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Building Research Equipment with Free, Open-Source Hardware

Joshua M. Pearce

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siderable challenge in the search for convergence, it may well also portend, just as it has in cancer, the development of both more personalized and more effective therapies.

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MATERIALS SCIENCE

Building Research Equipment with Free, Open-Source Hardware

A rapidly increasing selection of laboratory equipment can be fabricated with open-source three-dimensional printers at low cost.

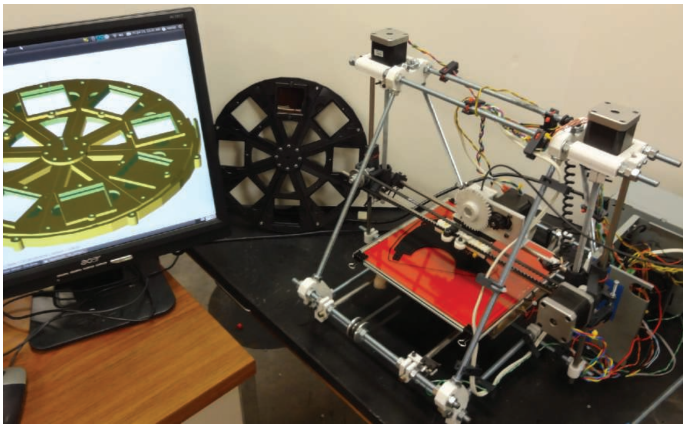
Joshua M. Pearce

Most experimental research projects are executed with a combination of purchased hardware equipment, which may be modified in the laboratory and custom single-built equipment fabricated in-house. However, the computer software that helps design and execute experiments and analyze data has an additional source: It can also be free and open-source software (FOSS) (*1*). FOSS has the advantage that the code is openly available for modification and is also often free of charge. In the past, customizing software has been much easier than custom-building equipment, which often can be quite costly because fabrication requires the skills of machinists, glassblowers, technicians, or outside suppliers. However, the open-source paradigm is now enabling creation of open-source scientific hardware by combining three-dimensional (3D) printing with open-source microcontrollers running on FOSS. These developments are illustrated below by several examples of equipment fabrication that can better meet particular specifications at substantially lower overall costs.

The FOSS movement emerged as a decentralized, participatory, and transparent system to develop software, in contrast to commercial software, which tends to be written anticipating user needs and does not allow modifications to the code, which is often proprietary (*2*). Although FOSS is a collaborative effort driven by user demands, this decentralized innovation process is still efficient and has been implemented in areas such as nanotechnology (*3*) and medicine (*4*), and the open and collaborative principles of FOSS have been readily transferred to hardware (*5*). A key enabling open-source hardware project is the Arduino electronic prototyping platform (*6*–*8*). The \$20 to \$30 Arduino is a versatile yet easy-to-learn microcontroller that can run a number of associated scientific instruments, including Arduino Geiger (radiation detector), pHduino (pH meter), Xoscillo (oscilloscope), and OpenPCR (DNA analysis). However, Arduino's most impressive enabling application is 3D printing. Open-source 3D printers can perform additive-layer manufacturing with polymers, ceramics, and metals. Such approaches have been popular in microfluidic lab-on-a-chip architectures, where flow paths are created layer by layer, but are adaptable to a much wider array of devices.

The most popular fabrication tool is the RepRap, named because it is a partially self-replicating rapid prototyping machine. Currently, the <\$1000 RepRap can fabricate about 50% of its own parts from acrylonitrile butyl styrene or polylactic acid polymers with no postprocessing and a 0.1-mm spatial precision. This ability for self-replication has resulted in an explosion of both RepRap users and evolutionary design improvements (*9*). Scientists with access to RepRaps have found many examples where it is less expensive to design and print research tools rather than buy them. A number of simple designs are flourishing in Thingiverse, a free and open repository for digital designs of physical objects (*10*). These include single-component prints such as vial racks (thing:25080), Buchner funnels (thing:25188), and microtiter plates (thing:11621). 3D printers have also been used to print custom chemical reactionware (*11*). For example, 3D printers can be outfitted with syringes to print with materials like acetoxysilicone to quickly make reactionware capable of in situ spectroelectrochemistry or easily alter reactor architecture to gauge the effects on chemical synthesis (*11*).

The 3D printers can also be coupled with existing hardware tools such as the portable cell lysis device for DNA extraction (thing:18289), a 3D printable adapter that converts a Craftsman automatic hammer into a bead grinder for use with DNA extraction, or the DremelFuge chuck (thing:1483), a printable rotor for



Factory for one. A parametric (easily customized) filter-wheel holder is shown in the OpenSCAD program on the monitor (**left**), with the completed inside of the Arduino-controlled automated filter wheel (**center**). An Arduino-controlled RepRap 3D printer (**right**) is printing out a component of a case design. All of the hardware and software for both the filter wheel and the RepRap are open source.

