Making
Open Science
Hardware
ubiquitous
by 2025

GLOBAL OPEN SCIENCE HARDWARE ROADMAP

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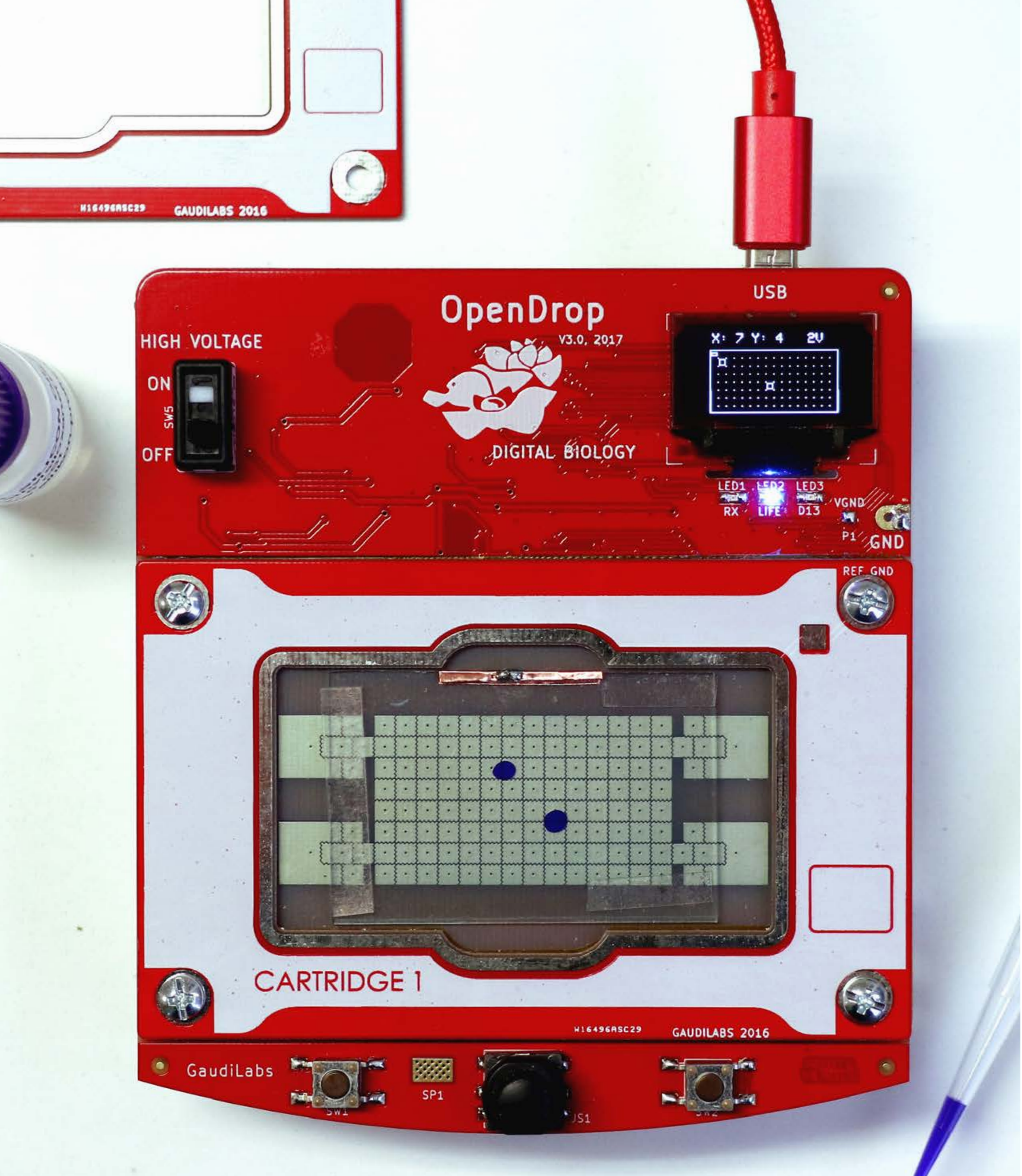


OpenDrop - Open Source Digital Microfluidics Platform by Urs Gaudenz, GaudiLabs 2017

EXECUTIVE SUMMARY

The ability to use, study, replicate, and improve scientific instrumentation is a central part of experimental science, and plays a crucial role in public life, research, and action. However, these activities are currently restricted by proprietary instrumentation, which is difficult and expensive to obtain and maintain, since they cannot be fully inspected, evaluated, or customized. This situation is fundamentally detrimental to the production of knowledge and its potential for creating equitable and sustainable solutions. The Open Science Hardware (OScH) community therefore seeks to bring together developers and users of scientific tools and research infrastructures to support the pursuit and growth of knowledge through global access to hardware for science.

This document describes what is required for Open Science Hardware to become ubiquitous by 2025, laying out challenges and opportunities and recommending concrete actions. These actions include: 1) creating institutional and funding support structures; 2) preparing guidelines for hardware designers, funders, users and newcomers on key aspects of OScH development, such as quality control and standards compliance, licensing, documentation standards, and social and ethical aspects of scientific work; 3) involving the members of the OScH community in the task of elaborating an assessment framework for OScH projects; 4) using the results of collaborative research to build a common pool of open educational resources; and 5) creating mentorship programs and support networks to increase diversity in the OScH community.

This document was contributed to, written or edited by over 100 people from different backgrounds and countries, working on or with OScH. It describes how the OScH community can: a) **LEARN** about itself, the contexts in which it currently operates, and the ways in which OScH impacts society; b) **SUPPORT** individuals and forge partnerships to create the conditions under which OScH can flourish; and c) **GROW** with respect to local differences, increasing the diversity, scale and impact of the OScH community.

WHO WE ARE

THE **GLOBAL OPEN SCIENCE HARDWARE COMMUNITY (GOSH)** IS A DIVERSE GROUP OF PEOPLE UNITED BY THE GOAL OF MAKING OPEN SCIENCE[1] HARDWARE UBIQUITOUS BY 2025.

GOSH 2017 share day at Pontificia Universidad Católica de Chile Centro de Inovación

We are part of a wider Open Hardware community and we seek to reduce barriers between creators, designers, and users, furthering the creation and use of open scientific tools to support the public pursuit of knowledge.

GOSH includes, but is not limited to, scientists, social scientists, lawyers and policy makers, engineers, artists, entrepreneurs, hackers, community organizers, professors, students, educators, entrepreneurs and freelancers. Diversity is crucial to the success of OScH, as differences are generative — the more points of view we see problems from, the more we can collectively identify ways forward and work toward solutions. OScH's greatest potential impact is on people and communities with a need for science hardware but limited access, such as those living in polluted areas or researchers in low-resource regions who are struggling to obtain the equipment they need to track disease, improve crops, or teach students.

Our values are laid out in the GOSH Manifesto, available at: http://openhardware.science/gosh-manifesto

GOSH 2017 breakout session on workshopology | OScH tool enabling teaching

INTRODUCTION

Open Science Hardware (OScH) refers to any piece of hardware used for scientific investigations that can be obtained, assembled, used, studied, modified, shared, and sold by anyone. It includes standard lab equipment as well as auxiliary materials, such as sensors, biological reagents, analog and digital electronic components. Given that proprietary "black box" instrumentation cannot be fully inspected or customized, and can be unreasonably difficult and expensive to obtain and maintain, we believe that scientific hardware design should be open to allow for the exercise of these basic freedoms.

The Global Open Science Hardware community (GOSH) aims at making OScH ubiquitous by 2025. The ability to access, use, replicate, study, and improve scientific instrumentation, which is a central part of experimental science and the public pursuit of knowledge, will contribute to making the concept and practices of Open Science synonymous with science in the near future. Besides having common goals, the community is united by shared values, which were initially laid out in the GOSH Manifesto[2] but are constantly revisited as the community grows.

This document is meant to be a compass for the OScH community. It is a collaborative attempt to describe what is required to realize the vision of OScH being ubiquitous by 2025, laying out the challenges and opportunities to recommend concrete actions. This roadmap was collectively prepared by the community to include the viewpoints of over 100 people from more than 30 countries, including educators, hardware engineers, community science activists, students, artists, software developers, researchers, and many others.

OPEN SCIENCE HARDWARE

The definition of Open Science Hardware is in part inspired by the Open Hardware[3] and Free Cultural Works[4] communities, but the terms "free" and "open" can sometimes be misinterpreted.

