Science and Technology Innovation Program

Wilson Center

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Open Hardware:

An Opportunity to Build Better Science

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Foreword

On October 28, 2020, the authors convened a virtual workshop that brought together 22 experts from the open hardware and open science communities, including representatives from networks such as the Gathering for Open Science Hardware (GOSH) and the Open Source Hardware Association (OSHWA), with the common goal of outlining key messages about open hardware for public policy communities. Following the workshop, participants explored key messages through a curated collection of insights hosted by the Journal of Open Hardware on Medium. This publication is a reflection and compilation of the ideas of workshop participants and Medium articles, which further explore many of the ideas presented here.

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Science is not moving fast enough to address our most pressing challenges: a global pandemic; climate change; sustainable development.

The challenges we face require *all hands on deck*, including experts in all forms of science and technology, supported by both accessible and state-of-the art tools. However, scientific progress too often focuses on the few: highly skilled experts, expensive equipment, specialized laboratories, venerable institutions, and top-tiered journals. Efforts to strengthen science typically focus on expanding the current system, such as increasing the budgets of existing institutions, or funding more expensive facilities to be used by a handful of highly trained staff.

Open hardware for science is an alternative approach to the creation and use of scientific instrumentation and tools. Open hardware (or open source hardware) are tangible artifacts—machines, devices, or other physical things—whose design has been released to the public in such a way that anyone can make, modify, distribute, and use those things.[1] Physical tools for science include sensors that monitor the environment, desktop 3D printers and microprocessors enabling customized equipment in university and industry labs, small satellites developed by students, and much more.

Beyond a set of scientific tools, open hardware represents "a diffuse, dynamic approach to creation" that provides an alternative to the scientific community's reliance on expensive and proprietary equipment, tools, and supplies.[2] "Open hardware gives people the freedom to control their technology while sharing knowledge and encouraging commerce through the open exchange of design."[3]

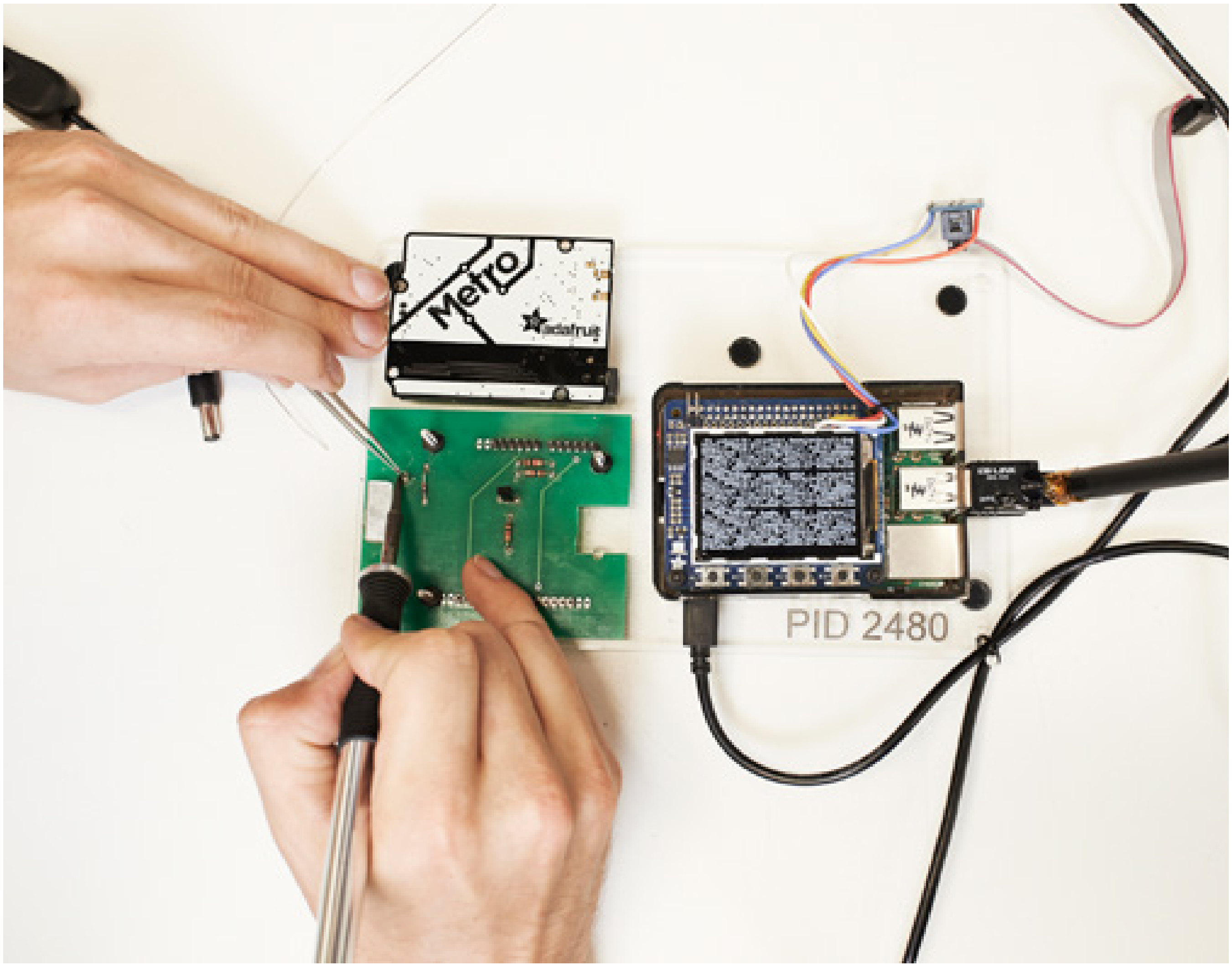
But while funding is important, the way science is traditionally done is changing. Continuing to invest in the status quo will yield increasingly limited returns. A growing number of thorny, interconnected challenges require the expertise of large, distributed and interdisciplinary teams. In addition, "the process of science moves quickly when a team can rely on a solid infrastructure".[4,5] However, today's research infrastructure, including scientific hardware, is unevenly distributed in the scientific community, severely limiting collaboration, customization, and impact.

