End-to-end test of open-source hardware documentation developed in large collaboration/team settings

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Abstract

Large international collaborations of scientists explore the frontiers of our knowledge and discover game-changing phenomena that captures the imagination of the public worldwide. Whether investigating the human genetic heritage or the collision of enigmatic cosmic objects, it matters not. They all use hardware technology on the bleeding edge of human capabilities, often more akin to art than engineering. That is why we refer to these efforts as *instrument science*. The enormous cost of these endeavours are often measured in billions of dollars and thousands of human years, inevitably fully funded by the international taxpayer. The support of the people is critical for success in fundamental sciences and it places the welcome burden on their hardware developers. Similarly to their data, they have to produce open source hardware that is fully documented and open to all, after all we the people paid for it all. Therefore, large scientific collaborations are an excellent opportunity for a case study in best practices implemented while developing open source hardware. We studied several international collaborations funded by the National Science Foundation of the United States. We evaluated many facets of the open source hardware development, including practices, awareness, documentation, longevity. We found that indeed large collaborations are extraordinary teachers, role-models, and test-systems for open source hardware development policy, control, and practices. We summarize the experiences and resulting recommendation with special emphasis of aspects and lessons learned where the open source hardware community can learn from the collaborations and vice versa.

(1) Introduction

This paper explores the longevity of open-source documentation in large collaborations. Open-source hardware is an incredible resource for the society as a whole as it can foster collaboration between scientific teams and the general public. Consequently, open source hardware projects can increase accessibility to and interest in science. For that reason, it is important to continuously evaluate open hardware principles to see if they truly support transparency.

In order to explore the pros and cons of open hardware, we had undergraduates and high school students with an interest in open-source hardware and design but no practical experience conduct an end-to-end exercise to test existing open-source documentation from the design of the Laser Interferometer Gravitational-Wave Observatory (LIGO) Timing System, which was built 10 years ago. The LIGO detectors are part of the global network of interferometers aiming to observe gravitational waves directly.

One hundred years after Albert Einstein predicted their existence, LIGO was able to make the first detection of gravitational waves. The detection was made by the Advanced LIGO detectors in Livingston, Louisiana, and Hanford, Washington. These detectors, while located at the same sites, were an upgrade to the initial LIGO detectors and the culmination of a multi-year team effort of research based on the experience of operating the original detectors for a decade. The Advanced LIGO detectors have ten times greater sensitivity and thus observe a thousand times bigger volume of the Universe compared to the initial installation, which significantly increased the likelihood of gravitational wave detection.

To support the upgrade, the initial LIGO timing system needed to be upgraded as well. The design choices were dictated by the operational goals and requirements of the timing system, a subsystem of the LIGO detectors. Making discoveries requires coordinating within the global gravitational-wave detector network and with other astronomy and astrophysics observatories that can detect electromagnetic and particle counterparts of gravitational waves and thus provide a complete multi-messenger picture of cosmic events. A new design was made that ensures the reliable operation of the detectors and also provides precise timing information of observed gravitational wave events. The new design also aimed to strengthen both the diagnostics capability and the ability to be able to track all synchronization errors.

As a large-scale collaboration, LIGO has its own documentation procedures that are intended to stand up to time. As such, the team that worked on the Advanced LIGO Timing System created documents that cataloged every step of the development and manufacturing process. They discussed the role of timing from the perspective of astrophysical measurements and data analysis; introduced and described the Advanced LIGO Timing System that will provide timing for the Advanced LIGO detectors; discussed the structure and specific components, the synchronization methods and system diagnostics; and, finally, presented performance tests of the Advanced LIGO Timing System that demonstrate its precision in practice and its robustness against environmental and configurational changes.

The National Science Foundation (NSF), which provided funding for the design research, mandated that the timing system documentation be open to the public. However, as it was not designed with open hardware ideas in mind, we decided to test whether outsiders can really use it efficiently and, if not, what changes need to be made. As the Timing System was designed ten years ago, we also were able to test whether the documentation can survive large timescales.

