Development and Sharing of Open Science Hardware: Lessons Learned from Wikimedia Fellowships

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Abstract

The promise of open hardware as a branch of open science is a sustainable change of research instrumentation towards more openly documented and licensed designs. Methods, code, and data are already valued by journal editors and peer-reviews to judge if a study's result can be replicated with the information provided in a manuscript. The open hardware movement seeks to include laboratory tools and research instrumentation into the same category. Availability of and access to open hardware equipment are set to democratize professional lab work and field studies as well as enhance the transferability of methods to civic science settings. Here, we report four case studies from the first five years of the Wikimedia Program "Free Knowledge", an open science fellowship funded by Wikimedia Germany and partners. The project developers discuss and evaluate the impact related to key aspects typically attributed with open hardware: costs, availability, adaptability, community and educational value. The open hardware projects covered in this review span from natural sciences to life sciences to education.

Keywords

Open Hardware, Lessons Learned, Funding, Neuroscience, Life Science, Nuclear Physics, Education

Introduction

With the growing demand and push towards open science practices, more than open data and publicly accessible results are needed. In order to facilitate independent confirmation of research through replication of results and reproduction of scientific methods, scientists require access to detailed description of the instruments and tools that have been used. Such open descriptions, broadly referred to as "open hardware", are typically implemented by sharing software and modifiable hardware designs of scientific tool-sets, alongside documentation and an open license, on public project repositories such as Zenodo, GitHub, and others. Beyond this obvious role in conducting open science, open software and open hardware often comprise two additional key advantages: Adaptability and low costs in comparison to commercial, closed solutions. Considering such universal relevance, a study for the European Commission has recently labeled open source software and hardware as "Public Good", emphasizing its importance in social-economic and political contexts (European Commission 2021). International as well as national research organisations have begun formally including hardware topics in their open science policies (EMBL 2021, CERN 2022, Helmholtz 2022).

Within the Wikimedia Program "Free Knowledge" (German title: "Fellow-Programm Freies Wissen"), running from 2016 to 2021, we have identified at least seven fellowship projects where open hardware played a major role (out of 70 projects in total, mostly related to social sciences and liberal arts). In this article, four of these fellows reflect on their open hardware projects spanning a diverse set of related fields: engineering & technology, education, physics, biology and neuroscience. The fellowships provided individual project funding of up 5000 EUR which fellows could use freely as private persons and independent of any institutional dependencies. Guidance by mentors, meetings with alumni of previous years, and workshops on various open science topics comprised the general program for a year.

General Aspects of Open Science Hardware

"Hardware is hard" is a commonly accepted stance among entrepreneurs within the commercial product world. This also applies to research instruments based on hardware. However, the reasons behind this common difficulty may be quite different. While, for example, the development of any consumer hardware product calls for a balance between resources versus features and respective market demands, the latter aspect is replaced by feasibility considerations in the context of science. Is the hardware setup that enables a certain scientific measurement at all available, and if so, can one obtain or build it with reasonable resources? Even if a solution of sufficiently low cost is available, development time and expertise also need to be considered. This tradeoff may vary between researchers living in high or low-income countries as the access to required hardware resources, know-how, and funds changes.

Another important driver of open hardware, closely related to costs and availability, is the ability to adapt hardware. For example, a vast number of different scanning microscopy methods have been developed since the past century - employing various physical effects. However, common in all such setups is the need for multi-dimensional translation stages that enable a scanning movement across specimens under a microscope at a precision on the micrometre scale or better (Sharkey et al. 2016). Once available as open hardware, a scientific instrument may be easily modified to cover new applications and methods not foreseen by the original developers. When building novel setups, open science hardware (OSH) removes the necessity of reverse engineering which is required for modifying commercial products ("black boxes") and resonates with the core of the scientific process - building upon previous knowledge. A detailed discussion of these central aspects can be found in (Chagas 2018), including an extensive list of OSH resources.

A number of appropriate open licenses exist for software, see for example www.opensource.org/licenses. Most require crediting the original authors and waive liabilities while defining user rights. Corresponding open documentation is typically well covered by the various flavours of Creative Commons licenses. For open hardware, typically represented in the form of electronics or mechanics design files, dedicated licenses should be chosen since specific aspects related to manufacturing and physical reproduction should be explicitly addressed. Focusing on OSH, we recommend using the CERN Open Hardware License which was recently diversified into three degrees of permissiveness (CERN 2020).

Lessons Learned

In the following project summaries, we review the lessons learned from our OSH projects on different levels of complexity and development stages. Each project is presented by the corresponding Wikimedia Open Science Fellow. Besides the hard facts discussed above, we also reflect on soft facts related to learning and community building as open science depends on well established sharing practices. We gathered some representative metrics on project impact and interest by evaluating for example the types of interactions on GitHub. The latter should only be regarded as a qualitative indicator as the scope and duration of the discussed projects varies considerably. The overview presented in Table 1 summarizes main aspects across all projects.