Open hardware is an opportunity to think differently about science. **By investing in open source tools and supporting communities of developers and users**, the United States government can build a foundation on which to more effectively distribute capacity across the scientific community and broadly support U.S. industry and scientific research, generating an enormous return on investment.[6] A new administration offers an opportunity to design a national science strategy that embeds openness into all aspects of scientific research for the benefit of science and society.

As the popularity of open science grows, more people are recognizing that meaningfully sharing research *products*, like open access publications or open data, also requires attention to the *process* of research. This includes broadening participation in science to include non-professionals, such as citizen or community scientists who collect local air quality data, and increasing the accessibility of hardware tools such as specialized microscopes that are typically confined to a small number of labs. By prioritizing open hardware in policy and practice, scientists and the

American public alike can have full access to tools, meaning many more people can use their skills and diverse experience to contribute to scientific progress and bring science more fully into their daily lives.

This report addresses the need to build a stronger foundation for science by prioritizing open hardware, describes the unique benefits of open hardware alongside complementary policy priorities, and briefly lays out implementation challenges to overcome.



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Background: A Wealth of Bipartisan Policy Achievements

An open approach to scientific hardware complements the existing broad base of policy support for open science and open innovation.

Many open science and open innovation activities were pioneered in individual agencies before receiving broader policy attention.[7] For example, Congress authorized pilot programs for prize and challenge competitions in the Department of Defense's Defense Advanced Research Projects Agency (DARPA) in 1999, and in the National Aeronautics and Space Administration (NASA) and the Department of Energy (DOE) in 2005, which encouraged broader participation in solving specific technology issues.

Building on these and other open government initiatives in the Bush administration, the Obama administration's Open Government Initiative worked to create "an unprecedented level of openness in government."[8] Under that umbrella, the White House Office of Science and Technology Policy (OSTP) released early directives to increase access to federally-funded scientific results.[9] Many of these priorities were reinforced by agency-specific policy documents. For example, the National Science Foundation (NSF) released a public access framework, "Today's Data, Tomorrow's Discoveries," that recognized "long-standing policies" promoting open access and open data, and introduced specific requirements.

