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The Potential for Low-Cost and Open Source Hardware Solutions to Scale

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INTRODUCTION

The Role of Hardware in Scientific Research

The foundation of many scientific disciplines is hardware.[1] The microscope is foundational to biology, though its impact took time to achieve.[2] While its creation is attributed to a father-son team working in the 1590s, the word "microscope" did not appear in print until 1625. But although Robert Hooke's 1665 *Micrographia* established value across research domains, it would be another few centuries before the microscope really scaled, either in terms of production or in terms of broadening access to and participation in science. Today's top-tier professional microscopes cost thousands of dollars, but lower-cost models at hundreds-of-dollar price points are found in classrooms around the globe.

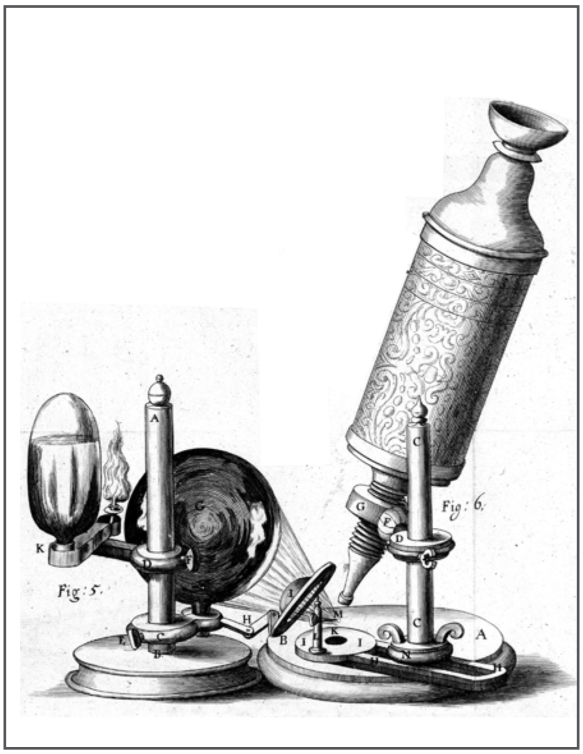

Figure 1. Diagram of the microscope that was first popularized by Robert Hooke ("Robert Hooke, Micrographia, detail: microscope" is licensed under CC BY 4.0),

Figure 2. Since their widespread adoption, microscopes have become increasingly complex and specialized, such as the transmission electron microscope pictured above ("transmission electron microscope" by EMSL is licensed under CC BY-NC-SA 2.0).

And scaling continues. Most recently, a team of Stanford researchers launched Foldscope, a 9 gram, pocket-friendly microscope with 2,000x magnification that "can survive being dropped from a 3-story building or stepped on by a person."[3] With a production cost of less than $1, Foldscope's founders set a goal to distribute 1,000,000 devices by 2019. The tool is notable for its price, its proliferation, and its capacity to support research outside conventional environments, aiding scientists on biology expeditions, and supporting medical researchers in low- and middle- income countries.

