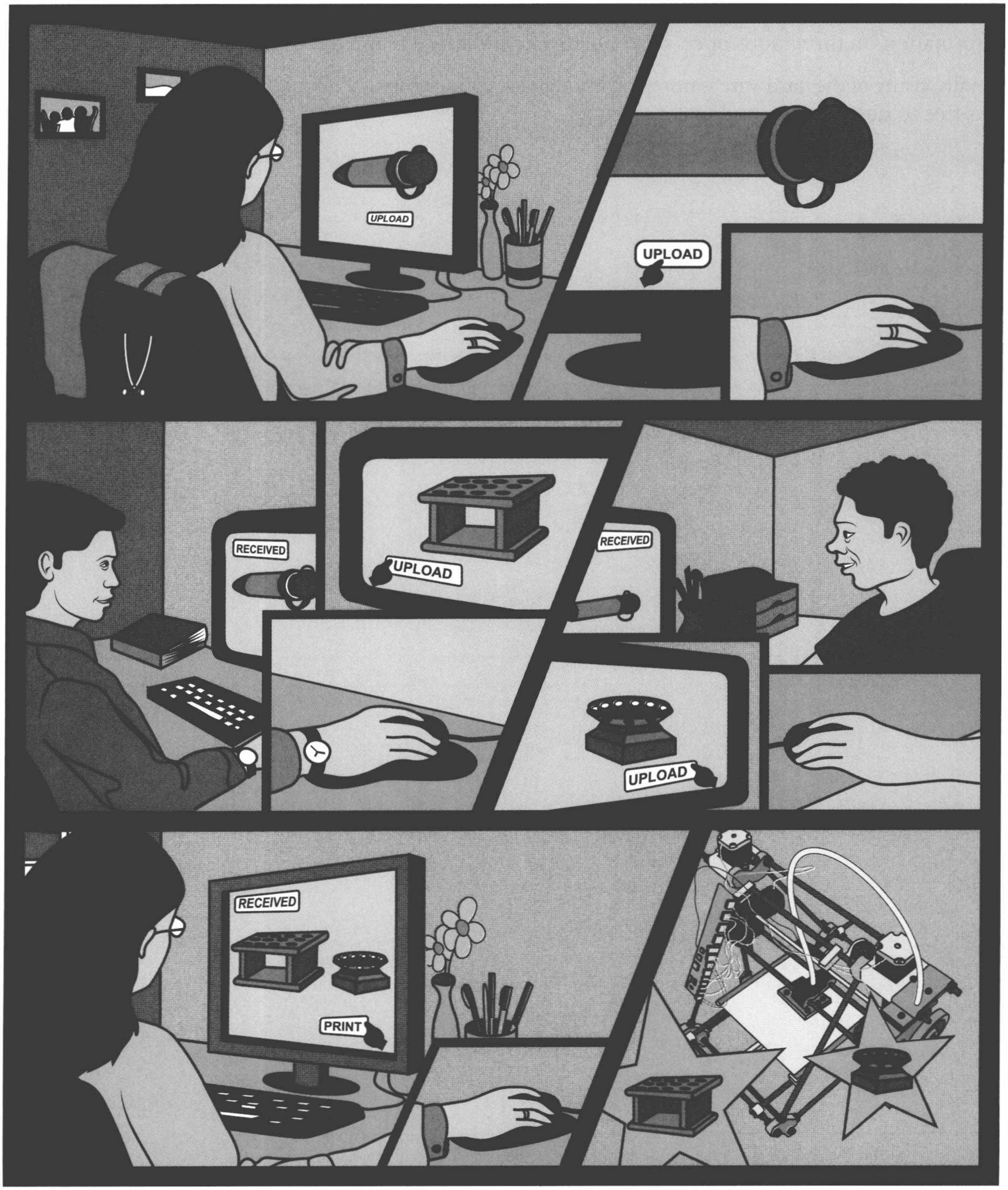
I would like to acknowledge helpful discussions about enabling innovation from Scott Albritton, Gabriel Grant and Garrett Steed. For their ongoing support, I thank the Appropedia community and, in particular, Lonny Grafman and Chris Watkins. A giant thank you goes to the entire GNU/Linux community for really showing us what is possible when we all work together and providing us with the free software we rely on. I would also like to thank the Arduino founders, Massimo Banzi and David Cuartielles, and all their collaborators for making the control of scientific equipment easy and fun. The entire world owes a great thanks to Adrian Bowyer and his many collaborators on making the RepRap project into the incredible success that it is. I would like to thank all the fantastic open-source hardware individuals, groups and companies that keep enabling us to reach higher. I want to thank the Open-Source Hardware Association and all their members, in particular, Alicia Gibb and Catarina Mota. I want to thank all those who have shared their brilliance with the world and help make my research a success because of their contributions in the scientific and engineering literature, as well as Github, Thingiverse, and Appropedia users. A special thanks to everyone who provided examples that are cited or shown in the book. Finally, I would like to thank the growing number of makers in the burgeoning maker community that inspire and teach us all.

DISCLAIMER

Although many people contributed to the contents of this book, all errors and omissions are mine alone. The technologies described in this book are constantly changing, and while every effort was made to ensure accuracy of this work, it is always best to go directly to the sources for the most up-to-date information on the various open-source hardware projects described.[1]

Finally, if any of the hardware is not good enough for you or your lab, remember it is free so quit whining and make it better!

[1]Wherever possible hyper links are shown in the footnotes and will be enabled on the digital version of this book.


UPLOAD
UPLOAD
RECEIVED
UPLOAD
RECEIVED
UPLOAD
RECEIVED
PRINT

Contents

CHAPTER 1

Introduction to Open-Source Hardware for Science

1.1. INTRODUCTION

By any standard, the process of development and licensing for free and open-source software, which is discussed in Chapters 2 and 3, has been a success. Because of this success, the method is now being applied to hardware. Thus, an opportunity has arisen to radically reduce the cost of experimental research in the sciences [1]. This opportunity has the potential to reduce your research costs and make your laboratory more productive—while at the same time vastly expanding the scientific user base. Specifically, this book focuses on the combination of open-source microcontrollers covered in Chapter 4 and open-source 3-D printing reviewed in Chapter 5. These two tools running on free open-source software enable the development of powerful research tools at unprecedented low costs. Chapter 6 provides several detailed examples of these tools for a wide range of science and engineering disciplines. Then, in Chapter 7, these developments and their likely trajectories in the future are explored and illustrated with numerous examples to lay out a path of mutually reinforcing and accelerating free and open-source scientific hardware development for the benefit of science.

1.2. WHAT IS OPEN SOURCE?

The term "open source" emerged during a strategy session between several hackers[1] of the early open software movement [2]. Free and open-source software (F/OSS, FOSS) or free/libre/open-source software (FLOSS) is a software that is both a free software and an open source. *FOSS* is a computer software that is available in source code (open source) form and that can be used, studied, copied, modified, and redistributed without restriction, or with restrictions that only ensure that further recipients have the same rights under which it was obtained (free or libre). *Free software, software libre or libre software* is software that can be used, studied, and modified without restriction, and which can be copied and redistributed

[1]Although the term "hacker" is often associated with illicit activity in public discourse, it actually refers to a computer programmer who develops free and open-source software.

Open-Source Lab. http://dx.doi.org/10.1016/B978-0-12-410462-4.00001-9