The Obama administration's OSTP also promoted the maker movement and makerspaces through a National Maker Faire and a National Day of Making, as well as public engagement in scientific research through agency attention to crowdsourcing and citizen science.[10] Alongside these OSTP priorities, agencies developed Public Access Plans and identified coordinators for interagency citizen science and crowdsourcing task forces, and entered their projects in a public facing catalogue.[11]

Across the Obama and Trump administrations, agency specific and White House-led initiatives were continually backed by legislative support. For example, the America COMPETES Reauthorization Act included prize and challenge competitions in 2010, and crowdsourcing and citizen science in 2015, solidifying bipartisan Congressional support. In 2018, Congress helped advance the open data agenda, as the Trump administration enacted the Foundations for Evidence-Based Policy Act into law.[12]

So far, domestic policies have not focused on open hardware, but there is growing attention internationally. In Finland, a framework for a national policy on open hardware was recently proposed to increase research innovation and improve the return on investment for science funders.[13] Initiatives by the European Commission such as the Open Source Hardware Strategy demonstrate an "ongoing paradigm shift" towards open science, including open hardware.[14] Globally, the United Nations Educational, Scientific and Cultural Organization (UNESCO) is launching an Open Science Recommendation as an international standard-setting agreement. The first draft, released in late 2020, features open hardware.[15]

At the same time, the benefits of open hardware are becoming better understood. Many benefits, such as reduced cost, increased access, enhanced collaboration, and acceleration of scientific progress are particularly tangible and immediate. Moreover, these benefits are complementary to a range of established policy priorities.

Now is the time for open hardware to achieve the policy recognition it deserves.

Why Open Hardware Works

"Modern microscopes used for biological imaging are expensive, are located in specialized laboratories and require highly qualified staff. Researching novel, creative approaches to address urgent scientific issues—for example in the fight against infectious diseases such as COVID-19—is thus primarily reserved for scientists at well-equipped research institutions in rich countries."[16]

Outside of highly specialized and often inaccessible tools for traditional imaging, a rich ecosystem of open source microscopes exists. Open source microscopes range from ultra low-cost (<$10) and smartphone-adapted ($5-$20) designs, low-cost (<$200) standard microscopes for research and diagnostic microscopy, and customized high-end ($10-50k) microscopes for cutting edge imagery and specialized research applications. Because open source designs are customizable, innovations include automated 3D microscopes, fluorescence microscopy, microscope-based cytometry, and two photon microscopy.[17,18,19,20] Some of these microscopes have enabled new types of experiments. For example, *OpenSPINMicroscopy* is an open source light sheet microscope system that enables scientists to conduct 3D imaging of cells and tissue in vivo. The open source design improved the spatial and temporal capabilities of this type of imaging, with one study finding better signal-to-noise ratios than two commercial two-photon systems. This innovation has made an impact in neurodegenerative disorder research by enabling high quality imaging of neural networks, data difficult to obtain previously.[21]

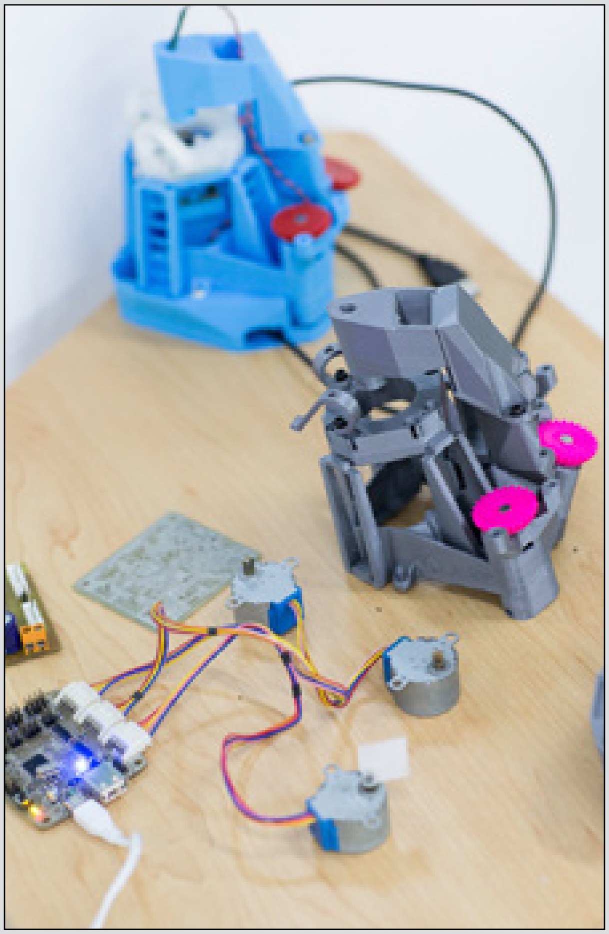

Image: AY7O4237 by GOSH Community is licensed under CC0 1.0 Universal

Although these microscopes represent different disciplinary traditions, were created in diverse circumstances, and are used for a variety of purposes, they share similar characteristics that lead to transformative work for the researchers that use them: they are low cost relative to proprietary products, they can often be built using locally-sourced materials to reduce supply chain challenges and desktop 3D printing which is convenient for small batch production, and they are highly customizable, allowing researchers to "swap" lenses, cameras, and stages.

