5-26-2015

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Joshua M. Pearce
Michigan Technological University

Recommended Citation

Pearce, Joshua M. (2013a). Commentary: Open-source hardware for Research and Education. Physics Today, 66(11), 8-9.
http://digitalcommons.mtu.edu/materials_fp/12

Physics Today

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Citation: Physics Today **66**(11), 8 (2013); doi: 10.1063/PT.3.2160
View online: http://dx.doi.org/10.1063/PT.3.2160
View Table of Contents: http://scitation.aip.org/content/aip/magazine/physicstoday/66/11?ver=pdfcov
Published by the AIP Publishing

Commentary

Open-source hardware for research and education

Physicists are established leaders in making their work accessible to the whole community. An example is the electronic repository of open-access e-prints at arXiv.org, now more than 20 years old. As some disciplines struggle to develop centralized archives for their fields, the arXiv has grown to house more than 825 000 articles in physics and other fields; some subfields, in fact, have nearly all their articles there. Access to such a large body of literature provides obvious benefits to the physics community. The greatest is that not only does it provide us with the ability to "stand on the shoulders of giants," but it ensures that we are standing on the tallest shoulders, regardless of how limited our local institution's library might be.

The software industry has had a similar revolution of shoulder-standing, in the form of the free and open-source computer software movement. Free and open-source software (FOSS) is available in source-code form and can be used, copied, modified, and redistributed without restriction, or with restrictions only to ensure that it remains open to future recipients and users. Open-source development is decentralized, transparent, and participatory, in contrast to the standard black-box, top-down, and secretive commercial approach. First widely demonstrated with the incredibly successful Linux, FOSS has become integral to society: Much of the internet now relies on it. FOSS is becoming the dominant approach for software development simply because it is superior.[1] With open-source development, more people are collaborating to solve problems, and users as a group are smarter than any one individual.

Physicists are well acquainted with FOSS: Some of the best simulation and research tools are based on it. In addition, many physicists have begun to use FOSS in the classroom. For example, the Open Source Physics project enhances computational-physics education by providing computer-modeling tools, simulations, and curricular resources.[2] Physicists are also already acquainted with the open-source culture of sharing good ideas. Academic physicists, who dedicate their lives to information sharing as researchers and teachers, even have a well-established gift culture solidified in the tenure process. You get tenure based on how much you have given away—the more valuable the better—not on how much you hoard.

That scientific sharing tended until recently to be focused on what could be published in academic articles—ideas or software, as it were. No more. Now the open and collaborative principles of FOSS are being transferred to designs for scientific hardware, with innovative digital manufacturing providing an unprecedented opportunity to radically reduce the costs of equipment for experimental research and education.[3,4]

Two recent open-source design and production developments are driving those reductions: Arduino microcontrollers and the RepRap three-dimensional printer. The new microcontrollers (http://www.arduino.cc) are a family of low-cost circuit boards, each with a core processor, memory, and analog and digital input/output peripherals through which they can sense and affect their immediate surroundings. The microcontrollers are relatively easy to operate and have been used in many research and education settings,[5] including student lab kits and basic equipment like photogates, which can precisely time the interruption of a light beam at a fraction of the commercial cost. One of the most powerful present uses for Arduinos is in the open-source 3D printer known as a RepRap (http://reprap.org), a self-replicating rapid prototyper capable of synthesizing approximately 50% of its own components. A RepRap can be built for less than $600, which makes rapid prototyping accessible to most physics laboratories.[4]

The 3D printing process is a sequential layering operation in which an extruder heats and expels a filament of the working material—such as acrylonitrile butadiene styrene, the plastic used for Legos—through a nozzle to deposit a 2D layer; the extruder then advances a step in the vertical direction and the process repeats (see Physics Today, October 2011, page 25). The RepRap uses computer-assisted drafting (CAD) designs, which can be shared easily over the internet. A useful CAD program for the mathematically adept is OpenSCAD (http://www.openscad.org), an open-source application that takes as its input a script describing the geometric specifications of an object. Once a user creates a design, anyone can quickly customize it. Dozens of designs for scientific equipment are already flourishing in Thingiverse, a free and open repository for digital designs (http://www.thingiverse.com). Thingiverse also maintains an application that allows OpenSCAD scripts to be easily manipulated.

To appreciate the elegance of the open-source hardware design approach, consider the recently developed open-source optics library of customizable printed designs[4] that can be rendered with off-the-shelf parts and Arduino microprocessors (http://www.thingiverse.com/jpearce/collections/open-source-optics). The collection of inexpensive 3D-printable components, from simple fiber-optic cable holders to automated filter-wheel changers, dramatically reduces the cost of optics equipment in labs and classrooms. For example, to outfit an undergraduate teaching lab with 30 optics setups that include 1-meter optical tracks, lenses, adjustable lens holders, ray-optics kits, and viewing screens would cost less than $500 with open-source hardware, compared with approximately $15 000 for commercial versions.[4]

Tools for physics experiments are less expensive to design and print than to buy, particularly if another user has already started the design work. Saving money in the lab, though, is only one benefit. More importantly, the user can customize optics equipment or other physics apparatus and automate its manufacture, which ensures that the components are exactly what the specific research needs. It also saves time: Printing a predesigned component is much faster than going to a lab supply store or ordering the component online. For researchers, the value of timely access to experimental equipment can hardly be overstated.

Perhaps the most important point about free and open-source hardware is that a user who alters an open-source design is required to share any improvements with the rest of the community. By taking that extra step, users help accelerate the availability of open-source scientific hardware for everyone, and they will directly benefit as the international open-source community takes the design, further improves it, and re-shares the results. You probably know of people who already design some of their own equipment. If they share it, the user community will do equipment R&D for free, and all will be better for it.

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Joshua M. Pearce
(pearce@mtu.edu)
Michigan Technological University
Houghton

Letters

More on black holes and quantum information

The article "Black holes, quantum information, and the foundations of physics," by Steve Giddings (PHYSICS TODAY, April 2013, page 30), reviews the challenges that black holes present to the foundational principles of unitarity and causality in quantum theory. The problems and paradoxes of black holes were inherent in the earliest discussions of the Hawking effect, and were brought to the attention of many physicists by Stephen Hawking himself. In reviewing the imaginative attempts, some of them quite radical, to reconcile black holes with quantum mechanics, Giddings ignores the simplest possibility of all: that because of quantum effects, a classical event horizon never forms.

The widespread belief that gravitational collapse leads inevitably to an event horizon is based on an essentially classical view of the collapsing matter and its equation of state, a view that rests, in turn, upon the assumption that quantum effects are negligible on macroscopic scales. This prejudice persists despite voluminous experimental evidence to the contrary confirming the nonlocal—but certainly not acausal—appearance of quantum phase coherence in macroscopic systems as varied as superfluids, superconductors, low-temperature atomic gases, Einstein-Podolsky-Rosen entangled photon pairs, squeezed light, and Aharonov–Bohm interference experiments. To those may be added the standard model itself, which features both quark and gluon condensates in quantum chromodynamics, and a Higgs vacuum condensate, which is uniform and coherent in space at very large distances.