Projects

Event Marking Interface for Neuroscience

The USB-to-TTL project was initiated shortly after old computer hardware was upgraded in the electroencephalography (EEG) laboratory of one of the authors' research institutes. EEG can be described as the non-invasive measurement of voltage differences on the scalp of a study participant (or a patient, in clinical settings). These voltage differences are directly influenced by brain activity and through advanced analysis techniques, researchers can make inferences about brain processes and may relate these to behavioral measurements like reaction times or value based decisions in experimental settings. Crucially for the present paper, EEG research involves the interaction between several computers and EEG hardware, such as amplifiers. While the upgrade of the computers to newer standards in one of the author's labs was a welcome change, it also presented an unforeseen challenge: Research hardware such as EEG amplifiers often connect to computers by sending so-called transistor-transistor logic (TTL) signals via a parallel port interface (see Fig. 1a). Yet, since the early 2000s, the parallel port is being increasingly replaced by the now ubiquitous USB port on modern consumer grade computers. Researchers thus often face a situation where sturdy and reliable research hardware that still relies on the parallel port cannot be interfaced with modern computer hardware anymore. Notably, this problem generalizes to research hardware beyond the area of EEG research, because the benefits of the parallel port (a technically very simple yet fast and reliable interface) were taken advantage of in many different fields of application. The goal of the USB-to-TTL project was to solve this problem by building, testing, and documenting adapters that connect from a USB port to the parallel port interface.

An initial search on existing solutions yielded seven different commercial products to address this problem – most often provided by manufacturers who also produce the respective research hardware that operates via a parallel port interface. However, these solutions typically had one or more of the following drawbacks: (i) they were very expensive, (ii) they did not operate on all major operating systems, or were not tested and/or documented for all operating systems, and (iii) they were targeted towards a specific hardware. Interestingly however, the search also yielded a large variety of deeply nested forum threads discussing the exact same problem, and proposing do-it-yourself solutions with commonly available microcontroller units (MCUs) such as the Arduino or the Teensy. As part of the fellowship, we collected, unified and documented this scattered wealth of information and built several prototypes to replace the parallel port. Then, we exhaustively tested and compared each prototype against the parallel port across different operating systems. Such tests were crucial to demonstrate the utility of USB-based interfaces when sub-millisecond timing precision is required, as could be provided by the parallel port. Note that as such, the USB-based interface combines advantages of being an easily accessible and available interface that is beginner-friendly, and is still achieving a high enough temporal precision for many applications in the domain of cognitive neuroscience. We published our results in the form of a journal article (Appelhoff and Stenner 2021) with an accompanying website (www.stefanappelhoff.com/usb-to-ttl) and all collected data and code, with the intention that future users in need of the present solution won't have to spend countless hours digging through specialized forums, books, and other resources.

The entire project took around two years from idea to conclusion; starting with an initial search after identifying the problem, followed by a year of prototyping, writing documentation, and analyzing testing data as part of the fellowship, and then following through with the academic publication process, including peer review. Such a long process might raise the question whether the whole project is worthwhile – especially given that the initial intent was to conduct an EEG experiment using the parallel port, and not to solve a problem of interfacing research hardware and computers via the USB port. However, overall the project offered many learning opportunities at the intersection of open hardware, documentation of open projects, licensing, and the academic publication process. Most importantly, the project now feels like a relevant contribution to the scientific community.

DIY Particle Detector

The DIY Particle Detector originated within a PhD project at CERN in 2017 and was developed as a hands-on workshop topic across several student summer camps taking place at CERN. It is geared towards practical physics education and integrated STEAM teaching (science, technology, engineering, arts, and mathematics). Silicon photodiodes are repurposed as solid-state radiation detector for measuring natural radioactivity qualitatively (electron detector variant) as well as quantitatively (alpha-spectrometer variant, shown in Fig. 2a). Instead of detecting visible light via the photo effect, more energetic radiation can directly ionise the small semiconductors and liberate measurable amounts of charge - a popular detector principle in modern nuclear and particle physics research. The low-cost open hardware design together with open source software and extensive documentation is available online (Keller 2019). The project was inspired from exploring pixelated silicon detectors as promising novel educational tools in nuclear physics. Due their prohibitively high price (at least 2000 EUR per device), this low-cost detector (ca. 25 EUR per device) was originally intended as a functional model of one pixel. The alpha-spectrometric version was added later and goes beyond the capabilities of a simple radiation counter. It enables the measurement of characteristic energy spectra, for example from common everyday objects like vintage ceramics glazed with uranium oxide paint. Detailed discussion and evaluation of different low-cost silicon diodes as well as reference measurements taken under regular ambient air conditions and in comparison with detector simulations are published in a dedicated article (Keller et al. 2019).

