Open Source Hardware for Instrumentation and Measurement

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Will you base your next sensor design on plans drawn up by a stranger and found in an internet search? The open source hardware (OSH) movement is sending some scientists and engineers in a new direction.

What is OSH?

The term "open source" originally applied to software projects with publicly available source code for others to modify, improve, and compile. Modified software projects were then often required to release their source code under the terms of the "open source" agreement [1]. Currently, "open source" is also available for hardware projects and includes printed circuit board designs, photomask layouts and mechanical assemblies.

While the scientific community requests journal authors to provide enough information for other groups to replicate their work, and patent examiners hold inventors to the same test, the OSH community requires even more details and prefers that they be available online. For example, downloadable electronic design files for printed circuit boards and 3-D printable enclosures make it possible for an engineer to modify an instrument design from the desktop, order the parts from several different manufacturers, and receive a customized kit for assembly—or even have the parts assembled and shipped. The original designers may remain completely unaware of the development or may receive credit or a royalty for their work depending on the terms under which they released the design.

Fig. 1 illustrates the many types of design files required for a typical open-source instrument including:

- text files such as documentation, parts lists, and source code, and
- binary files such as circuit board layouts, compiled firmware, and computer-aided design (CAD) drawings of mechanical parts (such as enclosures).

From the early days of the web in the mid-1990s, individual scientists and engineers have put their own instrumentation plans online in various formats. This was the era of the Homebrew Scanning Tunneling Microscope. (The original Homebrew STM site by Jim Rice in 1995 is gone, but [2] has home built STMs.) Few internet sites aggregated OSH designs beyond scanned collections of circuit diagrams, and few manufacturing capabilities were accessible online to small-volume builders. The situation changed for the better around the the time of the introduction of the Arduino microcontroller board in 2005 [3]. Hobbyists were attracted to the combination of a low-cost board (~$30 US), online forums to share example code, and a free and user-friendly programming environment originally created for artists and designers. By 2010, there were an estimated 100,000 Arduino boards in circulation.

As microcontrollers have grown faster and more powerful and the source code base has expanded, open source hardware devices are starting to rival expensive instrumentation. This is especially true for cost-sensitive users who need multiple sets of equipment. Examples include sensor projects where many simultaneous measurements are made in parallel and in educational settings that require individual setups for lab-based training. New OSH for instrumentation and measurement appear regularly. Table 1 lists some examples showing the variety of currently available instrument designs.

When is OSH a Good Choice?

A thriving open hardware project can come with an expert user community offering firmware updates, ports to new operating systems, and modifications for new functionality or suggestions for replacement parts. One open source hardware vendor, Adafruit Industries, says:

> There are many reasons a researcher would want to choose open-source equipment – cost, community, resources, documentation, and the ability to improve and even sell better versions.

Open source hardware can also provide a backup plan when parts are discontinued. If your project relies on a part from an outside company that stops producing it or goes out of business, you might need to redesign unless the design is

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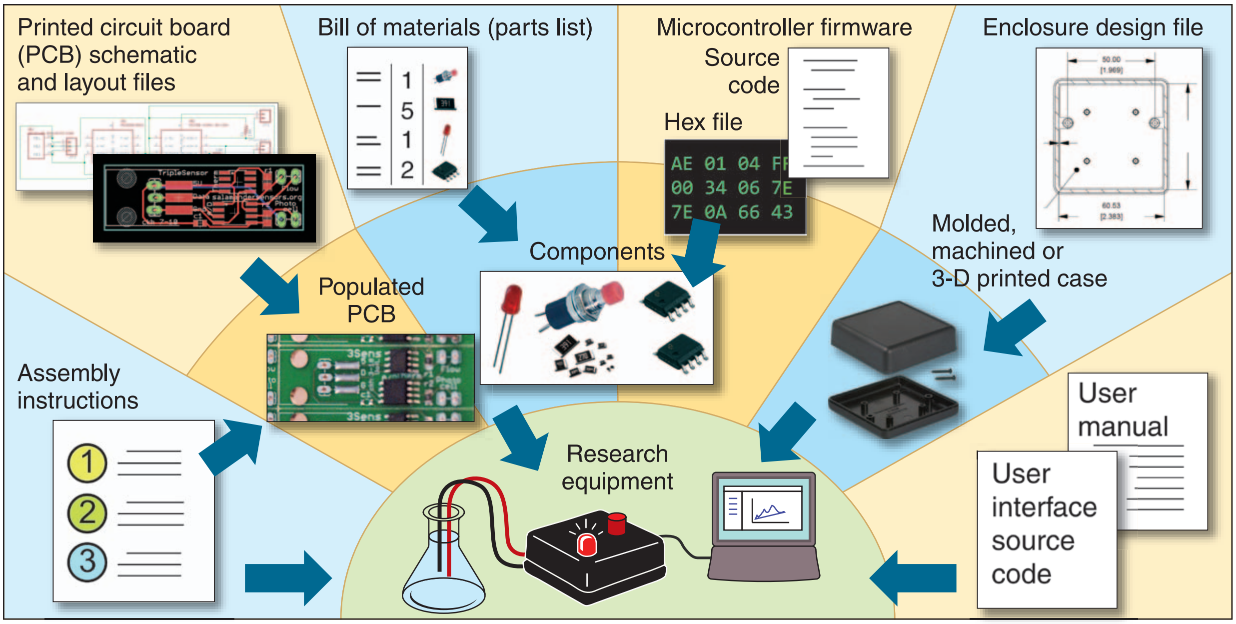