The English word "free" in the context of technology is often misunderstood to mean "free of charge." We are using it, however, to signify freedom from restrictions to buy, make, use, study, modify, share, and sell. These freedoms do not imply a technology has to be gratis or non-commercial.

We use the term "open" for scientific hardware to contrast with closed proprietary hardware, but keep in mind the definition of OScH and the values it implies when reading this roadmap.

In order to achieve the 2025 goal, the OScH community will need to carry out actions which can be divided into three categories, described in the three main sections of this document: **Learn**, **Support**, and **Grow**.

LEARN

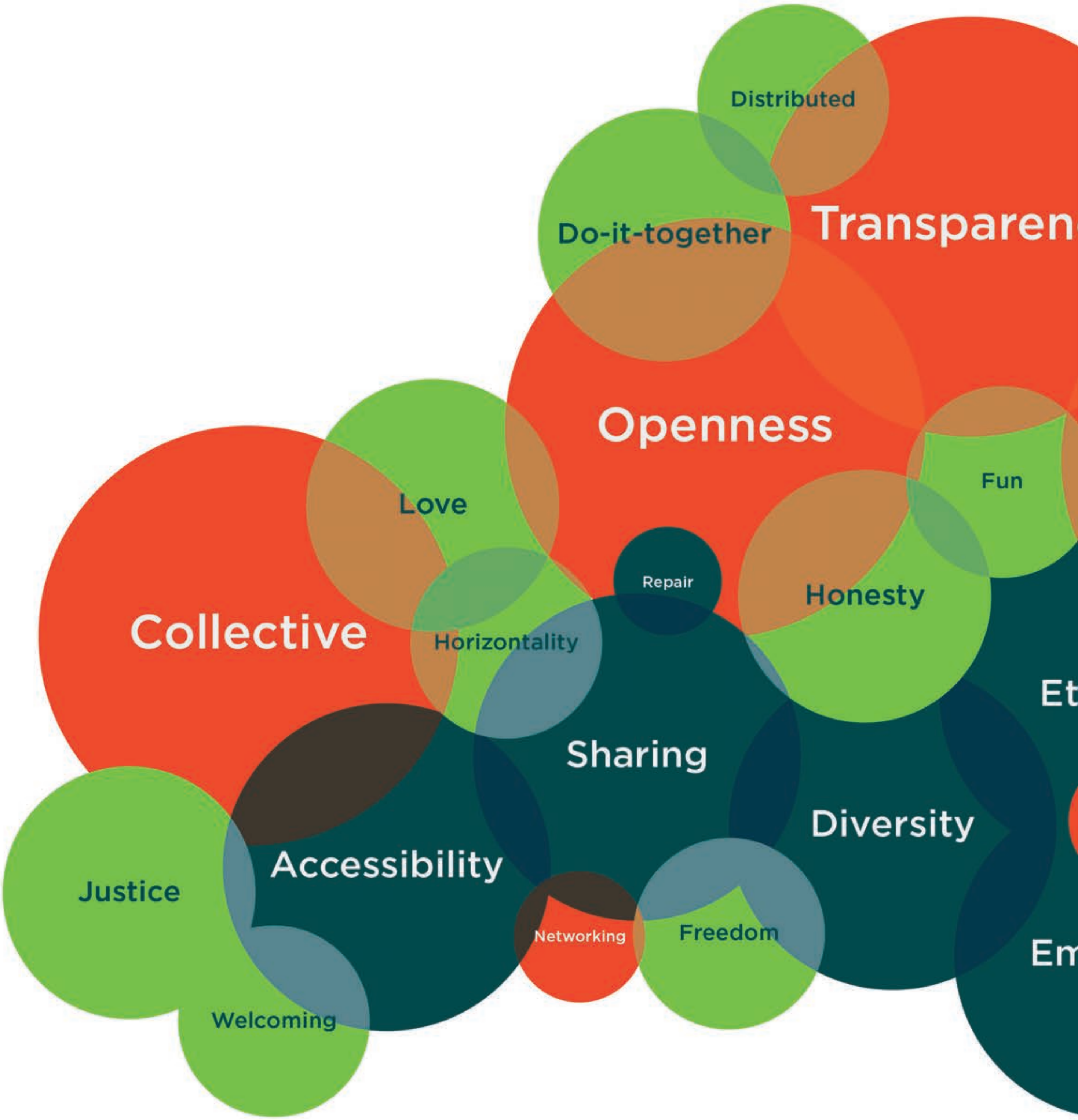
The Learn section describes activities that enable anyone to gain knowledge and find information about OScH and/or the community, so they can better help to support OScH.

SUPPORT

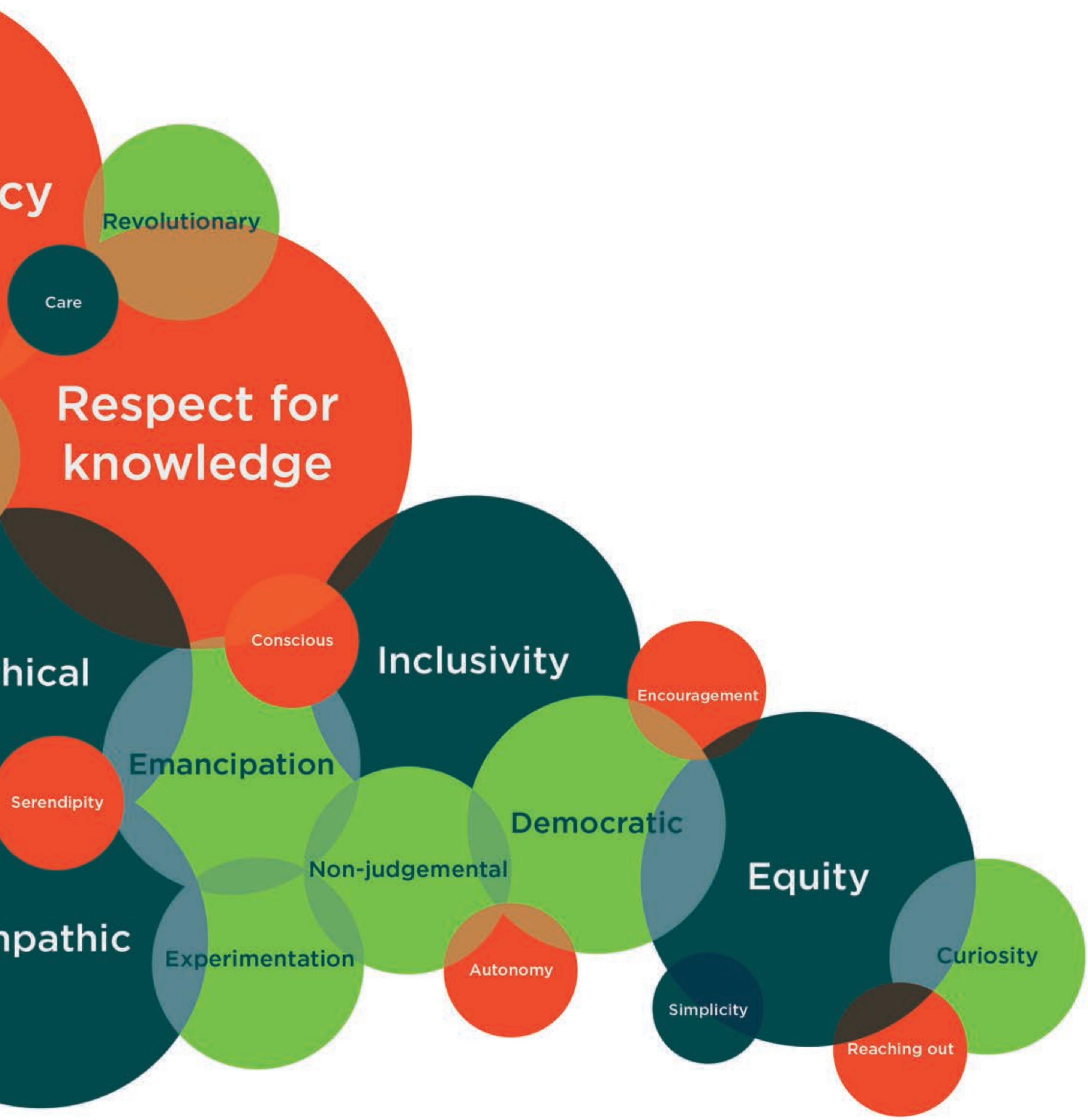
The Support section includes actions aimed at creating the necessary enabling conditions for the present and future of the OScH community, by supporting people, organizations, institutions and projects.

