

Return on investment for open source scientific hardware development

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Abstract

The availability of free and open source hardware designs that can be replicated with low-cost 3D printers provides large values to scientists who need highly-customized low-volume production scientific equipment. Digital manufacturing technologies have only recently become widespread and the return on investment (ROI) was not clear, so funding for open hardware development was historically sparse. This paper clarifies a method for determining an ROI for the development of scientific free and open source hardware (FOSH). By using an open source hardware design that can be manufactured digitally, the relatively minor development costs result in enormous ROIs for the scientific community. A case study is presented of a syringe pump released under open license, which results in ROIs for funders ranging from hundreds to thousands of percent after only a few months. It is clear that policies encouraging FOSH scientific hardware development should be adopted by organizations interested in maximizing return on public investments for science.

Key words: open hardware; science policy; return on investment; free and open source hardware; free hardware; open source.

1. Introduction

As prominent voices in the scientific research community have pointed out, funding cuts continue to reduce grant success rates (Anon 2014; Alberts et al. 2014). This creates hyper-competitiveness with the concomitant diminishing of risk taking and innovation among researchers of all ages and the desertion of many young investigators (Anon 2014; Alberts et al. 2014). In addition, researchers consume an ever-increasing fraction of their time with grant writing rather than actually doing science. Simultaneously, the national average overhead charged on grants (indirect costs primarily used to subsidize administrative salaries and building depreciation), has climbed to 52% (Jan 2013), which further limits scientists' ability to do research with the hard-earned funding they do obtain. Experimentalists are perhaps the hardest hit as the low-volume highly-specialized equipment needed to push further scientific progress continues to demand premium, and often shockingly high, prices on the market.

Fortunately, advances in low-cost electronics and 3D printing (Jones et al. 2011) enable a new paradigm of scientific equipment production where scientists in the developed and developing worlds can fabricate tools themselves from digital plans (Jones 2012; Pearce 2012a, 2014a; Anon 2013; Pearce et al. 2010). There has been an exponential rise in designs for hardware released under open source, creative commons licenses or placed in the public domain (Wittbrodt et al. 2013) including the 3D printers themselves

(Jones et al. 2011). This free and open source hardware (FOSH or open hardware) is shared between scientists by providing the bill of materials, schematics, assembly instructions, and procedures needed to fabricate a digital replica of the original (Pearce 2014a). FOSH reduces redundant problem solving in laboratories around the world, accelerates innovation due to rapid laterally-scaled feedback (Jones 2012; Pearce 2012a, 2014a; Anon 2013; Pearce et al. 2010). In this way hardware can benefit from the same methods that have proven so successful with free and open source software (Ball 2003; Lakhani and Hippel 2003). The number and variety of FOSH scientific tools is rapidly expanding (Pearce 2012a, 2014a; Pitrone et al. 2013; Gualda et al. 2013; Carvalho and Eyre 2013; Wolf 2013; Zhang et al. 2013; Herrmann et al. 2014; Gross et al. 2014; Chiu and Urban 2015). For scientists that need access to highly-customized low-volume tools the open source method and digital replication can result in significant cost savings (Pearce 2012a, 2014a; Pitrone et al. 2013). Although research capital goes further with digitally distributed open designs, it still costs money to develop them. This paper investigates the return on investment (ROI) possible for funding agencies such as the National Institutes of Health (NIH) or National Science Foundation (NSF) for developing open hardware for science. A brief case study is provided to illustrate the economic calculations. Policy recommendations are then made to maximize the ROI in R&D in any field accessible to open hardware design.

2. Calculations

The value obtained from a FOSH design can be determined from the downloaded substitution valuation (Pearce 2015) (V_D) at a given time based on the number of downloads (N_D) for a given design at time, t :

$$V_D(t) = (C_p - C_f) \times P \times N_D(t) \quad (1)$$

Where C_p is the cost to purchase a traditionally manufactured product, C_f is the marginal cost to fabricate it digitally (e.g. open source 3D printing), and P is the percent of downloads resulting in a product. It should be noted that P is subject to error as downloading a design does not guarantee manufacturing. On the other hand, a single download could be fabricated many times, traded via email, memory stick or posted on peer-to-peer websites that are beyond conventional tracking. The savings are maximized for custom low-volume scientific equipment where C_f is generally only 1–10% of C_p (Pearce 2014a; Zhang et al. 2013), creating a 90–99% savings.