Modular Design and "Building Block" Tools

Open hardware leverages innovations including the modular design of "building block" tools, and distributed design and manufacturing processes that can be customized to local needs.

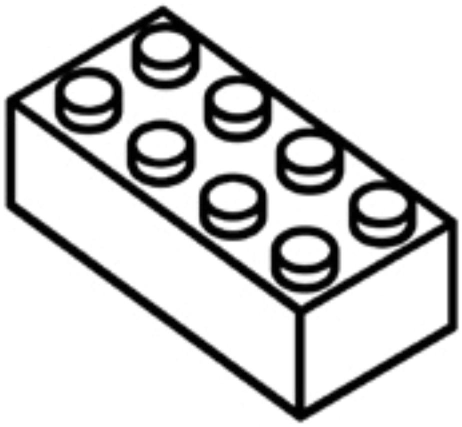

Image: Lego by Gerardo Martín Martínez, ES from the Noun Project is licensed under CC BY 3.0 US

"Most bits of open source [software and hardware] are designed to do one specific thing well, just like each LEGO brick looks unique and is used in a different way. The original LEGO brick may have been developed for a specific kit but, like LEGOs, that same brick can be used to build other things. **In open source [software and hardware], it means a component built to serve one company's needs can also be used for many other things**, like building government services software, educational software, games for kids, or data analysis tools for scientists."

—Greg Austic, *The best public investment in R&D? Think open*, Journal of Open Hardware Medium

Open source tools—including the microscopes described in Box 1—are like building blocks, because the designs are available and they can be modified and recombined in all sorts of ways, including many that the original developer would not have thought about. Over time these modifications and improvements are themselves shared in a way that others can build, replicate, and use, resulting in a more diverse ecosystem of tools. We can already see growing libraries of tools that are freely available for replicable and rigorous use across several disciplines. For example, the National Institute of Health (NIH)'s 3D Print Exchange is a library designed to advance biomedical research.

Distributed Design and Manufacturing Processes

"Scientific instrumentation built on open source hardware is a compelling infrastructure for science. It not only allows anyone to replicate or reuse hardware design files for free, but also establishes a community framework where physical equipment can be rapidly reproduced, refined and improved on."

—Andy Hill and Alasdair Davies, *Open hardware provides a better chance for scientific reproducibility*, Journal of Open Hardware Medium

These libraries and even the individual tools create a platform for further innovation. Instead of spending time building a custom research device from scratch, open source tools can be tweaked and built upon to meet specific research applications, adding cutting edge spokes and tyres without reinventing the wheel. Moreover, these tools are often designed to be reproduced by scientists everywhere through the widening availability of 3D printing and other digital fabrication tools. This means that production and customization can happen locally, and take advantage of local materials and resources, reducing supply chain vulnerabilities.