Fig. 1. Several types of electronic documents are needed to fully describe an open-source scientific instrument in enough detail to allow it to be modified and used by others.

open-source. In that case, a drop-in replacement may already be available from a different company, or at least a replacement can be manufactured from the existing design.

For items like a digital camera where volume keeps prices low and equipment is replaceable, closed source can make sense. However, if your research depends on custom instrumentation that is unavailable commercially, an OSH basic project can give an enormous head start.

What am I Allowed to do With a Design?

Check for a license in the project documentation to be sure your plans are allowed. Most of the time, you will find permission to copy, modify, and sell the design along with requirements to give credit to the original designer, and to indicate that the designer does not endorse your new version.

Your project's own license must usually inherit some properties of its "parent," so you may or may not be able to add a more restrictive license to your own work. There are some negative implications to restricting your design from commercial use by others [4]. Most open source licenses for hardware were adapted from earlier open source software work [5], but efforts are underway to create a new open source license specifically for hardware [6].

Career Benefits of Contributing to OSH

Most academic researchers seek to publish measurements and data for career advancement rather than specifications for the equipment that produced the data. It is possible to publish a design in journals that specialize in instrumentation or to list the hardware details as supporting online information for an article that focuses on the results of measurements. Conferences with demonstrations, tutorials, and workshops can also provide presentation venues for OSH creators.

Dr. Dan Steingart, a chemical engineering professor at the City College of New York, plans to publish an open hardware design with a Masters student and says, "Yes, it does give me academic credit." Dr. Rafael Gómez-Sjöberg, who developed an open-source microfluidic valve controller while a postdoctoral researcher at Stanford University, says

> I did not get any official academic credit for making the design public, but I think in the long run it benefits me by making my name better known in the microfluidics community, and it creates good will among people that one day could be collaborators and colleagues.

An online hardware repository is necessary to provide free global access to a design, and it can serve as a reference in a publication but does not equal a publication in most academic environments. The benefits to an academic career are longer term and more diffuse and can include recognition, attracting new collaborators, and simply improving lab organization. For example, my site, salamandersensors.org, serves as an online lab book, a source of information for prospective lab members, and a time-saving instruction manual for summer students.

How to Participate

Participation in the OSH community can range from building a single copy of an instrument to creating a business around an original design. Researchers and engineers may be more likely than hobbyists to make the transition to OSH designer, both because of their expertise and their access to libraries of proprietary hardware designs they may decide to make public.

Downloading and inspecting an existing open-source design is a good first step for an instrument designer. For an

Table 1—Online examples of open-source research instrument designs or collections	
Instrument type	**Online reference**
Scanning tunneling microscope (collection)	http://angstrom.de/index_r.htm
Applied/experimental physics devices at CERN (collection)	http://www.ohwr.org/projects
Ardustat open-source potentiostat/galvanostat	http://steingart.ccny.cuny.edu/ardustat
Environmental sensor network	http://salamandersensors.org
Wireless sensor networking hardware	http://www.freaklabs.org
Fluorescence microscope	http://www.etaluma.com/products/lumascope
Microfluidic valve controller	http://www.stanford.edu/group/foundry/testing/own_controller.html
Orbital shaker for biotechnology	http://www.thingiverse.com/thing:5045
The $100 Neural Spike Project	http://www.backyardbrains.com/SpikerBox.aspx
Many other biotechnology projects (collection)	http://openwetware.org/wiki/DIYbio/FAQ/Projects
Robotic weather balloon	http://whitestarballoon.com
Autonomous aircraft (collection)	http://diydrones.com
Data loggers and wireless power meters (collection)	http://www.adafruit.com
Fuel efficiency instrumentation	http://www.opengauge.org/mpguino
Application-specific integrated circuit (ASIC) design collection	http://opencores.org
Open-source projects beyond instrumentation and measurement	http://en.wikipedia.org/wiki/List_of_open_source_hardware projects

engineer without a software background, the main challenge may actually be keeping the diverse files in Fig. 1 consistent when a user downloads the latest version of the project. The circuit boards, housings, documentation and part lists are each evolving over time, and this can create headaches for even a small project run by an individual engineer. Now add new developers who will modify the designs in different locations and on different timelines!