GROW

The Grow section includes outreach and advocacy actions aimed at increasing the scale and diversity of the community in terms of who participates, learns, and contributes back to the initiatives of the community.



The GOSH community values, as expressed by the GOSH 2017 attendees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Experimentation
Autonomy
Curiosity
Simplicity
Reaching out

LEARN

Openness is an invitation to learn—whether learning about the inner workings of scientific instruments or learning how to develop stronger OScH projects both inside and outside established research centers. Only by learning about the technical, legal, and socio-economic challenges facing OScH can practitioners further support and grow the community, creating the conditions for positive social and technical change.

OScH has the potential to create new futures for science by widening where and how science happens, who is involved, and what types of knowledge are produced. The African continent, for example, produces just 2.6% of published research despite being home to 15% of the world's population, and access to funding and equipment is a major barrier to increasing this figure. In another problematic disparity, only 28% of researchers worldwide are women (UNESCO Science Report Towards 2030). The imbalances in where and by whom research is produced is reflected in the types of knowledge generated. Community science projects using OScH have been known to provide quicker responses to disasters in examples including the BP oil spill, and the Fukushima nuclear disaster, and to address other pressing issues such as water and air pollution.

This section describes three priorities for identifying and changing the structures and processes that affect wider production and adoption of OScH: setting a collaborative research agenda, increasing knowledge about Open Hardware licensing, and better understanding how to monitor and evaluate OScH projects.

SETTING A COLLABORATIVE RESEARCH AGENDA

STUDYING OScH

Studying OScH encompasses community-based research, academic research, and any other way of generating knowledge. This document does not use the term "citizen science", but instead the expression "community science" because "citizen" has widely different implications in different parts of the world. Our conception of science encompasses its practices and effects outside scientific institutions in order to take into account and value different ways of knowing.

To focus on "community science" instead of "citizen science" we aim to create conditions that support the involvement, ownership and inclusion of all people in science.

CHALLENGES AND OPPORTUNITIES

Interest in studying OScH is growing but research is still very limited, both within and outside academia. In contrast, extensive research has been carried out on Free and Open Source Software (FOSS) which has impacted the field of social computing (or informatics) more broadly. Examples include the importance of the research on commons-based peer-production[5] and the development of a whole new set of social networking protocols and services[6]. Another influential area has been the study of "open innovation," demonstrating how much sharing of information and resources happens in both typically closed firms and pioneering open innovation settings[7 8]. In the same way, research findings and other forms of knowledge gained about OscH could help to support and grow the OScH community helping to realize its goals.

Examples of research topics of particular relevance include: questions of diversity in the community, effective methods of collaboration and coordination in hardware development, sustainable business models, and the role of open licensing in innovation policies.

The global, diverse nature of the OScH community is unusual, even among similar networks such as the FOSS community. It therefore provides unique opportunities for research on community dynamics at multiple scales and across a range of international contexts. For example, there are opportunities to describe collaborative practices between grassroots communities, public institutions and companies working on OScH, and analyze power dynamics of gender, socioeconomic status, and technical expertise.

RECOMMENDATIONS

1. Organize a network of researchers and other interested community members with regular meetings.

2. Create a common research agenda, prioritizing topics that are relevant to the 2025 goal and those that support and grow the community. This agenda should be reviewed and updated regularly with input from the OScH community.

3. Publish research findings in OScH community forums and venues, such as the GOSH forum[9], the Journal of Open Hardware (JOH), conference proceedings, repositories, and community blogs.

QUALITY MONITORING AND EVALUATION

CHALLENGES AND OPPORTUNITIES

Evaluating and monitoring are key for learning more about OScH initiatives, but there are few existing frameworks to identify ways to support OScH and assess which actions lead to greater accessibility of hardware for science. Demonstrating the effectiveness of OScH projects makes them more accountable to funders, community supporters, and developers. Evaluation can also be conducted to assess how influential OScH is in changing how science is performed in different contexts.

This framework must be flexible and comprehensive enough to be applied in various contexts. Standardized metrics and assessment tools are crucial for comparing interventions, but may be insufficient to account for the local conditions under which OScH projects might be implemented. Metrics therefore cannot be "one-size-fits-all": they should be grounded in specific socio-technical, economic, and political conditions.

Once built the framework will allow for the development of product- or context-specific metrics, promote collaborative metric design and evaluation processes, and support open data monitoring to maximize learning from evaluations.

RECOMMENDATIONS

1. Build a common pool of open data on OScH projects to support the design of metrics based on concrete challenges and solutions across cases.

2. Create contextualized metrics for assessing the impact of OScH projects and promote their adoption by funders.

3. Engage researchers in Science and Technology Studies[10] (STS) who can contribute empirical studies of socio-technical[11] contexts for OScH design and development.

In "What is the Source of Open Source Hardware", Bonvoisin et al[12] (2017) elaborated a framework to evaluate Open Hardware projects and products. This framework is based on eight variables which describe key aspects of hardware projects, covering their openness on issues of documentation accessibility as well as community and commercial dynamics. This framework is very useful, but the OScH community needs to expand it to address questions of design and implementation of OScH projects across highly unequal contexts with respect to industrial and infrastructural access, socioeconomic divides and local demands for economic and environmental justice.

OPEN HARDWARE LICENSING

CHALLENGES AND OPPORTUNITIES

Open hardware licensing is complex, multifaceted, and heterogeneous. There is a lack of clarity with respect to degrees of openness, forms of protection, license compatibility and interactions between different forms of intellectual property. For example, many OScH projects make use of flexible copyright licenses such as Creative Commons; but hardware is mostly beyond the scope of copyright, and these licenses do not address problems with distribution and redistribution of the physical hardware.

Open licensing creates conditions in which the dynamics of competition and collaboration are not fully understood. Open projects are intended to create collaborative communities and provide opportunities for derivative projects that enrich the commons, from design files to educational resources. However, uncertainty about effective ways to ensure economic benefit can create challenges to achieving that goal. For example, accessing funding without intellectual property rights, or entering into agreements with different types of partners who may be best able to benefit from a project, can be complex and problematic. There is a risk that projects produced with public, collective effort could later become proprietary or be appropriated, as can be exemplified by the case of Makerbot[13] who closed and patented designs for their 3D printers despite many community contributions. Further research is needed to analyze the interactions and forms of exchange within and between communities and organizations, in order to determine effective licensing models for specific contexts.

RECOMMENDATIONS

1. Convene and collaborate with community members, researchers, businesses, and lawyers to improve Open Hardware licensing and contracting strategies for OScH.

2. Create templates for contracts (following the examples of the “ContractPatch[14]” project from the Software Freedom Conservancy), to help people make informed decisions about contracts and open licenses for their projects and products.

OPEN SOURCE HARDWARE

MUST

Allow anyone to study, modify, distribute, make, and sell the hardware.

Provide publicly accessible design files and documentation (the source).

Clearly specify what portion of the design, if not all, is being released under the license.

Not imply that derivatives are manufactured, sold, warrantied, or otherwise sanctioned by the original designer.

Not use the trademarks of other companies without permission.

Not be released as non-commercial or no derivatives.

