Haves and Have nots must find a better way:
The case for Open Scientific Hardware

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Abstract

Although many efforts are being made to make science more open and accessible, they are mostly concentrated on issues that appear before and after experiments are performed: Open access journals, open databases for data and code sharing, and many other tools to increase replicability of science and access to information. While great, these initiatives do not directly increase the access to the scientific equipment necessary to perform experiments and to generate new data. Unfortunately, their availability has always been uneven around the world, mostly due to monetary constraints and affecting mostly low income countries and institutions. In this paper a case is made for the use of free/open source hardware in research and education even in countries and institutions where funds were never a problem.

In 2013 Prof. Eve Marder published an article (Marder, 2013), expressing concerns about the increasing costs of equipment necessary to do state of the art research in the field of biology and the decreasing amount of funding available to be shared between an ever-growing number of labs and researchers. Unfortunately, with the US government decreasing the amount of resources earmarked for scientific institutions, these issues have only been exacerbated (current estimates show a decrease in 20 and 30% for the National Institutes of Health and the Environment Protection Agency, respectively). These concerns have been expressed for quite some time in many places of the world, where lower investment (as a proportion of GDP) in science and education makes research conditions suboptimal and access to bleeding edge technology and tools difficult. Now in times of shrinking funding, however, this difficulty is being felt by researchers in places earlier considered safe havens of science. One of the fears Prof. Marder expressed is that we might return to the “old days”, when only a few privileged men were able to do research.

A major reason for high prices in scientific equipment, is related to the way innovation, technological development and new knowledge generated inside universities and research institutes are introduced to the world: In order to make them commercially interesting and allow their development outside academia, they are protected using legal mechanisms such as patents, and/or copyrights, which are then licensed/sold to companies. Although this system enables universities and companies to work in collaboration and leverage from each other’s strengths, it ends up locking away research results funded with public money. Not only this is morally debatable, but it also:

1) Increases costs in product development, as each patent normally requires the involvement of specialised lawyers, and has high filing costs (between 10.000 and 30.000 US$ in 2000).

2) Slows down innovation cycles, as sometimes companies owning patents do not invest in further developing them into commercial applications, delaying derivative innovations that would rise from its implementation (Baker, Jayadev, Stiglitz, 2017). Kodak for example, patented the idea for a CCD digital camera (the same as today’s cameras) in 1978, but the first commercial versions were only released by Fuji in 1989.

3) Creates instruments/technologies that are “black boxes” since consumers are not allowed to open them up (for repair, maintenance, or simple curiosity). Which in the case of scientific equipment can lead to an incomplete understanding of how complex instruments work as well as their capabilities and limitations.

4) Equipment ends up being used in suboptimal conditions or thrown away instead of being repaired, especially in countries where manufacturing companies do not offer appropriate customer support (Perry & Malkin 2011).

An alternative to this production model exists, and it relies on a free distribution philosophy, in which code and design blueprints are shared freely so that anyone can study, build, modify and improve existing projects. This philosophy is strongly present in the software industry, more known as Open Source, where several companies act as service providers for their products, instead of leveraging scarcity and intellectual property (Raymond, 2005). One example of such a company, is Red Hat, which was founded in 1993 and has, as of 2015 reported over 2 billion dollars in revenue (Darrow, 2016).

As a consequence, researchers can now use freely available software for most of their work-related tasks (e.g. office suites, statistics, data analysis packages, see Table 1 for examples), which in turn helps reducing research costs and freeing resources for other expenses (as well as improving research quality and scientific outputs, Goble, 2014 - a more detailed description of the benefits of using freely available initiatives can be found below). For Eve Marder's main concern - the lack of funds to buy expensive equipment - a solution was still lacking. While this is worrisome, the increasing affordability of electronic systems to the general public, should provide relief to the problem, as they can be used to assemble tools in an open source way, where everyone is free to use and improve designs based on their specific needs. Smartphones, for example, carry powerful CPUs, camera, microphone and an array of sensors which makes these ever-present devices excellent tools for recording, analysing and visualizing data (Malykhina 2013). One popular application are smartphone based microscopes, where a glass bead or other inexpensive plastic lens (normally found inside a laser pointer) can be placed in front of the smartphone camera, for very large magnifications (see table 2 for examples. A brief online search for "phone microscope", will guide the reader to a wealth of similar projects). The quality of such simple microscopes allows users, among other things, to image blood samples for diagnostics (Switz, D'Ambrosio, & Fletcher, 2014), with costs in the range of 5-20 dollars (assuming users already have a smartphone with a camera).