The scope of the fellowship program funding period in 2021 was to improve the project documentation for a broader range of users (Fig. 2c), design new hardware adapted to measuring cosmic particle radiation, and most importantly the conduction of several workshops. These workshops were focused on interested amateurs (two German Fab-labs/maker spaces: FabLab Munich and Oberlab) as well as students (two German secondary schools, in Bonn and Oberland) as an attempt to further explore the project in the context of citizen science and outside of an established physics institute like CERN. Due to the emerging COVID pandemic, the majority of workshops had to be conducted online in video calls, with participants building the detectors remotely using material that was funded through the fellowship. The largely increased effort for communication and logistics caused by organizing remote workshops shifted the focus away from developing new hardware within the fellowship. A new circuit board was designed but testing and evaluation of it is still ongoing (cf. the Wiki on GitHub, Keller (2019)). In collaboration with the owner of www.Kitspace.org, a website dedicated to sharing open hardware electronics, several component kits were prepared and distributed as a first test case for disseminating further open hardware DIY kits through this website. While the electronic parts required to build the DIY Particle Detector may be purchased from several suppliers - optionally by utilizing the shopping cart export feature of Kitspace. Teachers and beginners in electronics were often found to prefer purchasing of completely prepared kits that include cabling and the custom circuit board.

As of July 2022, the project enjoys a sizable user base thanks to initial advertising via CERN's social media channels in 2020 which resulted in a popular post on Hacker News. The GitHub repository features over 400 stars plus forks with several users contributing to discussions, reporting issues, sharing pictures of their own builds and documenting adaptations of the open design to new use cases such as a random number generator (Fig. 2b). The low-cost aspect is central for this project, making it attractive for formal as well as informal learning environments. Adaptations of the DIY particle detector to new applications for measuring ionizing radiation are of course possible. However it should be noted, despite the simple appearance of the electronics - only a handful of components are used - expert knowledge is required for making functional modifications since the design is rather sensitive to electromagnetic interference and therefore carefully designed in its current form. This is reflects a central intention of the project which is the dissemination of all relevant context knowledge and related tinkering skills required for working with modern solid-state silicon sensors and using them for detecting radioactivity. A major aspect is the manual soldering of electronic parts which was purposely designed as beginner friendly. Running several DIY particle detector workshops, the author observed qualitatively an increased interest in tinkering and soldering aspects with young women compared to male-identified students. This could be a valuable lead for improving the gender balance regarding engagement in science and technology topics.

An unexpected artistic adaption of the project (cf. STEAM context) was created in collaboration with artist Vanessa Lorenzo and was also partially supported by the fellowship. Along improvisations played on other mostly DIY music instruments, the DIY Particle Detector was used to generate randomized experimental sounds from natural radioactivity, performed live in two "Other Planes of There" listening sessions at Gessnerallee Zürich in 2020.*[2] The audience was invited to discuss and ask questions, before as well as after the concerts, learning more about the detector and natural radioactivity.

Open Source Microfluidic Instrumentation for Single Cell Analysis

The project originally titled "Open labware for better life science" was less focused on a particular hardware than other projects in the program. Its aim was instead to explore a sub-discipline (microfluidics in life sciences) portfolio of instruments through the lense of open hardware, to test related open solutions that already existed, and organize and participate in related science outreach events such as GOSH 2018 in China and a HubHub seminar on the topic in Heidelberg (Meetup 2018). The instrument portfolio needed for droplet microfluidics (e.g., microscope, high-speed camera, precise liquid flow control via pumps, temperature control on microscopes, microfabrication of microfluidic chips, real-time laser signal acquisition system for droplet sorting, cell cultivation facilities, fluorescence microscopy) is broad, complex and usually very expensive, as well as in the author's experience, often driven by a secretive patent-focused academic community which does not often discuss details of their solutions in publications and conferences, or share designs and code. But there is also a growing open source community among microfluidics academics and DIY enthusiasts (Kong et al. 2017). During the project, the Minidrop design (Stephenson et al. 2018), open source syringe pumps (Wijnen et al. 2014), and a fluorescence-capable openflexure microscope (Sharkey et al. 2016) were built to understand the designs in detail and learn from them, see Fig. 3a, b, c. These re-builds required getting many individual components from different small global suppliers that would have been very difficult to acquire without the free disposal of the fellowship funds. This easy private acquisition is in contrast to laboratory money in institutional procurement systems that can only be spent according to strict purchase protocols and from registered suppliers that agree to special payment terms. In parallel to building hardware, a large additional design space was explored theoretically for other technical solutions needed for complex microfluidic experiments. This was achieved through literature research and many discussions with other developers, makers and technicians. The question was often where to draw the line - is it advisable to use an open source FPGA board and build the lab's own single photon detector for microfluidic droplet sorting? What proprietary modules are not worth replacing? What about the laser driver and the fluorescence microscope? Development notes, promising resources and items purchased for testing were documented on GitHub (Wenzel 2018) and lay the foundation for the development of a large instrument development project that goes beyond the original fellowship project (from 2018) and is still ongoing (in 2022), see also the later GitHub repository github.com/wenzel-lab/open-microfluidics-workstation. The ongoing instrument development efforts (see prototype in Fig. 3c, d) are focused on modernising and improving microfluidic instrumentation, but foremost on re-developing existing technical solutions as a low-cost, modular, compact and versatile platform for research optimized for digital and local fabrication. With this hardware, we want to provide access to advanced techniques such as droplet sorting and micro-gel generation, currently reserved for a few well-equipped and knowledgeable labs. To this aim we develop a design that is so easy to understand and modify, that a motivated biology student without technical training could contribute to future design changes and improvements relying only on maker skills that can be gained online. Within this approach, it has been particularly challenging to select a relatively accessible FPGA-based controller needed for real-time data processing in microfluidic droplet sorting. FPGAs are more difficult to program and develop with than most single board computers or microcontrollers popular in the maker scene (Oellermann et al. 2022). We are now using the RedPitaya board that allows python control with minimal Verilog programming and without relying on parts of the complex software pipelines that are usually needed github.com/MakerTobey/Open_FPGA_control_for_FADS. This board still relies on proprietary and rather complicated software (Vivado) for compiling the FPGA program itself before use. Promising alternatives with better accessibility across the whole FPGA software stack are currently emerging in the context of open source efforts headed by Yosys (Shah et al. 2019) and the founders of www.f4pga.org.