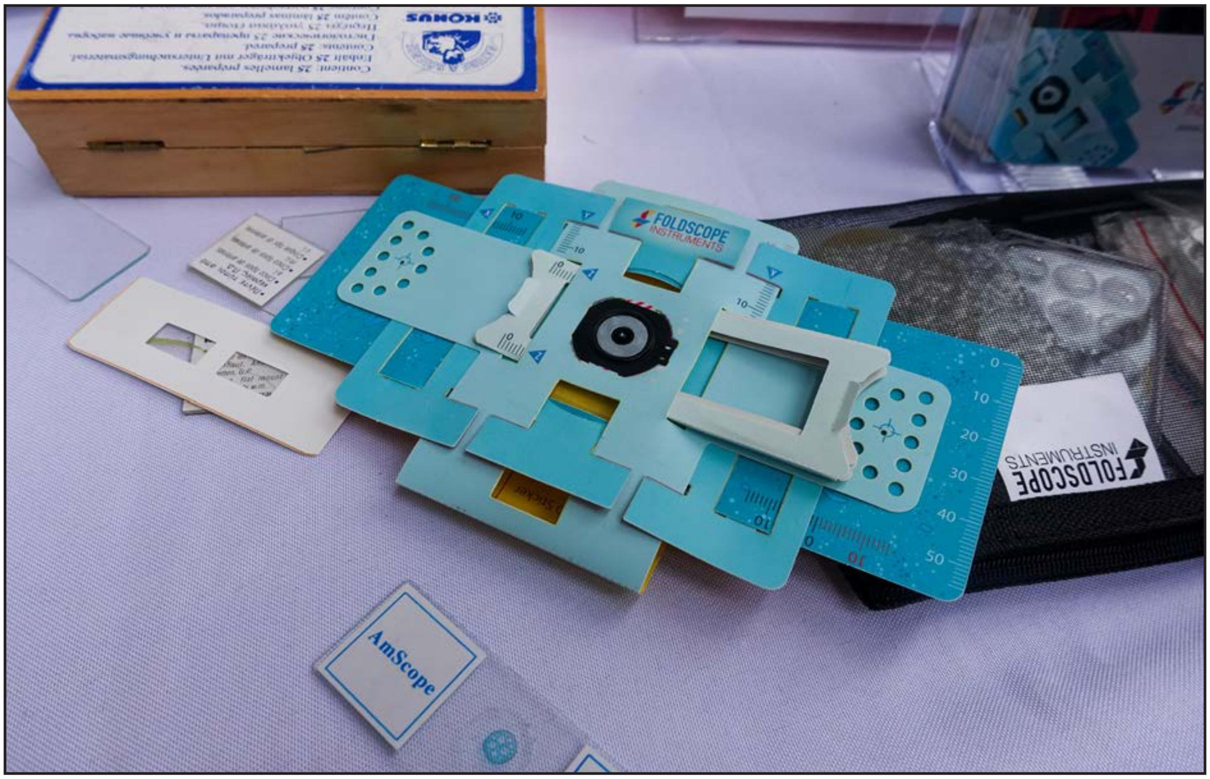

Figure 3. Low-cost microscopes, such as Foldscope ("Foldscope Instruments" by nicknormal is licensed under CC BY-NC-ND 2.0) are increasing access to microscopy.

Access to tools is more important than ever, and can be the limiting factor for the speed and quality of research. For the *hardware* that enables scientific work, innovations related to low-cost and open source practices challenge traditional product development processes, creating tools that accelerate and democratize science. Open source tools promise additional benefits, for example enabling customization and making it easier to fix broken devices, including by manufacturing replacement parts. But regardless of where a tool falls on the spectrum of proprietary to open (Box 1), these innovations appeal to individual researchers, formal institutions, and grassroots communities alike.

Realizing the goals of low-cost and open source hardware requires attention to how these tools can scale. One type of scale happens through production, when more tools are designed, manufactured, and used. A second type of scale happens when the enhanced availability of tools enables new and more diverse audiences to contribute to science. The goals of this white paper are to unpack scale from both perspectives, and to elucidate recommendations for accelerating and democratizing science through supporting low-cost and open source hardware.

Box 1: What is “low-cost”? What is “open source”?

Low-cost

More tools for science are emerging as low-cost alternatives to traditional tools.[4] For the purpose of this research, “low-cost” is defined as significantly less expensive than the status quo. For example, low-cost air sensors can be purchased for $100-$250 or built at a similar cost, while reference grade monitors traditionally cost $15,000-$50,000.[5] Although some tools are incrementally lower cost, many are significantly lower cost, and dramatically change accessibility and use. For example, air quality devices produced by Purple Air (low-cost) and Safecast (open source) are used by citizen science communities.

Open Source

Relatedly but separately, more tools are open source, meaning they can be “obtained, assembled, used, studied, modified, shared, and sold by anyone”.[6] “Open source” exists along a spectrum, but broadly aligns with the four freedoms of openness: the ability to make, modify, distribute, and use.[7,8] A related distinction is between “process” and “product” openness.[9] Product openness refers to the availability of documents–including design files, bills of materials, and assembly instructions–that allow others to exercise the freedoms of openness.[10] Process openness allows for open participation in design and development, and is implemented with support for version control, issue tracking systems, and other guidance.[11]

There is an important legal component to “open source.” Documents must have an open license that indicates legal permission for tools to be replicated, modified, or shared. For this paper, we use the general phrase “low-cost and open source” to recognize that both types of tools can accelerate research and make it more participatory. We use “low-cost” or “open source” exclusively to discuss tools or practices that are associated with proprietary or open approaches, and to recognize legal aspects of openness.