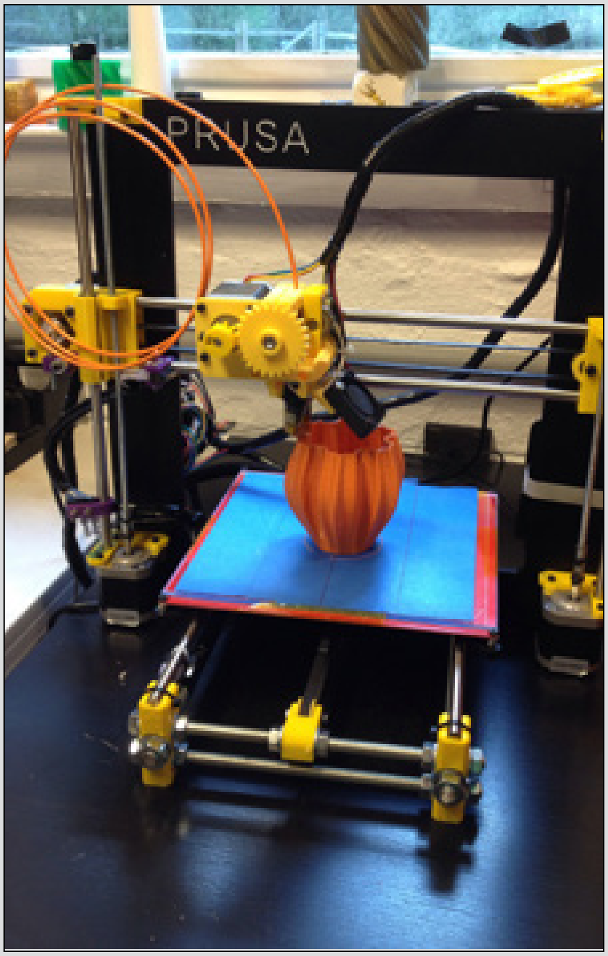

Image: *"Prusa i3 - RepRap 3D printer"* by *jabella* is licensed under *CC BY 2.0*

"RepRap 3D printers accelerate scientific progress through bespoke mechanical components for developing tool libraries for optics or syringe pumps as well as become scientific tools in the form of microfluidics prototypers, chemical handling systems and 3-D microscopes."[23,24,25,26]

The infrastructure of desktop 3D printers—and the communities that use them—is an example of how open hardware can enable accelerated and broadened scientific research globally, as well as form the building blocks for commercial success. "Desktop" or "personal" 3D printers are small and often low-cost tools that can produce 3D objects from a digital file, and have recently grown in popularity. The industry has its origins in open source scientific hardware; it emerged beginning in 2004 with one academic lab in Bath, UK, where Dr. Adrian Bowyer and 16 initial principal collaborators developed a prototype for a self-replicating, low-cost, open source 3D printer.[27,28] This spawned a vast network of collaborators, with improvements and alternative designs springing up worldwide.

Initially funded by the UK Physical and Engineering Sciences Council, the development of the initial RepRap designs grew into a global industry that includes numerous private, commercial firms that use both open source and proprietary approaches. This industry, in turn, supports the development of scientific tools including an assortment of microscopes (e.g. OpenFlexure, a 3D printed microscope with high precision mechanics). 3D printing has also enjoyed increased government and policy attention through agencies such as the National Institute for Standards and Technology (NIST).

Open, distributed design and distributed manufacturing create ideal conditions for iterative development approaches. Iterative development, a process where different designers and manufacturers improve a tool over time, results in multiplicative collaboration and faster innovation.

Collaborative and Human-Centered Design

Through collaborative and human-centred design processes, open hardware is a means by which people can co-create in new ways—for instance, linking educators with scientists in authentic research experiences that use advanced instrumentation to investigate local environmental concerns. Users of tools contribute to the development, support, and ongoing iterative design of tools, often through online project platforms. This organically improves tools and builds capacity for designers and users, ultimately contributing to enhanced scientific reproducibility and data reuse.

The pace of science should not be limited by the technologies researchers can gain access to. Having strong foundational technologies in place leaves scientists with more time and resources to focus on complex problems and innovative solutions.

Image: IMG_0968 by GOSH Community is licensed under CC0 1.0 Universal

Impact: Open Hardware Yields a High Return on Investment and Reduces the Cost of Research

In many cases, open hardware is a less expensive alternative to proprietary tools; in one study, researchers estimated a cost savings of 87% compared to "functionally-equivalent proprietary tools".[29] This cost savings allows research laboratories to stretch funding further—potentially much further—thus accelerating progress.[30, 31, 32]

Cost savings extend beyond the initial purchase of the equipment. Investment in open hardware is key to providing extended, improved access to affordable, repairable research instruments to the international scientific community.

High energy physicists have a long history of developing their own research instruments. At CERN, the European Centre for Nuclear Research and home of huge experiments in particle physics such as the Large Hadron Collider, hugely complex custom engineering projects are the norm. Open hardware has become a norm as well, and is now considered critical for quality control as it allows for distributed manufacturing, maintenance, adaptation, and collaboration at an affordable price and without vendor lock-ins or the creation of monopolies.