The artificial flower

The honey bee (Apis mellifera) is a widely-studied model in neuroscience and behavioral biology as this animal shows many interesting behaviors: the bee communicates distant food locations via waggle dance, finds novel shortcuts between food sources and has impressive learning capabilities. Most commonly the bees' learning abilities are investigated. Therefore, sucrose solution is presented and attached to a salient stimulus to attract the bee. In the lab one can do similar things with bees restrained in a tube to access their brain while they learn. The reward in the laboratory setup is biased and time consuming as the sucrose is presented on a toothpick in the hand of a researcher. A unifying solution would be an automatic system that would register when a bee comes close to the device and feeds them. It would be desirable to identify the bees and record the consumed liquid amount. This would be beneficial for many research questions and could be adopted in different ways. It became clear that this goal was overambitious. To this date there is no publication of any of the four working prototypes (Fig. 4). The cost of the project was very low, the time spent however was immense. Hundreds of hours, developing, testing and debugging. Since learning the involved skills was beneficial for the future, it was worthwhile. Reproduction of any version of the device is very inexpensive, at around 50 EUR per device. A related blog post (Paffhausen 2017b) shows the list of components and how to connect them for the first version. The sources are available in related repositories of the author's GitHub account: github.com/Neuro3en.

Adaptability is the main driver to keep developing this project. The universities however were not helpful in the gathering of hardware components. One has to purchase outside of the official procurement system with private funds. The main problem is that “no-name modules” are not sourceable. Those modules are small PCBs (printed circuit boards) that take care of all the specific components surrounding a specific chip and the result is a cheap module that can be used easily. The supposed solution is to buy the separate components and combine them on custom PCBs to end up with such a module. Recently there is an increasing number of companies (e.g., Prometheus and Adafruit) that are eligible for supplying modules to research institutes and Universities. Arriving at an intermediate state for publication is more difficult than anticipated (Paffhausen 2017a). The first running feeder is 5 years old. The best working version consists of flying cables, very hard to describe or document (Fig. 4a). By now three additional versions are all not perfect in some way. One has a clean PCB but the motor doesn’t work reliably. Another one is precise but consumes too much electricity to be used in the field (Fig. 4b). This class of device contains fine grained analog measurements, motors that draw a lot of current and precise movements of a syrupy liquid; those aspects don't go well together.

Discussion

Discussions among the authors revealed common themes of thoughts and shared experiences in various aspects of our projects. Those aspects deemed most important and most commonly shared are highlighted and discussed below, after providing additional context on the role of OSH in Open Science and the fellowship.

OSH integrates tightly with other areas of Open Science

Open source hardware integrates tightly with most other open science fields. For a researcher or individual to develop open hardware, one must learn about the language and principles used by the many open educational resources available. Desired research devices can usually be deconstructed into common modular elements which can be found in already existing public projects, which may include open source code, electronic circuit schematics and mechanical 3D models, among others (Bonvoisin et al. 2020). Some available open resources include corresponding analysis software for working with datasets, allowing detailed comparison of self-generated data with previously published reference data for quality control. The remixed hardware design can be peer reviewed and published open access, making it accessible to a broader audience, possibly enabling citizen science. Common procedures in open hardware already intuitively adopted micro publishing where every step along the way is citable and by itself documented.

The Free Knowledge fellowship context

With open hardware representing a rather novel topic, the size and flexibility of the "Free Knowledge" fellowship program allowed for explorations. The background of most mentors and training lecture topics were focused on non-hardware related open science topics, typically related to social sciences and the humanities. This diverse connection was beneficial as open hardware is particularly broad and overlaps with nearly every aspect of open science, while our devices needed to be developed and published in an accessible way. All projects contain code, supplementary materials, and were often used in educational contexts. We are grateful for receiving support for our hardware-related projects and for being given a chance to become ambassadors of open hardware. The networking facilitated by the fellowship helped us to connect better to the open science community and we benefited from discussions with experts in the fields of open licensing, documentation and other specialized areas. In the fellowship community, the fellows were also exposed to peers with similar goals which had a motivating effect. The "can-do" attitude of the community sparked activities ranging from the exchange of ideas to the organization of workshops all across the world. By exposing the fellows to open source activities, the low barrier of involvement became apparent. The fellowship highlighted the need for engagement in open source in every way and therefore motivated all fellows to contribute.