The Emergence of Low-Cost and Open Source Science Solutions

The proliferation of these tools can be traced to the early 2000s, when the emergence of Do-It-Yourself (DIY) electronics, makerspaces equipped with 3D printers, and internet-enabled online community platforms opened making and hacking to more people than ever before.[12,13] In addition to providing access to tools for making other tools, many community spaces fostered norms of community openness and sharing. They helped advance common design practices and modular design patterns, including the use of foundational components (such as microprocessors) in diverse solutions.

In some cases, making happened within the walls of established institutions, including student projects in university labs (Figure 4). But many communities, including critical makers, emerged either at the margins of, or distinct from, traditional technology communities.[14,15] Shenzhen's *Shanzhai* entrepreneurs are defined by their location in Shenzhen, which enjoys a unique distinction as a Special Economic Zone (Figure 5).[16] Shenzhen is also characterized by the close physical proximity of designers, manufacturers, entrepreneurs, and venture capitalists. Through policy and geography, Shenzhen supports innovation by "*operating at the margins*," blurring boundaries including traditional gaps between design and manufacturing, and proprietary and open source.[17]

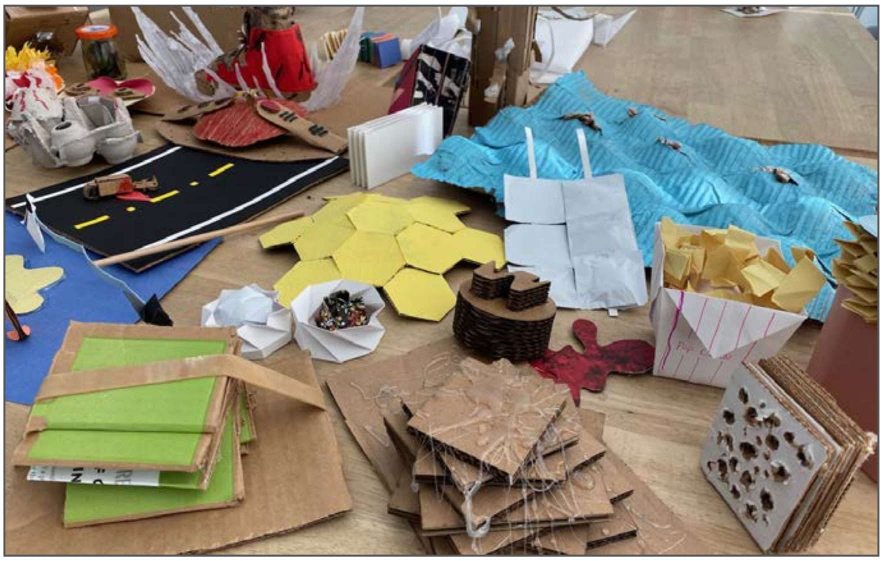

Figure 4. Scenes from a university class in critical making (Image by Eric Paulos is licensed under CC BY-NC-SA 2.0).

The idea of new spaces for new behaviors is also present in open source software (OSS). Just as DIY culture and makerspaces enabled hardware manufacturing practices, OSS was a critical conceptual enabler of open source hardware. However, those seeking to learn from OSS quickly discovered that the journey from bits to atoms was not entirely straightforward. For example, standard benchmarks such as the four freedoms and open software licenses do not transfer seamlessly (Box 2).

Figure 5. An electronics shop in Shenzen ("Electronics Everywhere" by randomwire is licensed under CC BY-NC-SA 2.0).

To help address the unique challenges associated with open source hardware, a number of convening organizations emerged. The Open Source Hardware Association (OSHWA) published a definition of open source hardware as "a term for 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."[18] The Journal of Open Hardware is a venue to build trans-disciplinary academic knowledge around the dynamics that shape design and production, including technical, legal, scientific, educational, economic, and sociocultural aspects.[19]

Beginning in the 2010s, there was also a growing realization that low-cost and open source hardware can support scientific research. Citizen science, particularly community-based science, leverages the research process to enrich narratives, re-balance power, and drive change.[20] These goals are sometimes achieved with support from hardware. Science, policy, and community perspectives now meet in communities like the Gathering for Open Science Hardware (GOSH).[21]