Investment in scientific open source hardware can thus create a ROI that can be calculated by:

$$ROI = \frac{V_D(t) - I}{I} \quad (2)$$

Where I is the cost of the investment in the development of the FOSH scientific tool.

3. Case study

Consider the case of a simple open source syringe pump library design (Wijnen et al. 2014), which may be government funded for scientific innovation acceleration, but also have applications in science, technology, engineering, and mathematics education and medicine. The low-cost open source pumps are completely customizable allowing both the volume and the motor to scale for specific applications such as any research activity including carefully controlled dosing of reagents, pharmaceuticals, and other applications. The design, bill of materials, and assembly instructions are globally available to anyone wishing to use them.

The pump library was designed using open source and freely available OpenSCAD (a script-based, parametric CAD package) enabling scientists to customize the design for themselves (Wijnen et al. 2014). The majority of the pump parts can be fabricated with an open source RepRap 3D printer and readily available parts such as a stepper motor and steel rods. The pumps can be used as wireless control devices attached to an open source Raspberry Pi computer. The performance of the syringe pumps generated by the open source library was found to be consistent with the quality of commercial syringe pumps (Wijnen et al. 2014).

As of this writing (February 2015) the designs for the open source pump, which were released in September 2014, have been downloaded from two digital repositories a total of $N_D = 1,035$ times (224 on Thingiverse (Pearce 2014c) and 811 on Youmagine (Pearce 2014c)). The cost to purchase a traditionally manufactured syringe pump, C_p , ranges from \$260–1,509 for a single pump and \$1,800–2,606 for a dual pump (Wijnen et al. 2014). C_f for the materials for an open source syringe pump is \$97 and \$154 for the single and double pump, respectively (Wijnen et al. 2014). The time to assemble either the single or double pump is less than an hour and can be accomplished by a non-expert. Although the time to print the components is less than four hours on a conventional RepRap, workers can do other tasks while the printing is underway.

The assembler hourly rate is assumed to be \$10/hour because no special skills are needed. P was assumed to be 1 as informal discussions with 50 RepRap owners found that the vast majority of designs downloaded were printed. This is because although RepRap owners may view many designs, they only download the STL files (STereoLithography is a file format used for 3D printers) of the designs they intend to print. This provides a saving for substituting the open source pump for a commercial one of \$153–1,402 for a single pump and \$1,636–2,442 for the double pump. Thus, following Equation (1) the value, V_{DT} , of the pump library on 5 February 2014 ranged from over \$168,000 to over \$2.5 million.

The investment needed to create the pump library was trivial in comparison to the savings. The mechanical designs were completed by experienced engineers in less than six worker-hours. To print and revise the five 3D printed components took three hours, assembly less than an hour and software development and Pi wiring less than 16 hours. The total design and prototyping time was less than 26 hours. This schedule was possible because the designers were experienced with similar designs and had access to all of the components. Let us assume that the pump design was completed as part of an NSF or NIH grant that involved overheads, materials, and validation testing from a PhD student over a semester, thus involving an initial investment, I , of \$30,000. By Equation (2) this provides ROIs ranging from 460% to over 8,300%.

These ROIs, however, are conservative as the value of the FOSH in labs is not only the amount saved for research directly, but also includes the value of the overhead (indirect costs) charged on grants to purchase the product commercially. When the national average overhead rate of 52% is included on the cost of conventional equipment, the ROIs increase to range from over 750% to over 12,000%, respectively.

4. Discussion

Some care must be taken in evaluating these ROIs. First, to be conservative it should be pointed out that although the majority of those downloading can be presumed to be American, not all of the savings would accrue to those that the US government funding agencies are supporting. Although improving science globally will help researchers in the USA indirectly, it may not be viewed as a direct ROI. On the other hand, the low end value is from a simple infusion pump with considerably less functionality than the FOSH syringe pumps. It is a safe assumption that the majority of those who are downloading are likely to be replacing more sophisticated scientific devices. In addition, it also is clear that the number of downloads and fabrications of the syringe pumps will continue to expand with time providing ever-increasing value for the scientific community and higher ROIs for funding such developments.