Joined summary of all project experiences

Here we investigate common ground and relevant differences in the development of open source hardware. An event marking interface for neuroscience, a DIY Particle Detector for radioactivity, open microfluidics for life sciences and an artificial flower for honey bees. These projects span across several disciplines of the sciences but the encountered problems and advantages related to open hardware were reoccurring. The Wikimedia fellowship benefited the authors in surprisingly similar ways. In short, the financial aid independent of institutional administration was very important to easily acquire components. Equally important was the support of mentors to motivate us and help us with covering knowledge gaps in documentation practices, legal questions, open publishing, practical licensing and similar aspects.

Adaptability

In all cases described here, adaptability plays a crucial role. On the one hand extreme, there is a device that could be used to interface many different kinds of instruments via USB (USB-to-TTL). The particle detector on the other hand cannot be modified very easily due to technical complexity. However, more importantly, when it comes to the handling of the detector output, common open hardware like modern Arduino boards can make use of the data stream and apply the documented calibration function. Such open access to data acquisition compatibility brings significantly more trust and reliability into research than common proprietary solutions. Such access is often necessary to develop custom setups (Wenzel in press). Scientific questions are our driving force in research and we cannot depend solely on the availability of proprietary hardware instead. In the case of microfluidic instruments, commercial equipment is usually not open to modify and reprogram. The related fellowship project therefore explored open alternatives. In the case of the artificial flower the adoptions are manifold, from pumps to moving containers that become accessible for the honey bees. Thanks to a central Arduino board as controlling unit, it is relatively easy to change the timing and supplied amount as well as adoptions of the general shape based on simple changes to the available 3D-printing models.

Costs and funding

The costs for most hardware projects are in the hundreds of euro and below. However, some components are difficult to source, either because they are unusual in the specific discipline, or they are solely sourceable from companies and resellers not complying with the formalities required by many research institutes. The funding supplied by the fellowship was directly deposited to the bank account of the fellows. It was therefore particularly easy to order any desired component outside of the registered suppliers at their respective research institutions. The most important component class is the electronic module. It consists of a printed circuit board (PCB) that connects one or more central integrated circuits (IC) with their required passive components like resistors and capacitors. Those modules can be interfaced with much easier than ICs alone. Unfortunately, those electronic modules are supplied in large by overseas manufacturers in Asia that often do not comply with formalities required to be eligible as an institutional supplier. The same is true for ordering custom designed circuit boards. Manufacturers based in China produce PCBs at several times reduced costs compared to European or North American manufacturers. The funding also allowed us to freely attend workshops and conferences aimed at open source (e.g. Chaos Computer Club Congress, Mozilla Festival Mozfest, Re:publica, GOSH 2018) that would often not be covered by the lab of the fellow. The fellowship helped to justify more working hours being dedicated to the projects. The funding approach of smaller budgets being awarded to many applicants is very fitting for OSH as we often don't need much money. By supporting many projects, an individual is more likely to be successful with an application. Every person involved becomes an ambassador for open source, accelerating the sharing knowledge versus hiding it. Once someone becomes a Wikimedia fellow, open source will be an even stronger vital part of their research identity.

It was also possible to organize outreach with the supplied funding. The presented projects were used in outreach towards other researchers as well as the general public to engage with science and hands-on empirical methods. The relatively low price of our devices allows users to build several units and limits financial losses in case one would break.

Joyful skill building

The process of acquiring a new skill such as learning about electronics, soldering, 3D-printing and programming microcontrollers was perceived as great fun for all fellows. When issues are encountered during the development, the debugging process can be quite difficult as a problem may be related to the hardware, the software or both at the same time. However, solving such a problem is extremely rewarding. Some scientists, due to seniority or temporal limitations, work long hours at a desk away from practical experiments. Under such circumstances, hardware projects can be a productive side activity that diversifies the daily routine. While in the basic sciences, the gap between the scientific problem and the solution may be counted in years, debugging must be often solved within hours or days in order to advance the next measurement. The resulting skills in developing hardware are attractive specifically for PhD students and postdocs. Later career steps, especially outside of academia, benefit greatly from the deep understanding of acquired data and practical instrumentation know-how.

Conclusions

Based on the presented four Wikimedia Program "Free Knowledge" / Open Science Fellows projects, we believe to have provided substantial evidence in support of our main claims: When compared with commercial alternatives, our projects offer reduced costs and improved availability, better adaptability, and a general educational value. We suggest the establishment of further similar funding schemes as they fit very well to the needs of scientists that want to contribute hardware tools and instrumentation to their research field in a sustainable and open way.