MAY

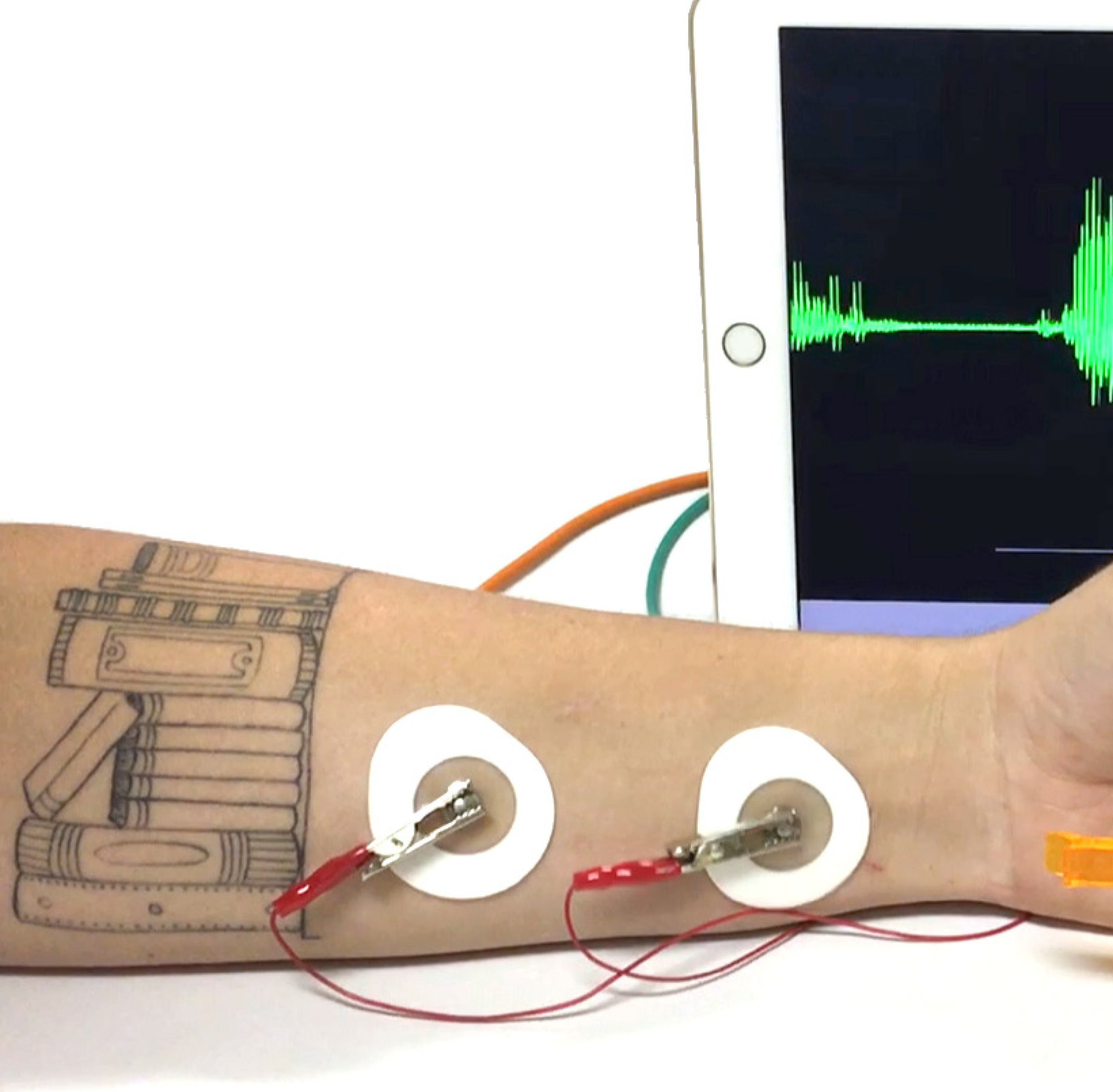
Require attribution be given.

Use the open source hardware logo to signify their hardware follows the open source hardware definition.

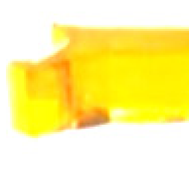
Require derived works to carry a different name or version number from the original design.

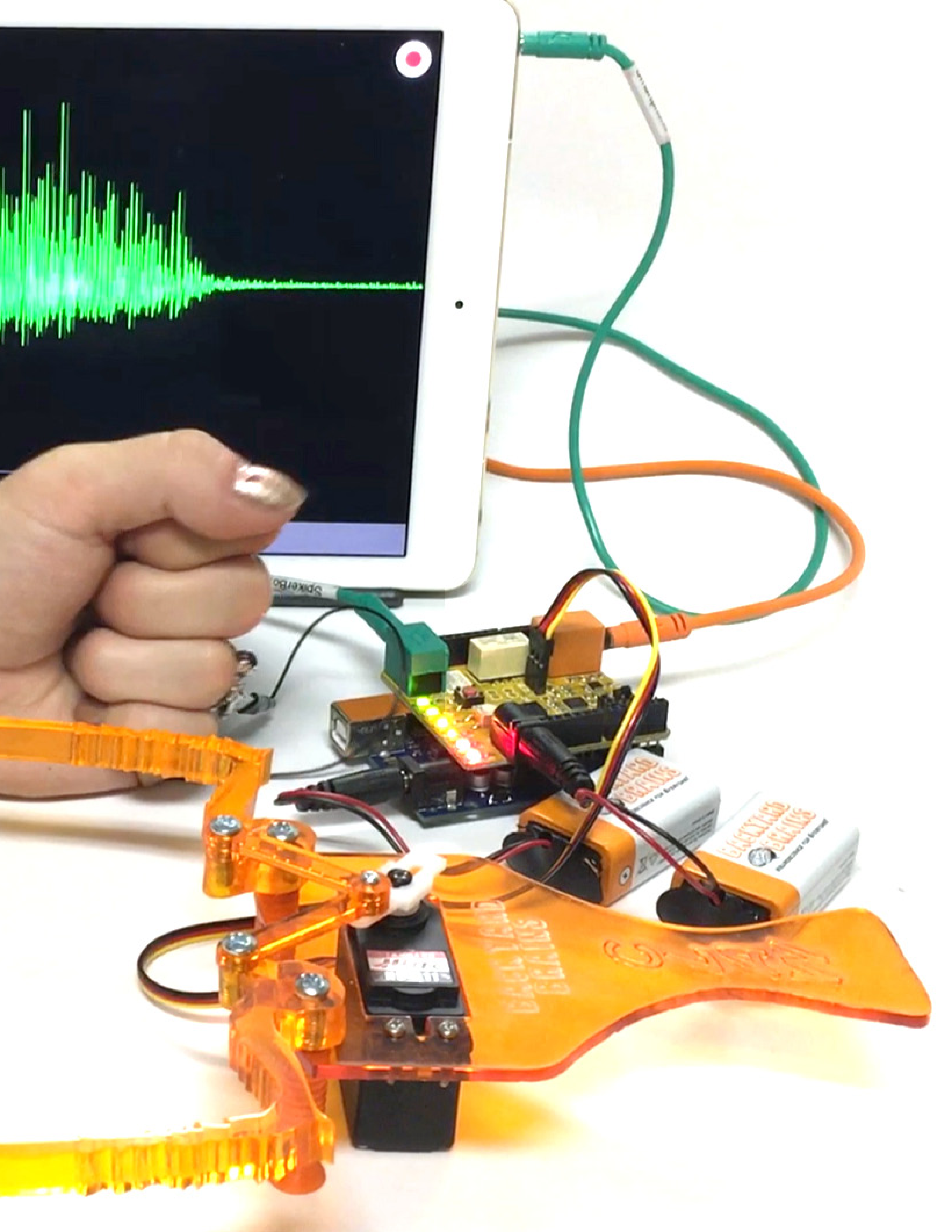
Be copied directly or have derivitives created from it.

Require a reciprocal license.



The Claw: An open-source neuroprosthetic for education that turns electromyography into servo action to close (a) and open (b) a claw device. Backyard Brains, CC-BY-SA, 2016





SUPPORT

Achieving the vision of ubiquitous OScH requires new and creative ways of tapping into existing institutional structures to support the specific needs of the OScH community. OScH projects can have a high entry barrier to participation, so it is important to ensure equitable distribution of resources and tasks, supporting people with different skills and types of expertise.

This section describes the top four priorities for creating structures of sustainability for OScH projects and organizations: institutional support, funding, documentation, and mutual support.

INSTITUTIONAL SUPPORT

Many people design, develop and use OScH while working within established institutions, such as universities, research centers, schools, government departments, museums, libraries and not-for-profit organizations. However, aside from some notable exceptions, there is currently no widespread institutional support for OScH.

CHALLENGES AND OPPORTUNITIES

Governance structures for OScH present different challenges and opportunities compared to traditional configurations. OScH usually involves distributed networks of contributors and a combination of paid and volunteer contributors, which introduces challenges for management and accountability. The agile, iterative and open development methodologies of OScH provide numerous opportunities for co-creation and co-development with communities of end users — whether academic researchers in high energy physics, underserved children in rural areas or communities at risk from environmental pollution. However, balancing the contributions and voices of diverse groups requires sensitive and responsive governance structures at all levels — from memorandums of understanding (MOUs) between coordinating organizations to models of direct participation by community members.

The remote and distributed nature of some OScH initiatives can also cause operational complications with multiple factors such as taxes and liability, and solutions that work in one geography are often not portable to others. Many OScH groups do not want the burden and overhead of an incorporated organization or are discouraged by such complexities.