Box 2: Open Licenses in Open Source Hardware

Open licenses enable tools to be replicated, modified or shared by other developers and users. They offer a legal as well as a normative basis for openness. Also working as a social contract, licenses "describe the conditions, obligations, constraints, and moral obligations for the public circulation of design documentation."[22]

Generally, open licenses relate to copyright or patent law, and may include:[23]

- ***Creative Commons licenses***, which apply to copyright protection for all kinds of creative work, from art and music to code and technical designs.[24]
- ***Open source software licenses*** for copyright protection, which are also commonly used for hardware; for example, the GNU General Public License and Apache license can be applied to hardware documentation as well as source code.
- Emerging ***open hardware licenses***, which are specifically designed for physical tools and may have components related to both copyright and patent law. The CERN Open Hardware license is the most well-developed and commonly used.[25]

Licenses created specifically for open hardware may be more adept at condensing with issues raised by the materiality of designs than general purpose or software licenses. For example, traditional software licenses protect the distribution of source code (including documentation or design files), but do not apply to the distribution of derivative products.

HOW LOW-COST AND OPEN SOURCE CHALLENGE TRADITIONAL PRACTICES

Product Development and the Innovation Funnel

Traditionally, hardware is created through the product development lifecycle, a structured, iterative process that mirrors software development.[26] The innovation funnel (Figure 6) is one framework for describing product development milestones along with business model and market introduction.[27]

One way traditional practices are challenged is through open innovation, a paradigm that suggests "firms can and should use external ideas as well as internal ideas, and internal and external paths to market, as they look to advance their technology."[28] Open innovation happens through *outside-in* approaches, where external perspectives inform internal processes, and through *inside-out* approaches, where internal tools and ideas are offered to external communities.[29] Open innovation can demonstrate return on investment (ROI) by accelerating the innovation, or by fostering the growth of communities that strengthen a product's value. One thing that distinguishes open innovation from other open paradigms is emphasis on the firm, a formal entity that acts as a product's owner and generally retains control over product development.[30]

From a firm's perspective, open innovation is a risky endeavor that requires careful consideration of intellectual property (IP). Firms operating in stable markets with many innovators may be especially conservative, for example by requiring external innovators to cede all IP rights as a condition of participation.[31] In stable markets with fewer innovators, teaming arrangements may bind partners–typically universities or other companies–during ideation and discovery, allowing each the freedom to develop IP after.

"Open innovation is a critical enabler of scale in proprietary low-cost hardware production. However, open source design and production is, by nature, distributed and decentralized. Terms like community-based production or co-creation are more effective at capturing open source dynamics."

Open innovation is a critical enabler of scale in proprietary low-cost hardware production. Open source hardware also benefits from opening participation, and has some epistemological kinship with open innovation. However, open source design and production is, by nature, distributed and decentralized, and the originators of open hardware projects are less likely to exert the same levels of control observed in proprietary firms. In recognition of this difference, terms like community-based production or co-creation are more effective at capturing open source dynamics than open innovation. Regardless of the name, the process openness that characterizes open innovation or community-based production challenges traditional product development processes at all stages of the innovation funnel, as explored in depth below.