Open Hardware Links Science and Society

"[Open hardware] allows whole communities to rapidly learn, reuse and modify tools to address new research challenges or urgent environmental and humanitarian disasters."

—Andy Hill and Alasdair Davies, *Open hardware provides a better chance for scientific reproducibility*, Journal of Open Hardware Medium

The nature of open hardware provides a strong foundation to more closely connect scientific research and tools with the priorities of society, by allowing for local adaptations of tools to emerge in response to these priorities.[33]

Open hardware is physical—typically made from functional chunks of metal and plastic—but the way it is developed, shared, and used generates a social infrastructure that has great potential to respond to societal challenges. For example, in the aftermath of the Fukushima Daichi Nuclear Power Plant disaster, technologists, scientists, and local communities came together to form Safecast, an initiative conducting "participatory, open source, citizen-science centered" radiation mapping and developing open source radiation monitors using "rapid, integrated, open development, simultaneously addressing requirements in several disparate fields, including hardware design, software design, engineering, radiation science, visual design and communication, and social design factors."[34] In the event of a similar disaster in the future, more than 1000 of these radiation detectors are in use around the world; moreover, the design and documentation is easily accessible for rapid scaling and deployment elsewhere by people with no prior experience building or using radiation monitoring devices.

Perhaps just as importantly, the Safecast response to Fukushima resulted in a network capable of responding to additional challenges; the Safecast community platform recently expanded to include tools for both air quality monitoring and COVID-19 pandemic response. The recipe that holds many open communities together has three ingredients: 1) formal value structures (e.g. codes of conduct), 2) licensing that enables intellectual property sharing, and 3) a clear, purpose-driven development goal, whether related to radiation, air quality, disease, or a future challenge.

Open Hardware Supports Better and More Accessible STEM Education

Open hardware provides opportunities to build in experiential, hands-on learning to STEM education at high-school and university levels. For instance, while COVID-19 has driven many schools to close, the combination of virtual learning and the availability of open hardware designs has allowed students to build their own tools for scientific inquiry from objects in their homes or locally available supplies, and provided more equitable access through lowering cost barriers. Open hardware provides a unique opportunity for students to build, troubleshoot, and understand data outputs both independently and as a part of a team. It can then serve as a connector between STEM education and local communities, helping students experience the value of science past the boundaries of the classroom and ask questions about their own neighborhoods.

Image: "K-12 STEM Education" by Idaho National Laboratory is licensed under CC BY 2.0

At a university level, building open hardware can ensure undergraduate and postgraduate students have greater insight into the inner working of important scientific instrumentation and provide fresh ways of thinking about experimental design. It can offer an ideal convening point for interdisciplinary education programs and projects, for example between biologists or chemists and engineers.

Open Hardware Builds Capacity for Innovative Manufacturing

"The [open hardware] network has revealed a capacity for distributed innovation and creativity that is core to the original and cherished American entrepreneurial spirit."

—Sabrina Merlo, *Open source hardware can unleash the core American spirit of creativity and innovation*, Journal of Open Hardware Medium

Image: Testing in Fab July 2016 by Adafruit Industries is licensed under CC BY-NC-SA 2.0

Traditional, centralized hardware supply chains typically use offshore manufacturers. Open hardware is often manufactured in a distributed way by individuals and smaller companies, and this can be an important alternative to existing supply chains.

Increased investment in open hardware therefore expands the need for distributed manufacturing infrastructure, which can bring production capabilities to local communities, support the American manufacturing sector, and build in supply chain flexibility.

One of the clearest examples of distributed manufacturing in action is 3D printing. Desktop 3D printers are part of a basic set of fabrication tools housed in local makerspaces, FabLabs, schools, and in homes and businesses across the country. When crises such as COVID-19 hit and traditional supply chains fail, this distributed manufacturing capacity can be critical.[35, 36] For example, a significant portion of the PPE manufactured by grassroots organizations in the COVID-19 response used desktop 3D printers.[37] Now that this capability is accessible to many labs and individual scientists, there is potential for a paradigm shift in the way that basic scientific tools are manufactured.

How Do We Get There? Implementation Challenges

Expanding the capacity for innovation, collaboration, and production in existing open hardware communities will benefit from a whole-of-government approach to elevating the value of open hardware. This will lead to a stronger infrastructure for future science and cement U.S. scientific leadership and innovation. Because of past progress in open science, open source software, and DIY and maker initiatives, the U.S. government is well positioned to quickly make concrete investments towards making open hardware the way that we do science in the U.S.