To solve this problem, a software version of tracking tools for managing text-based source code is now put to work managing binary CAD files. All files pertaining to a single instrument are put in a folder, and version-tracking software is installed on the designer's computer (for example, Git, Subversion or Mercurial). It logs any changes whenever the designer decides to "commit" to a new version. At each commit, the software prompts the designer to comment on the nature of any changes to the repository, and the user can optionally "push" the changed files along with the change log from the local computer to a remote online repository. Services such as Github [7] provide free space for hosting public repositories where users can download a zipped archive of all files necessary to build an open hardware design.

Version tracking allows the designer to recover previous versions and create branches when major changes are made. This approach has serious limitations where CAD files are concerned: it is currently not possible to highlight changes in a circuit board layout the same way one can view the actual line-by-line differences in a text file. Typing in thoughtful commit comments is essential. However, the tools are evolving rapidly. One of the dominant circuit layout programs used by the OSH community is changing from a binary description toward a text (XML) description of circuit board layouts [8]. Line-by-line "differencing" tools applied to text-based layout descriptions may someday be able to succinctly describe changes in board layouts from one revision to another.

Even if there is no OSH design that meets your project's immediate needs, it will help you get oriented to download an OSH project and inspect the structure of the repository and the file types. There are a few file types that dominate in each category (for instance, Eagle that is used for circuit board layouts), and the effect is amplified because distributors know that making a design available in the most popular formats means more users will be able to successfully build it. If you are designing your instrument using expensive proprietary software, or even using free software that is locked to a particular printed circuit board manufacturer, think about exporting your work to a more widespread format if at all possible. Formats that can be readily manufactured are good: most circuit shops accept Gerber for board layouts, machine shops accept .dxf for drawings, and rapid prototypers use .stl for 3-dimensional printing. However, some of these formats are dead-ends for users who want to modify a design. For instance, the 3-D printable .stl format does not capture the relationships between different solid parts of a mechanism, it only describes the outer surface. Consider the difference between compiled software which can only be copied and source code which can be modified and then compiled. Formats that can be meaningfully *edited* in free or low-cost software are better than those that can only be manufactured.

The need to put self-consistent information online motivates good documentation. If you do put your physical object designs in an archival, open format, the extra effort will pay off even if your design is not adopted by a large crowd. Keeping your design in a repository will make version management and bug fixes easier and make it more likely for your project to continue on after you are out of the picture. For instance, a future developer will have enough information to find replacements for obsolete parts.

Are there any other design considerations unique to OSH? Developers of general-purpose open hardware often design with through-hole parts for hand assembly in small quantities. For example, all parts of the Arduino except the USB interface chip are available in through-hole, and most boards use this part selection. However, scientific instrument users generally have better access than hobbyists to automated equipment that can handle tiny surface-mount parts or have a large enough budget to have instruments assembled from plans. Whatever the skill set of the person you envision building your design, clear documentation is vital.

Can OSH be Sustainable?

The open source software definition [1] was carefully crafted to allow commercial use of open-source code. This raises the question of how a business can survive when anyone is free to develop an improved product based on the hard work of the originators. The key is that most users just want a finished product that is easy to install and run—so excellent documentation and support and good customer reviews will help users select your product over others that may seem identical. Open-source software companies, such as distributors of the Linux operating system, depend largely on good documentation, customer support, and consulting for their success.

Because the costs of assembling and distributing are much higher for hardware than software, there is a barrier for a user to build just a single device. OSH businesses can survive by selling fabricated devices or by selling their expertise as consultants [9]. A 2008 case study of 54 OSH products from twelve companies found that in about half the products, the business model was fairly traditional: make a profit from sales of the fabricated hardware [10].

I was interested in what company representatives and OSH developers would say about these issues and conducted e-mail interviews with several individuals. Their responses follow in this section and the next one. To stay ahead of competitors, Adafruit cites volume and reputation as advantages in selling their own open-source designs:

> While you're giving away the recipe, it's unlikely everyone will want to cook it up on their own. You will be getting quantity discounts on the parts you're buying. You're offering support and customer service. Most hardware is a commodity, or will eventually be – it's the things outside the physical bits that make the difference, and this is what you provide.