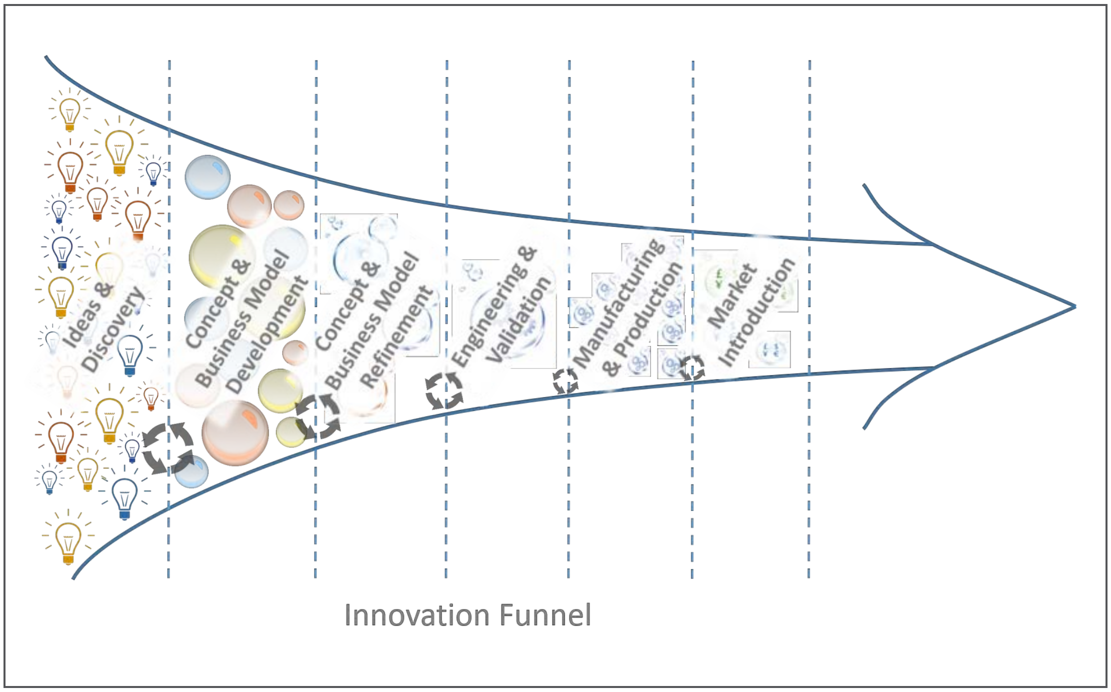

Figure 6. The traditional innovation funnel.