We considered that undergraduate and high school students new to the field of open-source science were the best proxies for outsiders as they would consider everything with fresh eyes. For that reason, we conducted surveys before the students began testing the documentation and after they completed all of their tests to see how their viewpoints changed with experience. The students also reflected on what they wish they had known before they started and that educators in academia should know before they start introducing their students to the field.

There are several key differences between original team of undergraduates, graduate students, engineers and scientists who worked on the original design of the timing system ten years ago and the latest cohort of undergraduates. The original team's object was not on assessing and creating open-source hardware. Instead they were prioritizing LIGO goals and objectives. Experts were also more closely involved during the original design process. In this new iteration of the project, scientists took a less active role and allowed the undergraduates to explore the documentation independently.

The undergraduates remodeled the process leading up to manufacturing. They looked for supply change shortages and obsolete items. While they did not manufacture any hardware, they obtained quotations from manufacturing firms to get a sense of the feasibility of production as well as the change in price. They also conducted a survey of electronics design software in the open-source context and looked into whether their team can contribute to design changes. For that, they needed design software that was not behind a paywall. They identified one and tinkered with it.

The undergraduates and high school students also conducted tests. Testing the boards involved following a step-by-step procedure outlined in the Advanced LIGO Timing System documentation by checking parameters such as voltage readings and visual signals. Both the high schooler and undergraduate teams performed this process on LIGO's Leaf and DuoTone boards. Their experiences learned from this process are further summarized in this paper.

(2) Remodeling Exercise

Safety

All high school and undergraduate students were given safety instructions regarding the use of laboratory spaces and equipment.

Preparation

The undergraduate students were tasked with two tasks, which are referred to in this paper as manufacturing and making open source. The following sections go into greater detail about the specifics of these two tasks. Notably, the students had minimal to knowledge of both the production and manufacturing of PCB's as well as working with PCB design software.

Manufacturing

The manufacturing group was charged with obtaining quotes from PCB companies for the Leaf board. By looking at the original gerber and bill of material files of the Leaf board, they were able to find manufacturers that were (1) domestic, (2) could provide a full turn key solution, and (3) were ROHS compliant. These companies accepted files in many different formts, the principal three being Altium, Eagle, and KiCad. The acceptance of KiCad is particularly noteworthy as it is one of the only free software suites for electronic design and thus is the most compatible with open source principles.

While they were able to compile a list of companies, the student team had no prior experience with PCBs, and thus found it difficult for the team to ascertain what a company's reputation was and what their usual clientele is, two key components in determining which manufacturers were the best for the job. In the end, the team reached out to around 10 companies and received 7 responses.

Some of the challenges the group encountered while requesting quotes were finding responsive manufacturers, finding replacement components, updating manufacturing techniques, and providing relevant manufacturing documentation. Since manufacturing standards have changed from when the boards were originally produced in 2009, manufacturers struggled with information that was not included in documentation at the time, such as drill programs, environmental standards, and production timeline.

There were two ways to obtain quotations. Some companies have websites that allow users to upload their design files directly; upon submission, an automatic quotation might even be generated. Others, which are typically smaller, ask prospective customers to communicate through email.

The students noted that even limited correspondence built a relationship that the ease of uploading a file directly on the website could not rival. They also found emailing companies more intuitive, as it did not necessitate familiarity with the different PCB file types needed for a quote.

While many smaller companies were responsive and willingly provided clarifications and answered additional questions, larger companies were less willing to provide quotes if they were not guaranteed the order. They were also less accommodating of missing information and obsolete parts.

All of the companies who supplied the team with quotations requested replacement parts for obsolete or out of stock components. As such, the students had to evaluate the data sheets of the company-recommended replacements, which often had different functionalities from the original parts, making it difficult to determine whether they were accurate replacements. The student group attempted further research into the original parts, but information was limited due to part discontinuation and general lack of knowledge about PCBs. Changes in certain components would often necessitate further changes in the bill of materials, leading to more ambiguity on the required components. Due to these issues, the manufacturing group was often unsure of replacement components and therefore overall production feasibility. Their experience emphasizes that those new to either open source hardware in general or to the specific field of engineering design should contact experienced individuals or the original designers of the project in question. Contact with the original designers or those who keep contributing to the project can increase the longevity of open hardware endeavours.