Learning how to make and use OSH may be beneficial early in the career as young students and researchers are more likely to take time learning a new skill. Thanks to low access barriers and generally high visibility of developers in open projects, active researchers can profit from social media effects such as high number of recommendations and followers on public dissemination sites like GitHub. The acquired skills will be useful for the whole upcoming career even if they are just providing the required language for effectively communicating with technical colleagues later on. Besides the financial aspect, the fellowship helped us with networking, diversification of our research topics, project management (time and budget planning, risk assessment) and it will certainly contribute to a stronger CV, publication record, and to positioning oneself in areas related to hardware.

Last but not least, we shall not forget how basic natural and applied sciences have been typically advancing in the course of history: By the invention of new methods, application of novel algorithms and by making of original experimental hardware setups. The latter are generally not yet available on the commercial science instrumentation market as they are an outcome of the scientific discovery process itself, preceding current market offers. Considering limited public resources and available budgets for experimental sciences, the only viable path of progress is the development and sharing of research hardware designs as openly as possible.

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Conflicts of interest

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Endnotes

*1 Links to publication sites of our projects are given within the corresponding paragraphs and the references.

*2 A description and recording of the session are online: https://web.archive.org/web/20220920160927/https://www.gessnerallee.ch/de/event/379/Other_Planes_of_There_Listening_Session_; https://soundcloud.com/vanessa-lorenzo-662135359/my-eyes-are-green-other-planes-of-there-lorenzo-keller-19112020 .

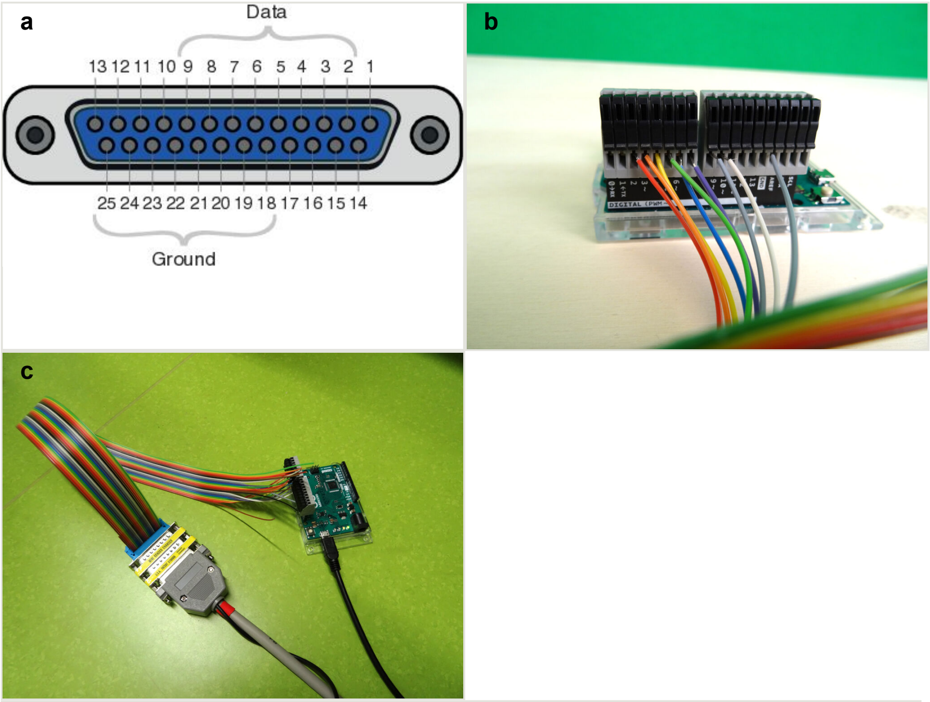

Figure 1.

Parallel port and microcontroller unit (MCU) interface. Figure originally published in (Appelhoff 2022) under a CC BY 4.0 license.

a: Schematic of the parallel port.
b: An Arduino MCU with wires interfaced via a spring-loaded terminal.
c: The complete interface from USB (black cable) via MCU to parallel port (gray cable).