In contrast to this the initial cost for a "scientific grade" optical microscope is in the range of thousands of dollars, with prices rising steeply for more complex designs, severely constraining access to such a fundamental tool. As such devices are core to scientific investigations, there have been several open source models beyond just the "basic smartphone hack", some examples can be found in Table 3. They have different capabilities and different levels of complexity, but all these freely distributed models have two key features in common: *(i)* they are produced with "off-the-shelf" components, which are mostly cheap and easy to get, *(ii)* their designs and bill of materials are available online, allowing anyone to build, as well as customize/improve them depending on specific needs. These features are nothing more than the translation of the open source software philosophy to the world of hardware (see the Open Source Hardware Association for a more detailed definition). Like in software, the adoption of this philosophy has deeper implications:

1) It allows more people to participate in the scientific endeavour, in turn allowing for research to be done outside academia, enabling people to exercise their curiosity and better understand the world around them. Public Lab and SafeCast are two good examples of non-profit organizations that use open source hardware to empower global communities to gather data about environmental variables and to understand the impact of human activity on the environment, health and quality of life.

2) Better understanding of the tools themselves because the available blueprints can be studied, leading to more informed decisions by users concerning the feasibility of experiments, and the results they can expect. This, in turn, can also lead to better reproducibility as researchers can calibrate their devices according to the blueprints more often and make sure they are performing consistently at optimal standards, avoiding discrepancies in experimental outcomes.

3) In long term projects lasting years or even decades, laboratories are less vulnerable to supply problems. If a company producing a certain device decides to discontinue its production or if the company goes out of business, researchers are left orphaned without means to repair or replace said device in case of malfunction. If all the build plans are open, scientists can take reproduce/repair it themselves, or find other companies to produce them on demand. A concrete example of this issue is provided by the European Organization Nuclear Research (CERN) where a specific hardware license and several businesses protocols were created to ensure that hardware developed and sold to the project would have to comply with this license. This has enabled close collaborations in tool development between CERN and the hardware industry (as CERN employees could freely apply their expertise, both as end users and as engineers), and made the project robust to fluctuations in the market, since the necessary tools could be sourced from many suppliers.

4) Employing open source hardware keeps the profits within a reasonable range from its manufacturing cost, since adding a very high premium would make potential clients use the "build it yourself path", preferring to spend a bit more time sourcing parts and building the device themselves over spending an unreasonable sum of money for a provided service.

5) The lower price tag on open source hardware enables scientists in regions that are normally constrained by lack of funds to address scientific problems previously outside their reach. It fosters the discovery of untapped talent and paves the way for inside out development, rather than relying on external aid and humanitarian assistance, a model that has had little success (Moyo, 2009). Trend in Africa, a volunteer-run non governmental organisation, is leveraging this idea to train researchers in Africa on basic electronics and 3D printing as tools to develop labware and to involve academics in the global "maker movement".

6) Open source hardware is also an excellent tool for education. As curious people learn how to build their own equipment, they are “forced” to learn about physics, electronics, biology (see Table 4 for examples), creating new teaching possibilities for both schools and universities. Content can be taught in a “hands-on approach” where students are challenged with a scientific question and try to solve it by thinking what kind of experiments will be needed, building the instruments, gathering data and drawing conclusions from them.

More examples of scientific equipment produced under the open source paradigm can be found for PCR machines, electrophysiology systems, supercomputers, prostheses, centrifuges, optics, spectrometers, diving robots and even electron microscopes (Table 5), The list is not exhaustive and new tools are added to online repositories and dedicated journals almost daily (Table 6).

In this modern version of the “do-it-yourself” (DIY) tradition, men and women are developing tools with bits and bytes, resistors and microcontrollers. They are still learning what works and what doesn’t, becoming ever more interdisciplinary, interconnected and increasing the complexity of their designs. Taking advantage of the internet, project repositories and information, hubs are coming alive, breaking down the ivory tower, as scientists, makers, DIYers and hobbyists interact on the same level, suggesting, contributing, and improving each others’ projects in a much richer peer review system, done by many, instead of just two or three pair of eyes, and in an iterative manner. A prime example is the community growing around the Gathering for Open Scientific Hardware, that recently had its second meeting, bringing together ideas from different fields and creating collaborative, inclusive documentation, a manifesto, a roadmap (for an ambitious but noble destination) - to make open science hardware ubiquitous by 2025, - and more importantly a truly global community spirit.