The quotes that the manufacturing team ultimately received were typically divided into the price of bare boards (PCBs without electrical components) and assembly (PCBs that contain all the components) with several different lead times to choose from. Additionally, some manufacturers required tooling expenses for the older components. The group received a total of 5 quotes, and Figure 1 compares the prices of these quotes, including the price of the quotes from 2017. Figure 2 compares the range of lead times from the various manufacturers.

Making Open Source

The group was supplied with the original PCB files used to manufacture the Leaf Board, which were designed in Altium in 2009. While Altium is currently the most popular software for PCB design, it is not conducive

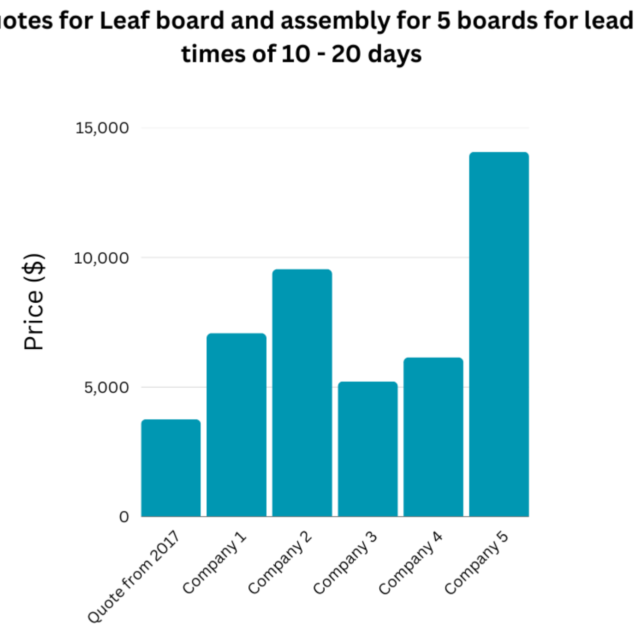

Figure 1: Price Comparison of Quotes Recevied

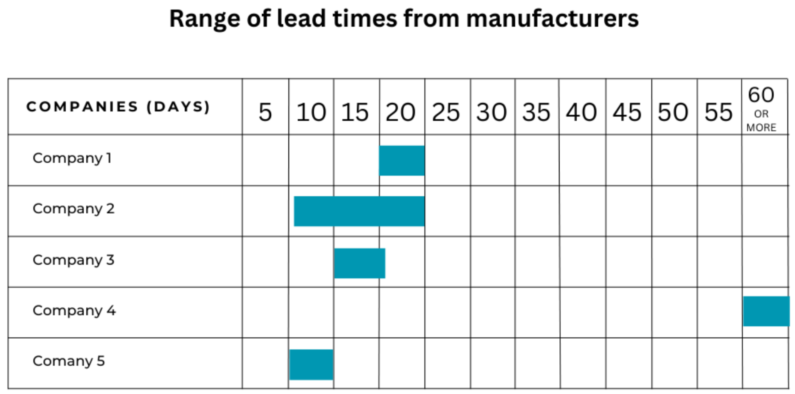

Figure 2: Rnage of Lead Times

to open science as it is behind a paywall. Engineering students can often gain access through their respective institutions, but this is not universal and usually expires by their date of graduation. Further, Altium is usually not available to non-engineering students. As stated above, this team comprised of both engineering and non-engineering students. Thus, the team set out to find an open source alternative to Altium for PCB design.