In addition, foundational knowledge and infrastructure already exists within open hardware communities, which policy initiatives can support and help to grow. This knowledge and infrastructure is in the form of shared facilities like makerspaces and FabLabs, and virtual and hybrid communities like the Gathering for Open Science Hardware (GOSH) and the Open Source Hardware Association (OSHWA). A new administration offers an opportunity to build on lessons learned and knowledge held within these communities. A collaborative approach to knowledge sharing is both timely and necessary in order to amplify effective activities and provide a shared foundation to maximize impact. However, a series of implementation challenges do remain.

Gathering for Open Science Hardware

The Gathering for Open Science Hardware (GOSH) is a community that organizes a forum, meetings, activities, and publications to reach a goal of making open science hardware ubiquitous by 2025. The GOSH Open Science Hardware Roadmap "describes what is required for Open Science Hardware to become ubiquitous by 2025, laying out challenges and opportunities and recommending concrete actions. This document was contributed to, written and edited by over 100 people from different backgrounds and countries, working on or with Open Science Hardware."[38]

OSHWA

The Open Source Hardware Association (OSHWA) aims to organize the open source hardware movement around shared values and standards for open source compliance as well as educate the general public on its benefits.

Open hardware requires us to think differently about how we invest in tools for science. The problem is not generating new ideas; designs for creative and useful tools are abundant. Instead, implementation challenges include: understanding how to deliver quality and reliability; addressing common institutional barriers to creating and using tools; and finally, manufacturing and commercial viability to embed open hardware within the scientific instrumentation market as a normal practice. Within each challenge, there are opportunities to draw from previous approaches to advancing open science.

Below we expand on these critical challenges to implementation that also represent policy opportunities.

Quality and Reliability of Tools

"Data is always contingent on the instruments that produce it"

—Tarunima Prabhakar, *Lessons from 17th Century Scientific Experiments: Data Commons Need Open Hardware*, Journal of Open Hardware Medium

Ambiguity about the reliability and quality of open hardware, and the data it produces, sometimes limits its use, and "making [open hardware] widely used and perceived as credible for scientific investigations is key to its success."[39] **It can be helpful to think about quality in terms of "fitness for use"—or in other words, whether hardware is "good enough" for the intended purpose.** For example, a microscope used for a specialized research application would naturally have a different set of quality requirements than one used for field diagnostics or classroom investigations. Standardized components, documented quality assurance and quality control mechanisms, calibration with reference devices, and validation against expected results all help test and document fitness for use and require increased attention from developers and users alike.

Knowledge of how data is produced determines how useful it is, and how readily it can be combined and used for multiple purposes. The documentation and exposure of the inner workings of tools—inherent in open hardware—can enhance credibility and reproducibility.[40,41] Building on open hardware's collaborative approach, there are opportunities to embrace community-based strategies for assessing and documenting tools. These include developing processes and norms like peer-review of documentation and incentivizing others to replicate devices and report back. Within open hardware communities, some informal peer-review already happens through collaborative and iterative design processes. There are also more formal processes, such as journals publishing peer-reviewed articles on open hardware projects, such as the Journal of Open Hardware (JoH) and HardwareX.

As different strategies are explored to raise the standard of open hardware for science, support from existing open hardware communities is key, especially in establishing best practices for documentation in the context of science hardware. Like the quality of the hardware itself, documentation standards and norms may also operate on a "fitness for use" basis. For example, best practice documentation for a critical control module for the Large Hadron Collider will look very different from a water quality sensor for educational use. Peer-review processes could serve as a starting point for developing standards and norms that can be adapted to different fitness for use cases.

Institutional Challenges of Creating and Sharing Open Hardware

Image: Osmar, the open-source microsyringe autosampler by Carvalho & Murray is licensed under CC BY 4.0

The development of hardware for science often occurs within established, publicly-funded institutions, such as universities, research centers, schools, government departments, museums, libraries and not-for-profit organizations with missions serving the public. However, despite the benefit of open source practices to science and society, open hardware and open science often lack institutional support.

Instead, "research organizations [should] recognize, prioritize, and actively support this shared public infrastructure in the long term"[42]—not least because open hardware can align with institutional missions and goals, particularly towards the advancement of science and the benefit of society. Cultivating champions can increase adoption, especially within federal research funding agencies, so briefings for institutional leaders and staff could build familiarity with open approaches and support this culture change.