Department of Materials Science and Engineering, Michigan Technological University, Houghton, MI 49931, USA. E-mail: pearce@mtu.edu

centrifuging standard microcentrifuge tubes and miniprep columns. These combination devices can radically reduce research costs. For example, the DremelFuge can be used in the laboratory or the field as an inexpensive centrifuge demonstrated to be effective up to 33,000 rpm or 52,000*g*. The price is ~$50—primarily for the Dremel drill—compared with commercial centrifuge systems, which cost a few hundred dollars (*12*).

The most aggressive research savings can come from coupling Arduinos with 3D printers to make full open-source scientific hardware. Consider the Arduino-controlled open-source orbital shaker (thing:5045) used for mammalian cell and tissue culture and bench-top science. The <$200 open-source orbital shaker fits inside a standard 37°C/5% CO_2 cell incubator and replaces commercial versions that start at more than $1000. As the scientific tools that are open sourced gain complexity, the cost differential becomes even more substantial. For example, it is now possible to make a <$50 customizable automated filter wheel (thing:26553) that replaces $2500 commercial versions.

For any given project, there may still be drawbacks to open-source 3D digital fabrication versus buying. Open-source scientific hardware is still at an early stage of the evolutionary process. Today, most major equipment is too complex to build in this manner (e.g., an entire nuclear magnetic resonance spectrometer versus a sample holder for one) or requires specialized materials that need to be fabricated in dedicated systems (e.g., ultrahigh vacuum semiconductor deposition). Commercial equipment may have longer lifetimes and, for instrumentation, may have better statistical validation of calibrations. If a new design is needed, it may often prove faster to buy than build. However, as more designs are shared, the level of complexity of open-source scientific hardware will expand rapidly. Not only can the scientific community enjoy immediate cost reductions by building and sharing but also, as with software, the costs of commercial versions will decrease because of price competition. We are on the verge of an era where low-cost, but highly sophisticated, scientific equipment can be put into the hands of the public and amateur scientists everywhere, while driving down the costs of research tools at our most prestigious laboratories (*12*).

References and Notes

1. Free and open-source software is 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 (i.e., free).
2. P. Deek, J. A. M. McHugh, *Open Source: Technology and Policy* (Cambridge Univ. Press, Cambridge, UK, 2007).
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5. Free and open-source hardware is hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design.
6. www.arduino.cc
7. Another emerging platform is Raspberry Pi (*8*).
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ECOLOGY

When Paths to Cooperation Converge

Cooperation now has many solutions, but recent work shows how two well-known mechanisms interact.

Thomas N. Sherratt[1] and Gilbert Roberts[2]

Observations of cooperation range from human philanthropy to fiddler crabs leaving their territories to help neighbors thwart an intruder (*1*). Two of the best-known explanations for such cooperation are direct reciprocity (*2*), in which cooperation evolves as a conditional strategy over repeated interactions, and population structuring (*3*), in which cooperators associate disproportionately with cooperators. However, many systems have the potential to generate cooperation through both of these routes; for example, common murres (see the figure) regularly preen both their mates and close colony neighbors over repeated interactions. How might these routes to cooperation interact? In a recent paper, van Veelen *et al*. (*4*) consider this question in a systematic way. Their answer is unexpected.

[1]Department of Biology, Carleton University, Ottawa, ON K1S 5B6, Canada. [2]Centre for Behaviour and Evolution, Institute of Neuroscience, Faculty of Medical Sciences, Newcastle University, Newcastle upon Tyne NE2 4HH, UK. E-mail: tom_sherratt@carleton.ca

One of the most challenging scenarios in which to envisage the evolution of cooperation is where mutual cooperation pays well, but not cooperating ("defecting") provides the higher immediate payoff to an individual, whether or not their partner cooperates. These inequalities help to define the Prisoner's Dilemma, and any cooperation that evolves under these conditions must overcome defectors that exploit short-term gains.

Interest among biologists in the Prisoner's Dilemma ballooned with the publication of a classic paper by Axelrod and Hamilton (*5*). The authors showed that although defectors would always rise to dominate a population in a one-off game, repeated interactions could facilitate cooperation by promoting the evolution of cooperative but conditional strategies (notably "tit-for-tat"). The role of cooperation in payoff-maximizing solutions to the iterated Prisoner's Dilemma had long been appreciated by economists as an unaccredited ("folk") theorem (*6*). However, Axelrod and Hamilton helped to show how natural selection can influence which of many possible competitively successful outcomes of the repeated Prisoner's Dilemma emerge. Moreover, they highlighted how the clustering of identical strategies in space (population structuring) could kickstart cooperation.

To evaluate how repeated interactions (which can facilitate conditional cooperation) and population structure (which can allow cooperative strategies to associate) combine to promote cooperation, van Veelen *et al.* started with the standard two-player iterated Prisoner's Dilemma. The authors used a coefficient δ to represent the probability that any given pair continues to play another round. At the same time, the authors represented the extent of population structuring in the system by using a coefficient α to reflect an increase in the likelihood of interactions between identical strategies above the baseline based on random pairings.

The authors show by simulation and analytical approximation that as one increases α, full cooperation always becomes more likely.

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