In determining which open source software to use, the undergraduate team evaluated both price and operating system and determined that KiCad was the software to best conduct this redesign project. KiCad is free, compatible with both Mac and Windows operating systems, proves a smooth user experience, and is already in widespread use among engineers, which ensures the availability of tutorials and online resources for students to become familiar with the software. It should be noted that KiCad also had an abundance of tutorials, which makes it much more accessible, though this was not taken into account while making the selection.

Software	Cost	Free Trial	Operating System
Altium	$$$	Yes	Windows
Eagle	$	Yes	Windows/Mac /Linux
KiCad	Free	N/A	Windows/Mac Linux
Circuit Maker	Free	N/A	Windows

Figure 3: Software Comparison Table

Next, the students converted the Altium file into a KiCad fileusing a third-party tool. However, they discovered that the libraries which Altium uses do not match the libraries used in KiCad, rendering the converted file useless. The students eventually settled on a procedure to convert the file manually from Altium to KiCad, which is outlined in Figure 4.

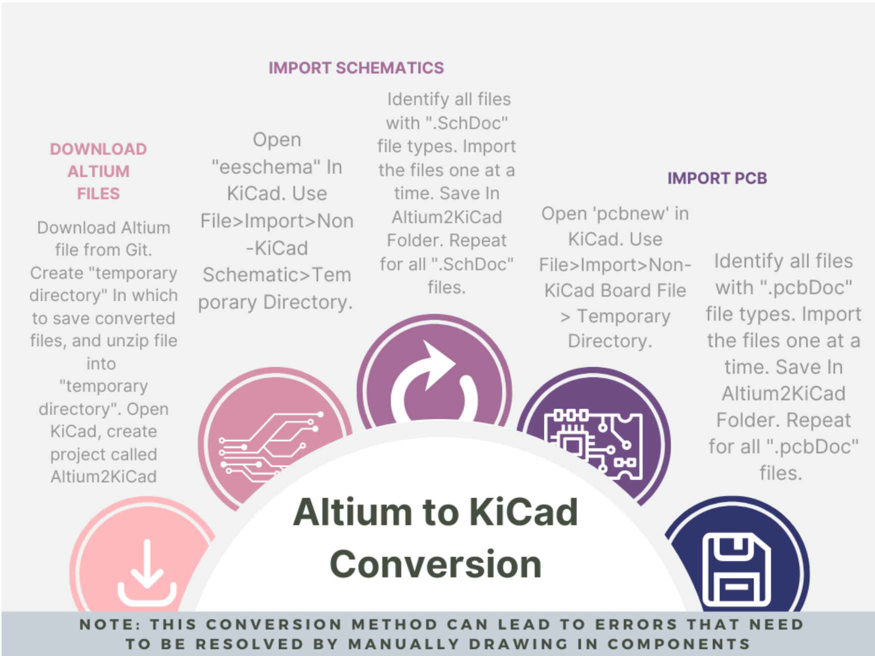

Figure 4: Process of Altium to KiCad Conversion

It should be noted that, while this conversion process was an improvement upon the first attempt, it was also not entirely successful. The gerber files were intact as were most of the PCB layout, but there were several problems with this conversion, including that (1) multi-page schematics were split into multiple schematic documents; (2) there is no link between the schematic files and the PCB layout, which can create problems when attempting to modify; (3) the drill hole sizes of the PCB layout were changed; (4) some wiring is missing in the schematic; and (5) there is no link from the footprints in the schematic to the library.

Despite these issues with the conversion, we still recommend using KiCad as a resource to make hardware files open source with the caveat that it is not a perfect process. On the side of the creator, this means being vigilant in checking the schematic and PCB layouts for any errors, as well as manually linking the footprints to the library. To address the issue of the multiple schematic documents, one option for creators is to make a "master schematic" which links the individual schematics. On the side of the user of open source hardware, we recommend communicating with the creator or another expert if the design is complex, as editing may create errors.