There are also other benefits. As the pump meets the standards for research and has already been vetted, it seems reasonable that university labs would be most likely to adopt it first. This would result in potential additional value for both scientific research and education. By decreasing the costs of research equipment more of the diminishing resources for science are available to do science. For example, if a quad syringe pump is fabricated for a molecular biology lab the savings would be enough to hire a summer undergraduate researcher, thus presumably increasing the scientific discovery rate. In addition, as the designs are FOSH, other labs are already improving the tool and re-sharing the improvements (Lynch 2014). This creates superior scientific equipment in the future with no additional expenditures. Similarly, due to lower costs, FOSH could be

used in classroom or lab courses at every level, thus improving education.

Quantifying the value of an increased rate of discovery in science and medicine because of lower costs or superior equipment or better education entails specific detailed studies. For example, these studies could utilize follow-up surveys targeted at all those who have downloaded the design and STL files to obtain a precise account of P , C_p and C_f . In turn, these initial calculated ROIs could then be augmented by following the results of groups/schools that have adopted the open hardware. This would be useful for obtaining exact values of ROI. However, the methodology used here provides reasonably accurate values based on conservative assumptions of simply replacing proprietary equipment. Qualitatively, it is clear that free and open source scientific hardware has ROIs set by the minimum calculated by Equations (1) and (2) and these are significantly higher than those involving proprietary investment by public funding groups.

It should also be noted that as FOSH becomes more commonplace in the scientific establishment there may be a cultural shift within labs to employ 'makers' to build and troubleshoot open source equipment. The 'maker movement' is a growing culture of hands-on making, creating, designing, and innovating at all ages (Dougherty 2012; Peppler and Bender 2013). Such troubleshooting is already provided in a limited way by technicians, research assistant students and research scientists, but would be expected to expand and provide positions for the growing number of makers as more scientific hardware becomes completely accessible and customizable.

Finally, it should be noted that there is nothing at all remarkable about the syringe pump used as an example here. Any one of dozens of other existing open source scientific hardware designs that have a C_f that is a tiny fraction of C_p (Pearce 2014a; Zhang et al. 2013) and that have been downloaded a small number of times would show similar enormous ROIs. In addition, there are numerous types of equipment that could be redesigned as FOSH with low fabrication costs that could be widely applied outside of scientific labs (e.g. hand-held nitrate testers for water quality or for farmers to use to determine fertilizer requirements) that would have enormous potential returns for society.

For entities such as the NIH, which are trying to leverage their investments for the greatest common good, FOSH development has extremely high potential ROIs. Traditional investments in proprietary development would not come close to such a return, nor would the source be available for others to immediately begin working on because of the 20-year external innovation hiatus demanded by the current patent system (Pearce 2012b).

It is clear that federal funding (such as through the NIH, NSF, Department of Energy, Department of Agriculture, Department of Defense, and NASA etc.) should be prioritized for the development of open source scientific hardware because of the enormous potential ROIs for the US's scientific community. This can be accomplished with a combination of traditional call for proposals (CFPs) for academic grants and programs like the Small Business Innovation Research (SBIR) program and the Small Business Technology Transfer program. In addition, the USA can run national contests like the X-prize or 'first to make' specific technical goal 'bounties'.

Just as proprietary tools on the market are vetted, tested and validated, all FOSH scientific designs should be treated similarly. This will largely eliminate the technical risks for labs when adopting the use of the hardware, while at the same time ensuring that scientific equipment no longer becomes obsolete as proprietary systems

can, when a company loses key personnel, discontinues a product line or goes out of business. Funding for this validation would be the major part of the cost of scientific FOSH. Then, in order to ensure the widest distribution of the free technologies, NIH's 3D Print Exchange should be expanded to act as a free, national, online catalog of tested, vetted and validated free and open source scientific hardware. The NIH's 3D Print Exchange should be augmented to be able to house the bill of materials, digital designs, instructions for assembly and operation, and the source code for all software and firmware.

5. Conclusions

By funding open source hardware designs that can be manufactured digitally, the relatively minor development costs results in enormous ROIs for the scientific community. As the designs are reusable, with solid modeling and 3D printing, designs can be expanded or joined together rapidly increasing the rate of innovation. The case study presented here found ROIs of hundreds to thousands of percent from a relatively simple scientific device being released under open licenses. It is clear that free and open source scientific hardware development should be funded by organizations interested in maximizing return on public investments.

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