Other companies custom fabricate and sell designs they do not own and pay part of the profit to the originator. The automated "BatchPCB" service [11] does this for circuit boards; not only can customers upload and purchase their own circuit board designs, but US-based customers can choose to make their designs publicly available and set a royalty fee that they collect every time another customer has the design fabricated. The service shows ambitions of expanding beyond circuit boards to parts procurement, enclosure design and perhaps assembly. Such a system can be a good choice for researchers who want to distribute their design but are not interested in dealing with customers or spending a lot of time on licensing agreements.

Still other companies produce copies of an originator's design in larger volumes and return some profit to the originator based on an agreement. The agreement need not be very restrictive. An example is the relationship between the company Dangerous Prototypes, which designed the "Bus Pirate" tool for communicating with microcontrollers, and the company Seeed Studio, which fabricates and sells the design and returns a percentage to Dangerous Prototypes for each one sold [12]. Meanwhile, Dangerous Prototypes keeps the design files available for users to download and modify and also sells the product through other distributors. The result is very different from the uniformity of a factory-produced consumer product. At least seven Bus Pirate circuit board variants have been produced by users from these schematics [13], and different enclosure styles abound, but the Seeed Studio circuit board is the most common by far.

The openness and informality of the above examples will clash with the previous experience of most industrial and academic researchers, who are often required to apply for patents on their inventions. Steingart offers the following perspective based on developing the Ardustat, an open-source Arduino-based potentiostat/galvanostat:

> Prior to the Ardustat, I patented [through a previous employer] another small galvanostat based on a very different principle. Nobody cares a lick about that one, it cost the school ~5 to 10 K to file the patent, and it has produced no kind of revenue. This isn't to say patent protection isn't important, but one should really consider the need for the patent. Nothing in either design was capital intensive nor did it need specialized hardware. The markets are also of

close to zero interest to a venture capitalist, but as a lone inventor I was able to make a few thousand dollars in my spare time even though I gave the Ardustat away.

To his financial benefit, Steingart discovered that some users prefer a ready-to-use solution over the do-it-yourself approach: "As a post-doc, I released the designs for free and suddenly got inquiries for Ardustats-for-sale. I was able to immediately realize profits (more than enough for beer money plus some gadgets)."

The "Pay-It-Forward" Mentality

The developers interviewed for this article cited the sense of community engendered by contributing to open source hardware as a motivation for contributing. Steingart said,

> The OSH conference last fall [14] was wonderful: folks getting together and openly discussing designs, schematics, and ideas without fear of people stealing or misappropriating ideas. At formal conferences and tradeshows it's next to impossible to strike up a conversation with someone you don't know and talk shop without a non-disclosure agreement or the like. Free tools developed by the open-source movement don't hurt. The Ardustat leverages all sorts of great open source platforms (Python, Java, Arduino), tools I use every day that don't cost me a dime.

Likewise, Gómez-Sjöberg says,

> I have greatly benefited from other people's opensource work (from software I routinely use to lab equipment), so making my controller design public is a very small way to 'pay forward' for those benefits I have received over the years.

Although Gómez-Sjöberg doesn't keep track of exactly what users do with his valve controller, his list of researchers who have built one includes people from all over the world: Canada, Hungary, Australia, New Zealand, South Africa, Hong Kong, Korea, Iceland, and the United States. "Part of what I like about being an engineer is precisely creating tools and machines that help other people do different things," he said.

Steingart said, "It's fantastic to see folks use and modify the design." He enjoys providing users with a "low cost entry point to electrochemistry" and agrees that "open sourcing anything is a kind of pay-it-forward mentality." He hopes that users of his design will want to open source some of their own designs in return.

Projection for the Future

The OSH movement, once the domain of hobbyists, is increasingly a source of scientific instrumentation. The equipment may be purchased pre-assembled, built from online plans or redesigned for a new purpose by the end user, much as open-source software can be downloaded for immediate use or modified and compiled. However, there are major differences between OSH and software in cost of replication and the larger variety of data files and tools required to build an OSH design. Examples from the open-source software community can still help predict outcomes for OSH, for instance easier tracking and resolution of "bugs" and the ability to adapt designs from another person or company for a new purpose. Whether one is an instrumentation designer or an end-user of scientific equipment, OSH designs provide a new source of laboratory tools and a new opportunity for expanding your engineering skill set.

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