Once the team had converted the files into KiCad, they were tasked with replacing a custom-made electronics part in the design with a generic version with similar specifications. Retaining the custom part in the design would have been a barrier to accessibility; the custom voltage-control oscillator in question was only required to fulfill LIGO requirements about frequency. Hobbyists or members of the public would not be able to buy this part, and even if they could, custom parts are infinitely more expensive than their generic counterparts. Most crucially, the part is not necessary for the broader public. Buying the standard available generic part is much cheaper and easier.

After selecting the new part, the students replaced the component on the KiCad schematic. While this process was not technically difficult, the undergraduates still doubted that they had correctly replaced the part due to their lack of familiarity with PCB design. They reached out to one of the original designers to verify that the substitution worked, showcasing how open hardware projects are most successful when the creators are accessible.

Testing of Existing Hardware

The group then set out to test the existing hardware by following the steps from two public LIGO documents: "Test Procedure for the Timing Slave Board" and "Test Procedure for the Clock, Gate, and DuoTone Signal Interface." These documents were authored by the original members of LIGO who designed the hardware.

During this process, students encountered two key problems. The solutions they devised are outlined below.

Problem 1: Working with Old Software and Hardware

One issue encountered by both the high school and undergraduate teams was understanding how to use old hardware and software. While both teams were able to successfully test the boards, it was only possible because of the expertise provided by a supervisor familiar with the hardware and software. For example, the high school team relied on help to follow the Altium Designer instructions provided in the duotone board test and required clarification to understand the difference between ports P1-P8 and their sub-ports. This reliance on expert supervision suggests that groups that wish to test LIGO hardware would experience difficulty if they lack access to an expert to clarify confusion or if knowledge of old software and hardware, such as Altium Designer and the ten-year-old boards that were tested, is either lost or diminished. In addition to the above recommendation regarding the improvement of instructions within documentation, a supplementary guide with more general instructions and information about how to use Altium Designer and the various duotone board ports would have made the procedure more easy to follow and less reliant on expert help.

Takeaway

Since hardware and software become obsolete over time, it is important to update documentation frequently and preserve instructional materials on old hardware components and outdated versions of software.

Problem 2: Ambiguity in Hardware Testing Documentation

One problem encountered by both the high school and the undergraduate group when following the testing procedure of the boards was ambiguity in documentation. The documentation was clearly written for scientists who were familiar with the software as well as with the hardware itself. However, to the untrained student, its details were difficult to decipher. For example, the figures showing the board orientation were not intuitive, with the schematic often rotation with respect to the physical board, resulting in difficulty identifying the correct pins for the procedure. Further, certain indicators off the success or failure of the testing procedure were unclear. One instance is with the flashing of what is called the "soft LED." The language of the manual led the students to believe that the LED in question was on the board, when in fact it was on Altium. Language formulated in this manner may be obvious to the original scientists who worked on the timing system, but can be a source of great confusion for students.

Takeaway

Documentation files should be written assuming little prior knowledge of the project itself and should be very specific when referencing hardware components.

(3) Conclusion

Evaluating open hardware practices in large international scientific collaborations using teams of high school and undergraduate students provided insight into current benefits as well as areas for future growth.

We noticed that current documentation practices are geared towards other scientists and engineers, and not undergraduates of members of the public, who form the next generation of innovators. Scientific collaborations create design files on platforms behind a paywall, or use highly-technical language in their documentation and how-to manuals are scarce. We also found that it is difficult for outsiders to the scientific community to find replacements for obsolete parts, even in documents designed for longevity such as those for the LIGO Advanced Timing System. By far the most important factor was access to the creators or experts, who could guide newcomers to the field.

By remembering that open hardware is truly "open" and should serve both scientists and the public, we can increase accessibility to hardware. Creative open source hardware can also teach about new designs, accessible documentation modalities, and the rich universe beyond bare function to focused scientists. It is a mutually beneficial situation with tremendous potential.

Paper author contributions

Concept: Writing: Surveys: Experiments: Other: Task (e.g. design, assembly, use cases contribution, documentation, paper writing), contribution, author name.

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Competing interests

The authors declare that they have no competing interests.

References

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