In 2013 Prof. Marder was concerned by the number of times the phrase “The haves and the have nots” was being used in academia and the divide it represented. Even if the problem was solved by unlimited funding it did not address the fact that in the current system, institutions and labs that belong to the group that “has” are still in a system held hostage by their own tools. In order to solve this issue we don’t necessarily need more money, but rather reassess our relationship to knowledge and technology, how it determines our role in society, and how we want to spend grant money entrusted to us by the people. By making our tools and knowledge truly free, “haves and have nots” will not only erase the divide, but will actually move together to a better way.

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Table 1 – comparison of proprietary x open source software

Software type	Proprietary	Open source
Operating system	Windows 7	Linux (e.g. OpenSuse, Ubuntu)
Office suite	Microsoft Office	Openoffice, Libreoffice
Data analysis - statistics	SPSS	R, Jasp, ImageJ
Programming language	MATLAB	Python
Image processing	Photoshop	Inkscape, Gimp
Motion tracking	v120 duo system	OpenCV
Total cost (12.2016)	4,310.00€	0€

Table 2 - Smartphone based microscopes

Project	URL
PNNL Smartphone Microscope	https://availabletechnologies.pnnl.gov/technology.asp?id=393
10US$ smartphone to digital microscope conversion	http://www.instructables.com/id/10-Smartphone-to-digital-microscope-conversion/
PhoneScope	https://www.thingiverse.com/thing:280004
Smartphone clip-on microscope	https://www.amazon.com/KINGMAS-Microscope-Magnifier-Universal-Smartphones/dp/B00PQ9XV2E

Table 3 – Open source optical microscopes

Project	URL
FlyPi	http://journals.plos.org/plosbiology/article?id=10.1371/journal.pbio.2002702
Low cost and open source multi-fluorescence imaging system for teaching and research in biology and bioengineering	http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0187163
OpenFlexureMicroscope	http://tutorial.waterscope.org/
Foldscope	https://www.foldscope.com/
The open source Microscope	http://openlabtools.eng.cam.ac.uk/Instruments/Microscope/
Public Lab Basic Microscope	https://publiclab.org/wiki/basic-microscope
Free and open-source automated 3-D microscope	http://onlinelibrary.wiley.com/doi/10.1111/jmi.12433/full
Hackaday.io list on optical microscopes	https://hackaday.io/list/12057-optical-microscope-projects

Table 4– Using open source hardware for science education

Entities	URL
Trend in Africa	http://trendinafrica.org/blog-posts/open-source-workshop-and-sona-conference-in-durban/ http://trendinafrica.org/blog-posts/open-labware-course-in-addis-ababa-has-kicked-off
Biohackacademy	http://biohackacademy.github.io/bha2/
Lego2Nano	http://lego2nano.openwisdomlab.net/index.html
Public Lab	https://publiclab.org/
PhotosynQ	https://photosynq.org/education
Conector Ciência	http://www.conecien.com/
ScienceXplore	https://www.sciencexplore.org/
Backyard brains	http://blog.backyardbrains.com/2015/03/gift-from-iran-thanks-to-open-source-cockroach-research-tools-and-experiments-made-by-students/

Table 5 – Examples of open source hardware from individuals and companies.

Equipment	URL
PCR machine	http://openpcr.org/
5 dollar PCR machine	https://hackaday.io/project/1864-5-dna-replicator
Electrophysiology system	http://www.open-ephys.org/
Raspberry Pi supercomputer	http://www.southampton.ac.uk/mediacentre/features/raspberry_pi_supercomputer.shtml explanatory video: https://www.youtube.com/watch?v=Jq5nrHz9I94&list=UU63kOMam6uIR2il5tTRYRCA&index=1&feature=plpp_video
Prostheses	http://www.openbionics.org/
Optics	http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0059840
Generic lab equipment	http://www.gaudi.ch/GaudiLabs/?page_id=328
Scanning electron microscope	http://benkrasnow.blogspot.de/2011/04/diy-scanning-electron-microscope-image.html

Table 6 – Repositories/information hubs for open source projects related to sciences

Name	**URL**
Appropedia	http://www.appropedia.org/
Hackaday repository	www.hackaday.io
Hackteria	http://hackteria.org/
BioHackacademy	https://github.com/BioHackAcademy
Plos Channels – Open Source Toolkit	https://channels.plos.org/open-source-toolkit
Openeuroscience	www.openeuroscience.com
Github	https://github.com
Open Plant Science	http://openplant.science/
Journal of Open Hardware	http://openhardware.metajnl.com/
HardwareX	https://www.journals.elsevier.com/hardwarex