OScH could have substantial benefits for knowledge transfer, but its uptake is hampered by a lack of clear institutional policies on open approaches to dissemination and commercialization. OScH is not a widely recognized concept at any level of institutional hierarchy, a challenge also faced by other forms of Free and Open Source software and hardware. Technology transfer departments, for example, are often unfamiliar with collaborative models and may be unable to provide useful advice. More concerningly, policies on intellectual property (IP) ownership may impede OScH by applying strong pressure to commercialize hardware using proprietary business models.

OScH has potential both to broaden participation in science and to advance knowledge production, but very few institutional programs contribute to a culture of hardware sharing. This issue has been well-studied in open research data and open access to publications. One of the major challenges is that there are few incentives for working on OScH within institutions: promotions and funding do not reward openness, but do reward a narrow set of metrics and achievement, such as publication in high impact journals. Academic journals for OScH, tools for sharing high-quality hardware documentation and community networks are now being established which may offer institutional researchers greater opportunities for participation in OScH projects, but they need further support.

RECOMMENDATIONS

Institutional policies should by default support and proactively incentivize OScH development and use by:

1. Providing appropriate support for OScH translation and commercialization through technology transfer offices. Specifically, this should include adoption of Open Hardware licenses and agreements such as TAPR OHL[15], CERN OHL[16], Solderpad license[17], and the Open Material Transfer Agreement (OpenMTA)[18].

2. Ensuring that OScH is part of Open Science conversations. These already address the issue of academic credit for sharing research outputs at multiple levels, from academic promotion boards to national and international funder policies.

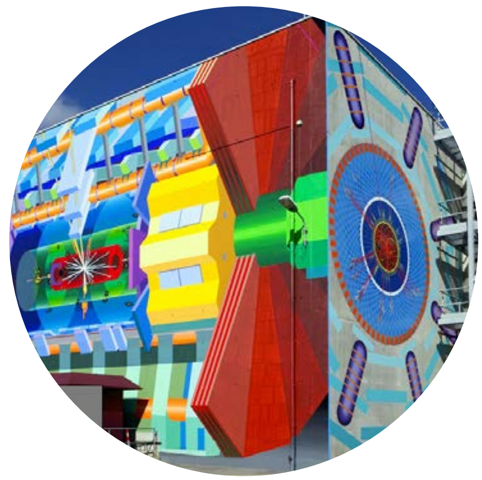
3. Offering direct support for OScH development through shared facilities such as hackerspaces, maker spaces and Fab Labs combined with professional engineering and technical support.

EXAMPLES

INSTITUTIONAL SUPPORT

TECNOx (Latin America)
www.tecnox.org

TECNOx is a Latin American community sponsored by UNESCO that promotes the development and adoption of Open Source technologies for education, research and capacity building. TECNOx organizes an annual competition that challenges multidisciplinary teams from across the continent to apply open source software, hardware and/or biological materials and reagents to address local problems. Projects are encouraged to involve local communities and to adopt open licenses for their outputs.

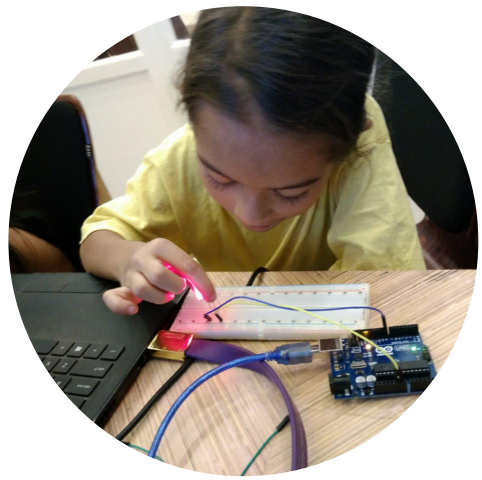


CERN (Switzerland) - OHWR and license
http://www.ohwr.org/

In 2010, CERN published a directive for the support of Open Source for R&D and technology transfer activities. One year later, the Open Hardware initiative was created and became one of the most influential programs for OScH in existence. With proper institutional backing, CERN engineers and knowledge transfer officers successfully published printed circuit boards (PCBs) for the control and timing network of the accelerator complex under open licenses. In addition to releasing design files, CERN has created its own Open Hardware repository and open license (CERN OHL).

Centro de Tecnologia Acadêmica (CTA) at UFRGS (Brazil)
http://cta.if.ufrgs.br

The Center for Academic Technology from the Physics Institute at the Federal University of Rio Grande do Sul in Brazil has as its goal to develop and apply Free and Open Source technologies. In addition to the development of their own Open Science Hardware technologies, they teach and disseminate student projects under Free and Open Source licenses.



The Tech Academy (Bangladesh)
http://thetechacademy.net/

Tech Academy is an educational institute that preferentially uses Open Source Hardware to teach children about science, technology and engineering, using Arduino[19] and Backyard Brains electrophysiology equipment. It runs free schools in remote and underdeveloped areas in Bangladesh, subsidized by charging for teaching middle income and high income families in urban areas.

Xiamyra Daal talking to students during the GOSH 2017 share session


Teacher Bootcamp
July 2017

ADVOCACY TOOLKIT FOR FUNDERS

1. Appropriate metrics and evaluation methods to compare the impact of open and proprietary innovations. For example the toolkit for impact measurement in OScH projects[20] from GOSH 2016.

2. Examples of successful licensing strategies, business models and organizational models to demonstrate that the necessary tools and infrastructure exist to achieve social, economic or academic impact through open projects.

3. Case studies that illustrate the benefits of openness in alignment with the funders' mission. For example, the White Rabbit project at CERN is an example of OScH which has demonstrably saved money and time, while creating economic value for companies with no vendor lock-in for research institutions. These benefits would be likely to appeal to public research funding bodies; other examples of OScH improving community formation, capacity building and learning may appeal to funders seeking social change.

4. Community-contributed lists of OScH-related resources and projects for further reading.

SUPPORT FROM FUNDERS

OScH requires funding along its entire value chain: from research through development, innovation, and distribution. However, resourcing is a perennial issue. Funders have significant power to advance or hinder OScH projects and the role of OScH in creating positive social and environmental change. Currently, OScH remains a rather unknown phenomenon and lacks the popular hobbyist appeal of projects such as Arduino. However, there are funding options beyond commercial markets, and many organizations and individuals are already motivated to support OScH development.

CHALLENGES AND OPPORTUNITIES

Lack of funder awareness about OScH prevents projects from securing seed funding. There are limited funding options for OScH projects: for example, venture capital is hard to procure for projects using open licenses, and academic grants seldom include support for custom equipment development. Borrowing is not an option for most groups undertaking OScH development, who are typically situated in academia or community organizations. Raising awareness among funders about successful OScH projects and products could provide a partial solution to this challenge.

RECOMMENDATIONS

1. Draft a comprehensive guide for public and philanthropic funders on supporting OScH development and related activities, with the goal that by 2025 funders should preferentially fund open projects and require a well-justified case for exceptions. This guide should be periodically updated with information indicating progress toward specific benchmarks, focusing on equitable projects with concrete impacts on research quality, cost, and societal impact.

2. Identify investment partners and funders who already recognize the value of Open Source technologies, such as UNICEF, the Alfred P. Sloan Foundation, Shuttleworth Foundation, and Helmsley Charitable Trust, and seek advice on how to influence their peer funding agencies to support OScH projects. The case for support may be stronger with funders focused on global challenges and development goals such as the UN's Sustainable Development Goals (SDGs) due to the potential social impact of OScH and the values of equity and justice that drive the GOSH community.

3. Produce a guide to existing and potential funding models. This would involve identifying and creating a network of investment partners, including incubators, accelerators, and recommended production partners.

Agreeing on GOSH values at the 2017 meeting in Santiago de Chile

ENGAGING INVESTMENT PARTNERS AND FUNDERS

1. Identify major funders that are investing in global challenges in the next five years.

2. Co-author editorials with supportive funders, and publish in journalistic and academic outlets that are visible to other funding agencies.

3. Directly target funders and their policy officers when distributing this roadmap and related opinion pieces.

4. Work with funders to evaluate their experiences funding OScH and share them with other funders and the OScH community.

COMMUNITY SUPPORT FOR OScH PROJECTS

For OScH to be widely adopted and achieve its potential impact in science, high-quality, well-documented, and well-supported projects are needed. OScH projects have overlapping needs that could be addressed through shared resources provided by the OScH community. Platforms and tools need to be established that leverage the shared community participation to unlock the power of Free and Open Source development models. These should be inclusive to contributions from many people including non-experts, and effective at reducing barriers to sharing and collaboration in order to realize the benefits of wider participation.