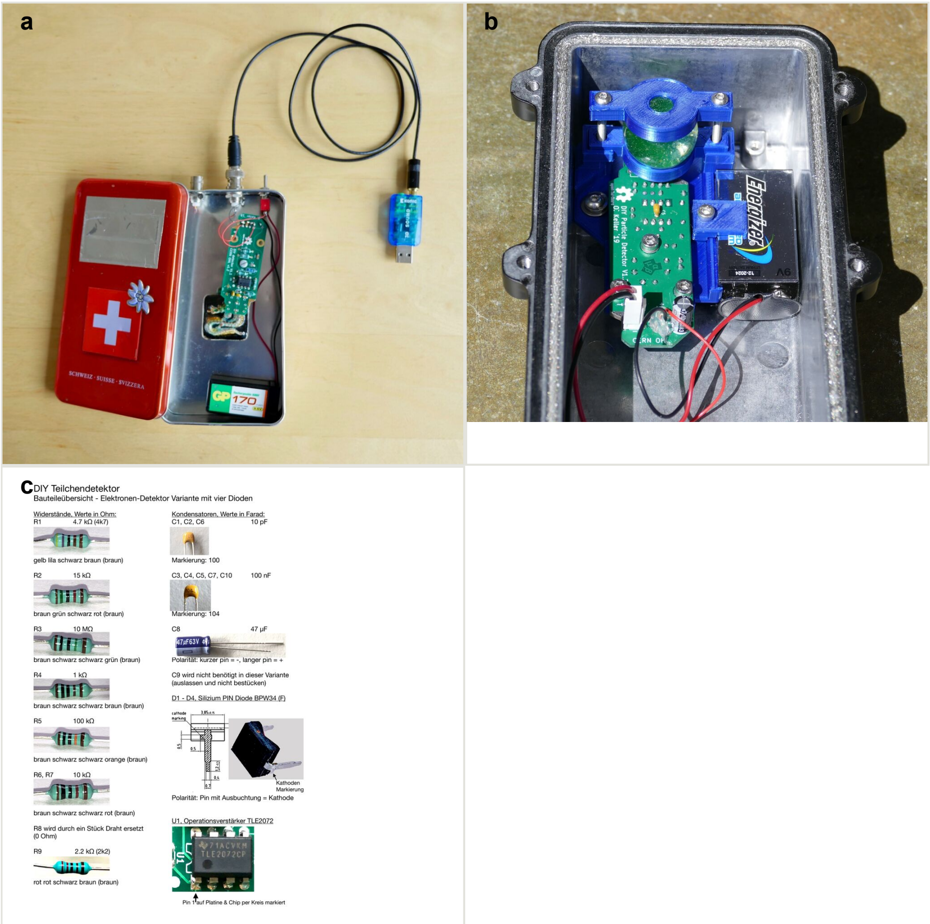

Figure 2.

DIY Particle Detector.

a: Alpha-spectrometer version in a chocolate tin box, connected to a low-cost USB sound card.
b: Adaption as random number generator by GitHub user @rdagger in 2021.
c: Handout sheet in German, listing all electron detector parts for manual assembly.

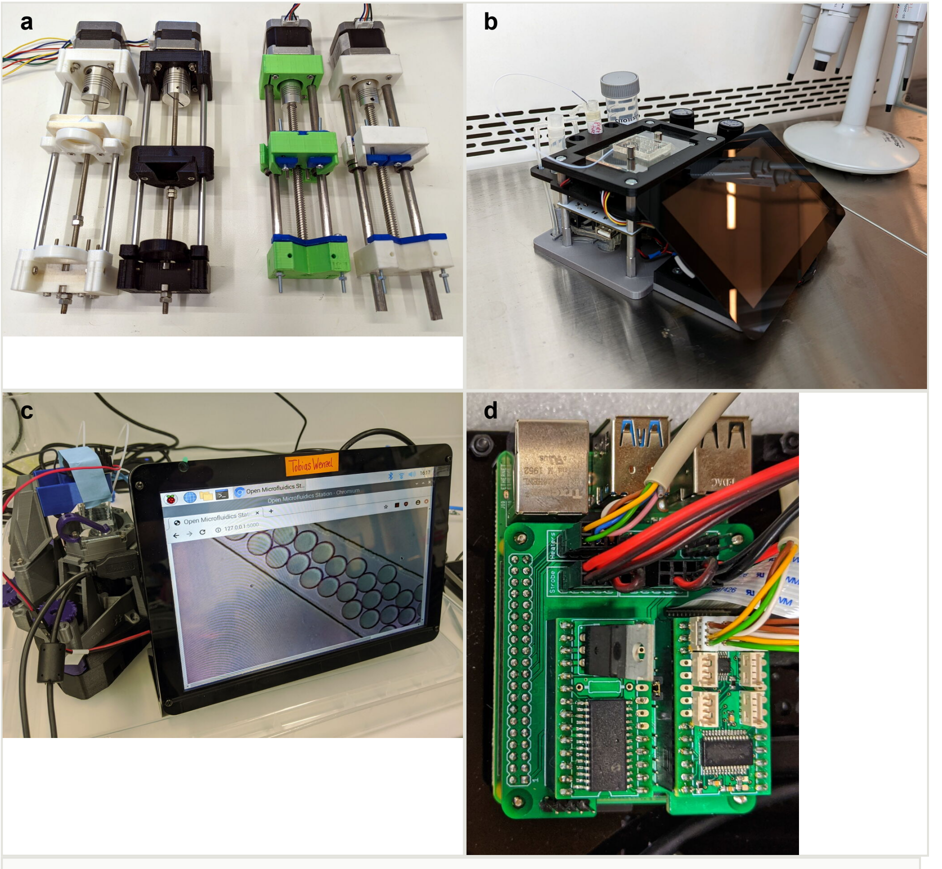

Figure 3.

Microfluidics related open source prototypes.

a: Assembled pairs of two types of third-party 3D-printed syringe pump designs.
b: A built of the Minidrop workstation.
c: 3D printed OpenFlexure microscope with custom built strobe LED illumination and pressure control generating first proof-of-principle microfluidic droplets.
d: Custom open hardware Raspberry Pi hat with two modular controller boards: one for strobe light control and one for pressure and flow control of samples.