Once open hardware is accepted as legitimate and supported, institutional policies can be developed to support and incentivize its development and use.

For example, many institutional policies restrict or discourage open hardware by encouraging or even requiring proprietary licenses and business models to be adopted for technologies arising from publicly funded research. Decisions on licensing are typically made by the institutional Technology Transfer Offices (TTOs) who may lack standard norms, practices or policies for open hardware. TTOs may have limited understanding of open hardware approaches and licensing, making it difficult for them to accurately assess opportunities and risks.

Moreover, there is hesitancy and fear in industry, government, and the University system that open sourcing a design makes it impossible for profit to be made and a viable market to be built, even if demand for a piece of scientific hardware is demonstrated and larger-scale manufacturing is possible. However, there are many commercial success stories and thriving businesses selling open hardware, including desktop 3D printers, the Arduino microprocessor, and OpenTrons liquid handling robots. There is also an opportunity to support commercial enterprises using existing open hardware-based business models.[43] While this is promising for long term commercial viability, the market for scientific tools looks very different to consumer electronics and evidence is still needed on the most effective business models for different types of hardware, application and sector.

To overcome some of these institutional uncertainties and challenges, training will be needed for research and technology transfer staff to navigate specific considerations, such as open hardware licensing. Other tactics may include prioritizing open hardware in procurement policies, encouraging open hardware in institutional funding and granting requirements, and providing support to faculty members for custom equipment development.

Commercial Viability and Scale

Despite its potential for impact, most open hardware has limited reach: small numbers of devices are used within a research lab, for small groups of collaborators, or in small communities.

There are numerous models to help open hardware scale. Investing in "building block" components can make it easier for open hardware community members to design and develop a wide range of solutions. Pre-built ("off the shelf") and user-friendly open hardware and supporting software can broaden access to those with less technical training.[44] Alternately, recognizing that many problems and solutions are necessarily local, open hardware developed for a specific context can lead by example—and then be tweaked and re-purposed to meet a different local community's needs.

Scaling can also happen through mass production. However, one significant barrier to broader adoption is the complexity of manufacturing and distribution. Traditional manufacturing requires significant volume and up-front costs, and is out of reach for many open tool developers. **Building support for local production capacity through small-batch manufacturing and production can significantly reduce these barriers and diversify supply chains.** For individuals and small organizations, virtual development platforms can help people find and share designs while local makerspaces or FabLabs enable fabrication. Innovative financial mechanisms, such as crowdfunding and collective purchasing, drive down assembly costs and can help ensure that supply matches demand.

Conclusion: Think Differently About How We Invest in Tools for Science, and Prioritize Open Hardware Now

"We are facing wicked problems related to energy, the environment, and inequality. The complexity of these problems dictates the complexity of the science we need to address them. We do not have time to waste. If scientists are encouraged to work together on their shared infrastructure, it will be easier for them to work together on our shared planet. Open source hardware is one way to win some time."

—Nadya Peek, *Open hardware accelerates the process of science and addressing challenges*, Journal of Open Hardware Medium

Since the early 21st century, the U.S. has witnessed encouraging trends: science is becoming more democratic, and government more open. Both executive and legislative actors have an opportunity to take stock of what has already been accomplished, and develop a strategy to build back better with science.

With open hardware as a vehicle, science is now in the hands of people who are using it in a plethora of ways. Open hardware helps to ensure that scientific knowledge production is not just found in research settings, but that it supports the public use of science, aligns the use of science for societal needs, and broadens who, how, where and when people can participate in, and use, science.

Open hardware requires us to think differently about how we invest in tools for science—and helps us understand how it can become more democratic and participatory. There is an opportunity to design a national science strategy that embeds openness into all aspects of scientific research. Open hardware can help create a robust, reusable, and inclusive research infrastructure.

By prioritizing open hardware, we can change the paradigm of public investment in science; we can build a rich public resource of science tools to accelerate science and benefit society. A policy strategy that provides formal, high-level support for open hardware will help elevate the value of complementary open science approaches in publications, data and software. Prioritizing open hardware will also build a shared foundation and the building blocks of U.S. science leadership, and accelerate scientific progress to address global challenges.

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