Currently, documentation for existing OScH projects is often insufficient for users and developers to learn, build and create derivative projects. Without sufficient documentation, OScH might be openly licensed but it is neither useful nor truly open to participation. The lack of clear guidelines for build instructions, use of Free and Open Source design tools, or protocols and techniques for quality control and validation of OScH, creates serious barriers to delivering many of OScH's proposed benefits, such as improved reproducibility of experimental work, which is considered a key characteristic of science.

CHALLENGES AND OPPORTUNITIES

Many people are discouraged from using and developing Open Hardware due to poor documentation. Documentation for existing OScH projects is often insufficient for users and developers to learn, build and create derivative projects. Bad practices are a barrier to participation, particularly for those who require quality standards and accuracy of measurements. This situation results in a lack of credibility for OScH when compared to proprietary hardware.

There is little guidance on documentation practices even at a basic level, for example, using simple, accessible and understandable language. It is also difficult to choose between existing platforms for documentation and among the multiple tools required for dealing with complex, modular projects. Important features include version control[21] and support for collaborative approaches like code replication, wikis for participatory documentation, issue trackers, and discussion forums. This toolset is also an opportunity for empirical research and information gathering on effective practices to inform community peer-review and documentation guidelines, expanding those formulated by the Open Source Hardware Association (OSHWA), and at the GOSH meetings in 2016 and 2017.

OScH is generally seen as being lower quality than proprietary alternatives, but there is an opportunity to change this perception, surpassing proprietary offerings. There are many proof-of-concept projects, and the challenge remains to promote and enable high-quality projects that offer reliability and ease of use. There is a need for further training on “Design for Manufacture” (DFM) practices to maximize the potential of OScH to scale from DIY[22] to early adoption to commercially available hardware, where commercial manufacturing is appropriate. The OScH community is striving to incorporate the needs of people who would use and benefit from the hardware, from ideation and creation of projects to the design of the final product. Training is also required for this “human-centered design”[23], which could include producing designs that encourage but do not require tinkering or modification in order to function, that enable testing, calibration and validation to challenge concerns around quality through peer review at various project stages.

Quality control and validation is key for building the credibility of OScH projects. One of the biggest institutional barriers for OScH at present is the lack of assessments of OScH-based scientific instruments in many areas. Alignment with industry standards remains a challenge. It is therefore important to consider open quality management protocols that can take the place of industrial certifications for hardware in various areas, such as environmental sensors and medical devices. More effective practices of quality control would necessarily include best practices of hardware documentation and community support.

User support is a limiting factor for many projects, particularly for volunteer developers. Different participants in the OScH ecosystem have different support needs. The distributed nature of the OScH community, however, creates unique opportunities for technical support in local community spaces and laboratories, fostering stronger collaborative ties and regional networks for hardware sharing and fabrication.

Technical assistance and training are not prioritized due to the difficulty of distributing the project workload. One of the current challenges is to improve and expand access to technical assistance and training. Although OScH tools offer increased flexibility and control, this often comes at the cost of imposing greater demands on users' expertise.

OScH designs can be very complex, and so require distributed forms of collaboration for which existing tools and practices are not optimized. In contrast with proprietary hardware, OScH blurs the distinction between users and developers. Users are encouraged and, at times, expected to become active participants in the development process. This close relationship should translate into hardware products that are a much better fit for end-users, but the challenge is to design processes that facilitate collaboration. Some of these are technical and resource challenges, such as determining common interfaces and tools for all stages of OScH development, and distributing kits to recruit a larger development community. Communication initiatives, for example academic journals and documentation platforms, are also important for data management.

RECOMMENDATIONS

1. Prepare and disseminate OScH documentation "best practices."

2. Build a shared publication framework for OScH documentation.

3. Support the development of Free and Open Source tools for hardware design to allow OScH design files to be shared and edited by anyone.

4. Create guidelines for testing, calibration, and validation of OScH with respect to existing standards, sharing testing rigs with assembly instructions whenever possible.

5. Provide training sessions and workshops to support current OScH projects. Online groups could also be identified or created to seek and provide feedback to OScH developers.

6. Identify and encourage the development of modular software and hardware components, libraries and resources that make it easier for non-experts to build, assess and contribute to OScH projects.

Lawrence Ndeny and Fernando Castro at GOSH 2017 building an Open Flexive microscope designed by Richard Bowman

GROW

Achieving the vision of ubiquitous OScH by 2025 implies changing the status quo and acquiring critical mass to transform a small, niche community of practice into the mainstream mode of design and development for scientific hardware. The OScH community currently represents only a small proportion of people using and developing science hardware. Moreover, OScH remains largely unknown to institutions that could greatly contribute to and benefit from it.

Key priorities to grow this community are: 1) increasing the number and the diversity of OScH community members through active support and mentorship for new members, 2) advocating for OScH within established institutions and ensuring OScH is supported by policy makers, 3) facilitating wider distribution of OScH.

INCREASING THE SIZE AND DIVERSITY OF THE OScH COMMUNITY

Diversity is a key criteria for OScH's success and growth: including broad capabilities and perspectives underpins the potential of OScH to surpass traditional scientific hardware development. Science and technology cultures often exclude groups including women, people of colour, indigenous people, people with disabilities, LGBTQIA[24] community members, non-English speakers, and people outside well-funded research institutions of Europe and North America.

Other communities with similar goals and values, such as Free and Open Source Software, Open Science, and Open Access, suffer from a lack of diversity. The OScH Community has taken steps to address this problem using the GOSH meetings as a venue to form networks that serve underrepresented groups. Those communities who could benefit the most from increased access to science and OScH, like civil society organizations working with people affected by environmental, social and political issues, wil be strong partners when working toward the goals identified in this roadmap.

CHALLENGES AND OPPORTUNITIES

Increasing the number and diversity of the OScH community requires outreach aimed at multiple audiences. The GOSH community is an existing example of a diverse community within OScH, which might help attract people from groups traditionally marginalized in science and technology. But groups exist even within the GOSH community whose participation is particularly difficult, such as non-English speakers, non-established researchers, or people with limited or no access to the internet and electronic equipment.

RECOMMENDATIONS

1. Organize and promote **online forums and face-to-face activities**. Global events, such as GOSH, can encourage international collaborations and enable wide dissemination of OScH. Local and regional events would help overcome language barriers, cost of travel for people who have difficulty securing funds, and cultural differences, thereby enabling development of more context-relevant design and use of hardware. All such activities should be welcoming spaces, particularly for those from underrepresented groups, by respecting diversity and ensuring accessibility through proactive facilitation, implementation of codes of conduct, and translation to non-English languages.

2. **Design and implement mentorship programs** bringing together mentors and mentees with diverse backgrounds. These programs will help disseminate OScH values and principles, and promote skills exchanges that recognize the reciprocal learning that happens between 'professionals' and 'amateurs' on a given topic.

3. Develop **Open Educational Resources**[26], localizing them where necessary. These resources should cover i) the fundamentals of OScH in the context of open science practices; and ii) practical development and use of OScH. Educational activities should be informed by contextualized evaluation methods wherever possible.

4. Support **outreach activities** aimed at broader audiences. For example, promoting the visibility of OScH in mass media and social platforms, along with other Open Hardware outlets and networks such as Arduino, Instructables, Hackaday, and PLOS. These activities should emphasize the diversity of the OScH community, while avoiding the usual stereotypes associated with science, scientists, and scientific equipment.

The second Gathering for Open Science Hardware took place in March 2017 in Santiago, Chile, aiming to bring the spirit of the GOSH Manifesto to life. The expected outcomes from this gathering included establishing working groups and launching the roadmap, but one of the main objectives was scaling up the community, both locally and globally. To achieve this, specific actions included intentionally increasing the diversity of participants to account for the breadth of the open science hardware community. There were:

ADVOCACY FOR OScH

Advocacy work requires justifying openness, explaining the need for incentives, and providing examples of success and failure to demonstrate the importance of OScH. Making OScH widely used and perceived as credible for scientific investigations is key to its success.

CHALLENGES AND OPPORTUNITIES

There are institutional barriers for wider adoption of OScH. Key decision makers typically know little about OScH and its potential benefits. This challenge presents an opportunity for the OScH community to engage in advocacy activities aimed at a wide range of stakeholders to ensure that development, use, procurement and promotion of OScH becomes ubiquitous.