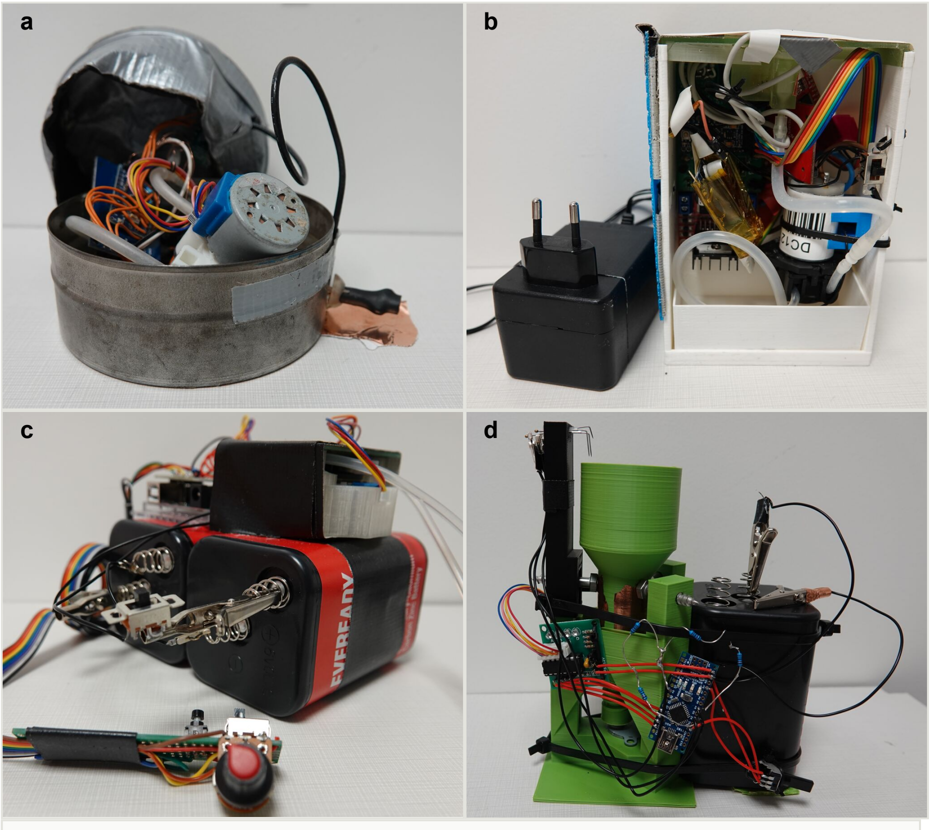

Figure 4.

Four versions of artificial flowers to automatize honey bee feeding.

a: The first version was built during the fellowship in 2016. It works as intended but is flimsy and difficult to reproduce as it directly connects all parts by wires without a central PCB.
b: This version (2019) is easier to reproduce and is based on a PCB. However, the motor is too weak for viscose sucrose solution.
c: A custom peristaltic pump mechanism was used but it is not reliable (2021).
d: The most efficient version facilitated a cup attached on a screwing mechanism situated below a mesh on which a bee could stand and drink through once the cup is moved upwards sufficiently (2022).

Table 1.

Project overview.

Fellowship Project	**Event marking interface for neuroscience**	**DIY Particle Detector for radioactivity**	**Open microfluidics for life sciences**	**Artificial flower for bee feeding**
Published[1]*	homepage, GitHub, Journal	Kitspace.org, GitHub, Journal	GitHub, conference presentation	GitHub, homepage, conference poster
Availability of parts	OSH modules	common analog electronics parts, custom PCB	3D-printing, CNC-milling, custom PCBs and parts	modules, 3D-printing, common parts, PCB
Adaptability	easy (uses Arduino and comparable MCUs)	possible but difficult due to sensitive electronics	yes, key criterion for doing novel research	yes, extremely important
Community	GitHub issues, E-mail	GitHub discussions, ~150 user builds	GitHub, GOSH, Heidelberg Biotop	E-mail, personal
Unit cost	~30 EUR	~25 EUR	~2000 EUR	~50 EUR
Commercial alternatives	~7 devices, 10x more expensive; most less flexible and not multi-platform compatible	10-100x more expensive; abstract black boxes hiding operating principles	10x+ more; expensive where commercial alternatives exist	10x price
Educational value	learning Arduino basics, parallel port signals, soldering	integrated STEAM learning, nuclear physics	mostly self-learning in course of project, shared online	teaching behavioral biology, self-learning
Licensing	CC BY 4.0	BSD, CERN OHL	CERN OHL	MIT
Impact	several positive interactions within the research group, on Twitter, and GitHub	outreach: social media & blog posts; users: students & teachers, maker spaces; GitHub	workshop, conferences, basis for further technology development	conferences, colleagues
Related fields	cognitive neuroscience	nuclear physics, citizen science, education	life sciences	behavioral neuroscience
Remarks	the solution was needed to continue research in the lab	education and citizen science as main focus from the beginning	was an exploratory project for a new field	needs to be published at intermittent version