RECOMMENDATIONS

1. **Encourage use of OScH** in publicly-funded institutions. Key strategies include: 1) promoting procurement policies that favor OScH, including use of institutional equipment funds; 2) providing targeted evidence of the benefits of OScH to institutional leaders; 3) recruiting knowledge transfer professionals with greater experience of OScH to provide briefing sessions for colleagues and fellow professionals.

2. **Develop campaigns** that turn the need for OScH into an issue that cannot be ignored by decision makers. Tactics include: 1) producing campaigns in partnership with civil society organizations tackling specific problems through the use of OscH or with student groups whose education is affected by lack of access to science hardware; 2) partnering with allies in influential leadership positions; 3) sharing advocacy materials based on the example of effective campaigns for Free and Open Source Software.

3. **Collaborate on a global open hardware platform to address significant challenges** e.g., infrastructure assessment pre- and post-disasters or environmental monitoring for major pollutants. The process and outcomes should be evaluated to demonstrate impact and benefits, as part of ongoing research into OScH (see **Learn**).

INCREASING OScH DISTRIBUTION

Manufacturing, continuous development, and distribution can be barriers to broader adoption of hardware, and must be adapted to specific contexts. The current low quality of much OScH documentation and support is a major hindrance to increasing adoption.

CHALLENGES AND OPPORTUNITIES

There is no shortage of OScH designs but mainstream access to the hardware itself is limited. Most OScH never makes it beyond the research lab or a small community, and this greatly limits the potential uses and impact of the tools. The recent proliferation of digital fabrication tools, hacker and maker spaces, and open development platforms have considerably reduced these barriers and facilitated small batch production, new possibilities for customization, and opportunities for collaboration using increasingly common hobbyist-grade fabrication tools (e.g., 3D printers, laser cutters, etc.).

Traditional manufacturing processes favor high-volumes and have large up-front costs. Historically, this has posed a significant barrier to new hardware development, especially for non-commercial projects and those not designed to serve mass markets. The Open Hardware community has created alternatives by organizing collective purchases, which lowers the cost of access to manufacturing facilities for running prototypes and small batches (e.g. the OSHPark PCB service).

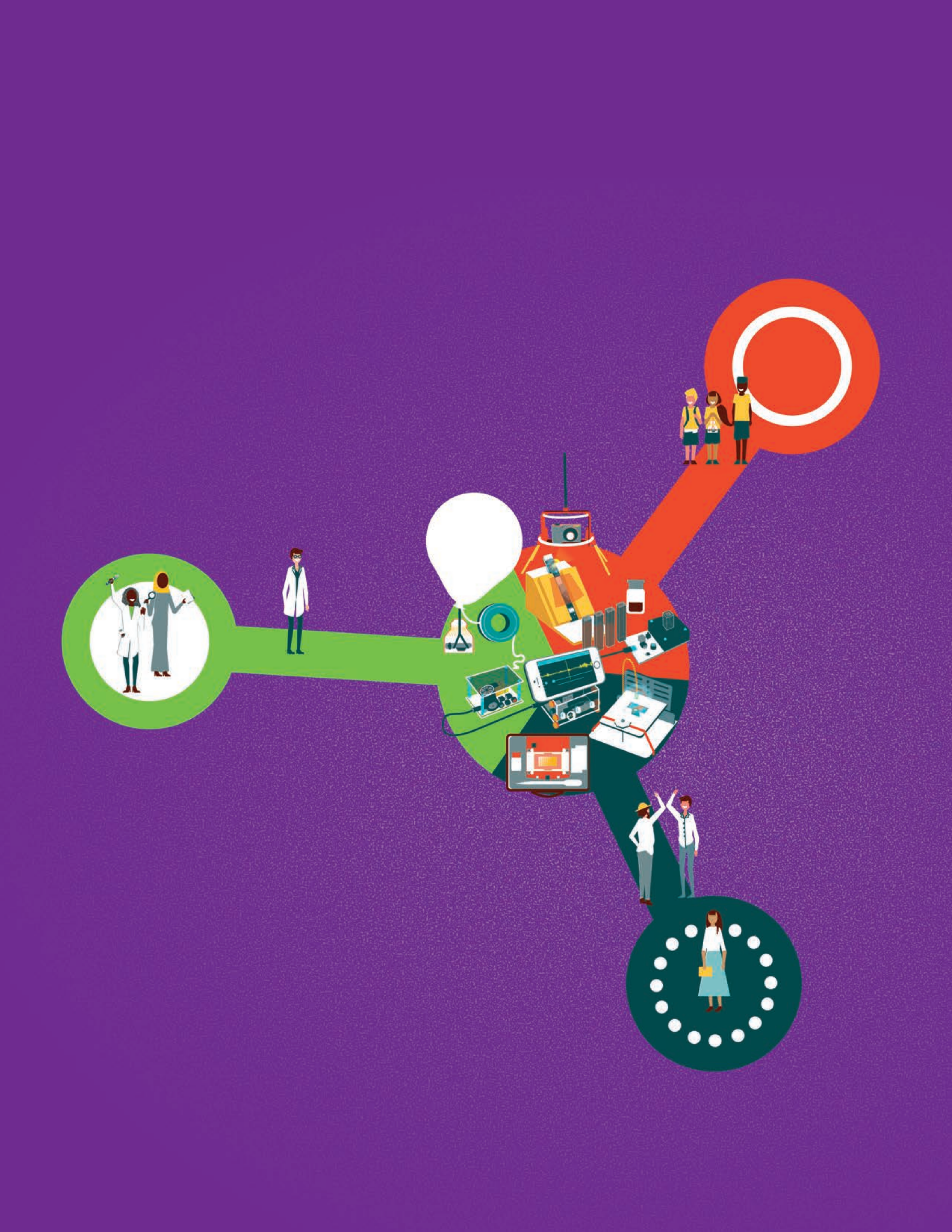
There is a major opportunity to build local capacity for supplying OScH to markets which are not served due to shipping costs, importation taxes, and lack of interest from big companies. In these contexts, researchers are more likely to build their own equipment, so sharing manufacturing techniques would help to create local capacity.

RECOMMENDATIONS

1. **Support the development of OScH distributor networks**. Enable a network of distributors to increase the mainstream supply and availability to diverse users, while mutually benefitting a wide range of producers and users. This can collectively drive down the resource costs of launching OScH projects and products.

2. **Identify or develop resource sharing best practices** for scaling up and contextualizing manufacturing and distribution via decentralized routes.

Prorto Labs rapid injection molding facility by Mahart922 on Wikimedia Commons licensed under CC-BY-SA International 4.0



CONCLUSION

We set out in this document to describe the key areas of activity for the OscH community for the next decade: to **learn** about our projects and community dynamics, helping to better **support** them and **grow** in diversity and numbers as we move forward. Each of these areas have milestones to be reached through our collective efforts and can be also thought of as modules with **inputs** generated through OScH community initiatives and **outputs** which can themselves become inputs for related community effort.

OUR MILESTONES

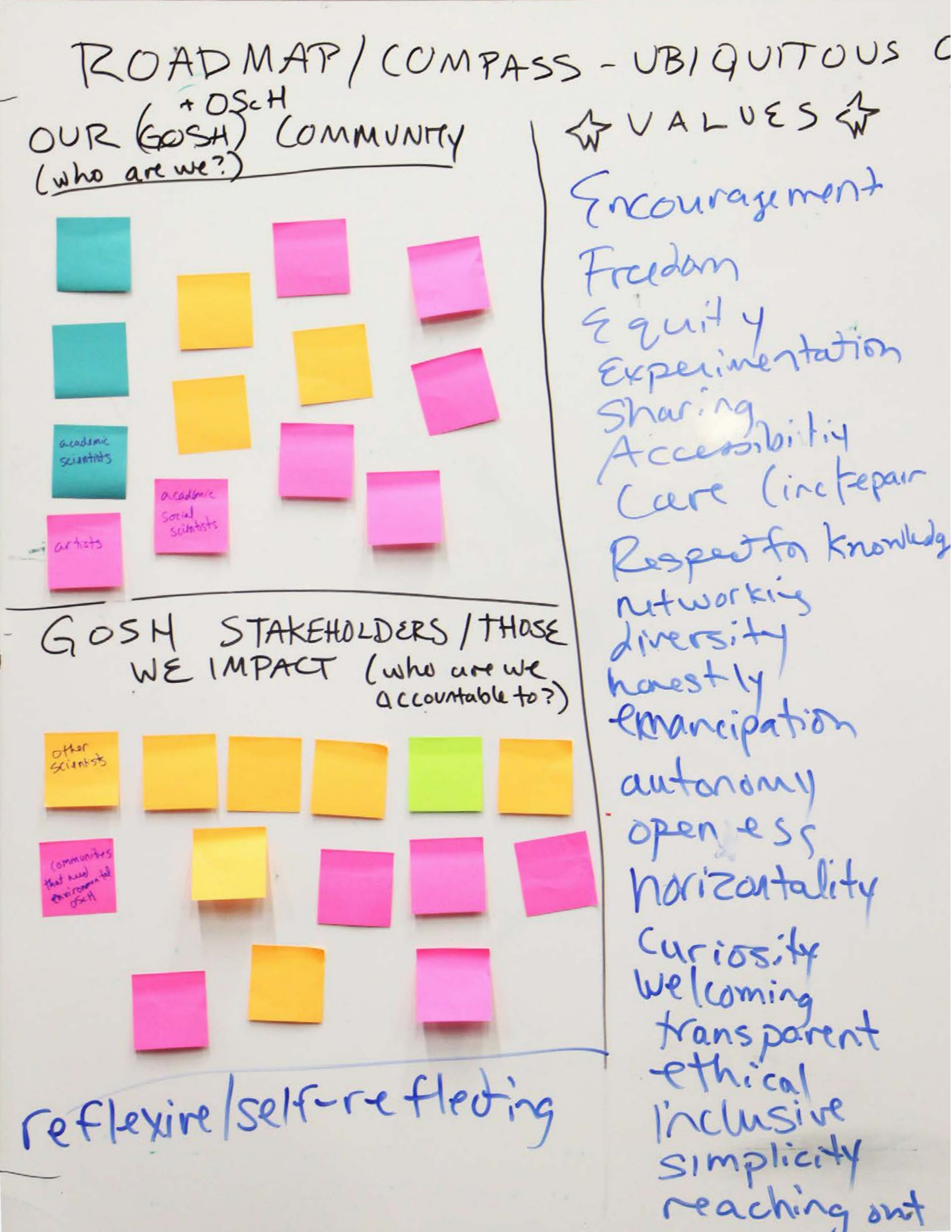
LEARN: we will know we have created the necessary conditions to help our projects when a common pool of open educational resources, empirical Free and Open Source studies, and Open Hardware documentation and licensing guidelines have been produced and widely adopted. The outputs of this module will serve to support various institutional, community, and professional initiatives around OscH, based on the application of our community-approved project assessment framework.

SUPPORT: this milestone will be reached when there is evidence of widespread institutional and community support for OScH. Institutional mandates and policy-level debates in support of Free and Open Source technologies will necessarily include Open Hardware for the sciences. Accessible and steady sources of funding for projects will also be available. The outputs of this module will help grow OScH as a mainstream practice for developing experimental instrumentation for the sciences: for basic research, industrial innovation, and community projects.

GROW: transforming the contexts in which science and technology production leads to inclusivity, equity, and respect for differences is the ultimate milestone. This goal will be reached when equitable conditions are well-established for OScH development, dissemination, and use. The outputs of this module can be used to transform OScH research and development and inform our Learn and Support activities, thereby generating a virtuous circle of production, reproduction, and innovation with higher societal benefits and much lower barriers for public participation.

The OScH community invites everyone who shares our vision of ubiquitous OscH to join us and help reach these milestones by 2025.

Join us now and share your Open Science Hardware!


ROADMAP / COMPASS - UBIQUITOUS C
OUR (GOSH + OScH) COMMUNITY
(who are we?)
academic scientists
academic social scientists
artists
GOSH STAKEHOLDERS / THOSE WE IMPACT (who are we accountable to?)
other scientists
communities that need environmental OScH
reflexive/self-reflecting
VALUES
Encouragement
Freedom
Equity
Experimentation
Sharing
Accessibility
Care (inc repair
Respect for knowledg
networking
diversity
honestly
emancipation
autonomy
openness
horizontality
Curiosity
Welcoming
transparent
ethical
Inclusive
simplicity
reaching out

LEARN MORE

1. GOSH community page: http://openhardware.science

2. GOSH community forum: https://forum.openhardware.science

3. GOSH Manifesto: http://openhardware.science/gosh-manifesto

4. Open Source Hardware Association: https://www.oshwa.org

5. Open Source Hardware Definition: https://www.oshwa.org/definition

6. “Building Open Source Hardware: DIY Manufacturing for Hackers and Makers” by Alicia Gibb

7. “Open-Source Lab: How to Build Your Own Hardware and Reduce Research Costs” by Joshua M. Pearce

Max Liboiron documenting OScH community values at GOSH 2017 in Santiago de Chile

FOOTNOTES

WHO WE ARE

1 “A movement to make scientific research, data and dissemination accessible to all levels of an inquiring society, amateur or professional. It encompasses practices such as open research, open access, and open notebook science.“ Source: https://en.wikipedia.org/wiki/Open_science

INTRODUCTION

2. Source: http://openhardware.science/gosh-manifesto/
3. Source: https://www.oshwa.org/definition/
4. Source: http://freedomdefined.org/definition

LEARN

5. Benkler, Yochai. 2006. The wealth of networks: How social production transforms markets and freedom. Yale University Press.
6. Oram, Andy (ed.). 2001. Peer-to-Peer: Harnessing the Power of Disruptive Technologies. Sebastopol, CA, USA: O’Reilly & Associates, Inc.
7. Chesbrough, H. W., Vanhaverbeke, W., and West, J. 2014. New Frontiers in Open Innovation. Oxford: Oxford Press.
8. Hippel, E. von. 2005. Democratizing Innovation. Cambridge, Mass.: MIT Press.
9. GOSH forum is an online space for discussion of topics of interest in Open Science Hardware. Source: https://forum.openhardware.science
10. “Science and Technology Studies” is an interdisciplinary field of research on historical, sociological, and cultural aspects of science and technology.
11. Socio-technical is a term for an approach from science and technology studies which does not separate scientific and technological systems from their sociological, historical, cultural, and political contexts.
12. Source: https://openhardware.metajnl.com/articles/10.5334/joh.7/
13. “Pulling back from open source hardware, MakerBot angers some adherents.” Source: https://www.cnet.com/news/pulling-back-from-open-source-hardware-makerbot-angers-some-adherents/

14. Source: https://sfconservancy.org/blog/2016/aug/04/everything-is-negotiable
15. Source: https://www.tapr.org/ohl.html
16. Source: https://www.ohwr.org/projects/cernohl
17. Source: http://solderpad.org/licenses/
18. Source: https://biobricks.org/openmta/
19. "Arduino is an open-source electronics platform based on easy-to-use hardware and software. It's intended for anyone making interactive projects." Source: http://arduino.com

SUPPORT

20. Source: https://docubricks.com/impact-tools.jsp
21. Version control is a technique of managing changes to documents (usually employed in the context of software development) and software tools for controlling versions of different documents, allowing for traceability of different versions across time. Source: https://en.wikipedia.org/wiki/Version_control
22. "Do It Yourself" is an expression of autonomy for individuals or small groups when studying, creating, and distributing OScH projects or products.
23. Human-centered design is a form of design that takes human action fully into consideration.

GROW

24. Groups of people who identify with non-exclusive gender categories, such as lesbian, gay, bisexual, transexual, queer, intersexual, and asexual.
25. Source: http://openhardware.science/logistics/gosh-code-of-conduct/
26. "Freely accessible, openly licensed text, media, and other digital assets that are useful for teaching, learning, and assessing as well as for research purposes. Open educational Resources include full courses, course materials, modules, textbooks, streaming videos, tests, software, and any other tools, materials, or techniques used to support access to knowledge."

ACKNOWLEDGEMENT

The Open Science Hardware Roadmap is a community-authored document that originated from the GOSH 2016 (CERN, Geneva) and GOSH 2017 (Santiago de Chile) meetings. We would like to thank all the attendees and contributors, including those who co-authored the GOSH Manifesto and other documents that informed this roadmap.

The Global Open Science Hardware community (GOSH) would also like to thank the Alfred P. Sloan Foundation for its ongoing support. We also thank CERN IdeaSquare and Centro de Innovación UC Anacleto Angelini, Pontificia Universidad Católica de Chile for providing space for our gatherings.

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