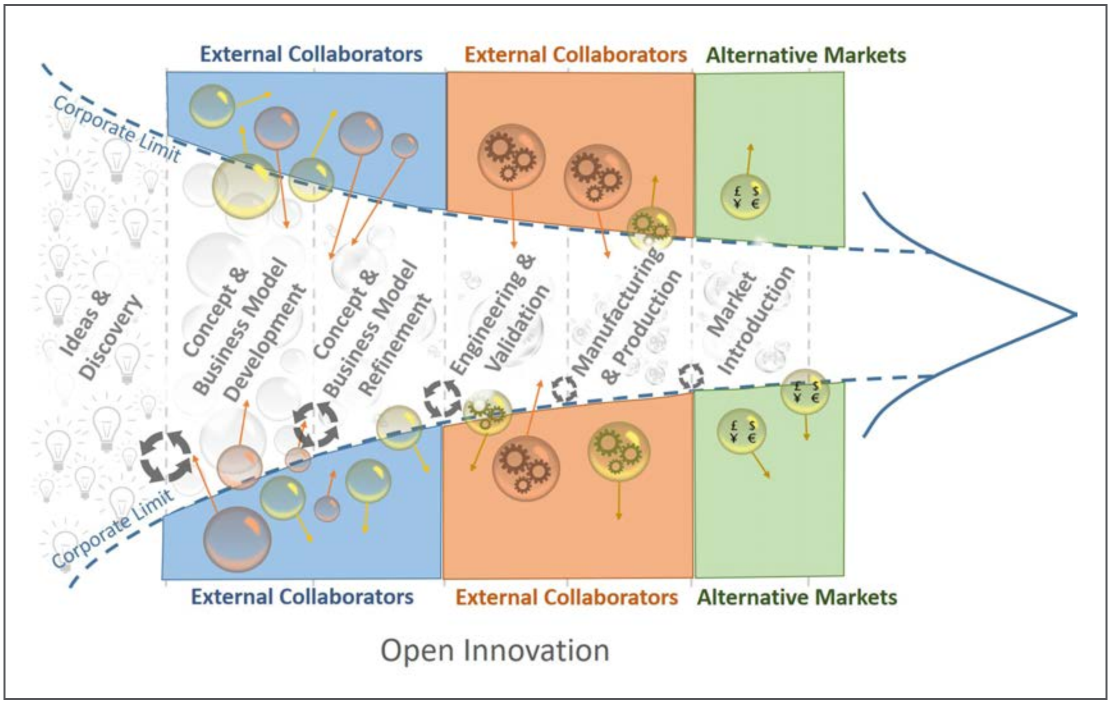

Figure 7. Traditional open innovation

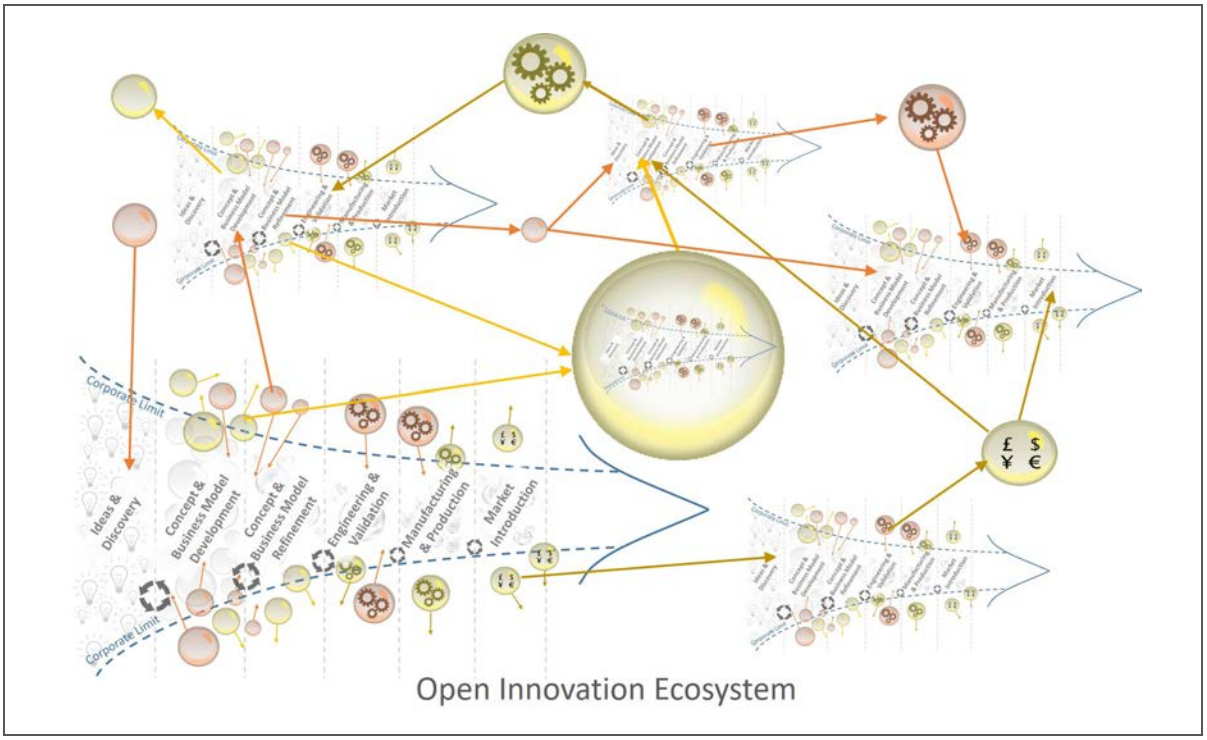

Figure 8. The disruptions associated with open source hardware production. Open source hardware supports the creation of many derivative products across all phases of the innovation funnel, ranging from concept and business model development and engineering and validation. This allows open source hardware to scale when any component of the design or development process can spin off a number of other tools–and associated innovation funnels–at any given point in time.

Ideation and Discovery

Both traditional and low-cost proprietary hardware communities may embrace open innovation approaches, such as calls for participation in ideation challenges and prize competitions. For example, in Spring 2020, the U.S. Army launched a prize competition for a low-cost, readily manufacturable emergency ventilator to augment capacity during the COVID-19 pandemic.[32] The Army's tiered model began with a $5,000 prize for "novel solutions," and extended through funding for a prototype and the potential to contract.[33] Notably, while the competition did not exclude open source solutions, the Army offered assurance that IP rights would be protected.

In open source environments, collaborative idea generation and discovery are enabled by process openness, and various aspects of *product openness*. Transparency is enabled by publishing the source of a product or design, namely a CAD design file or other documentation, with an open license. Transparency is so foundational to open hardware that an empirical assessment of "openness" found that sharing CAD design files is the most common open practice observed in complex hardware systems.[34] In addition to broadening access, transparency supports quality by enabling peer-reviewed assessments, and fostering trust.

Beyond design files, platforms such as project showcases provide inspiration for new ideas, especially when backed by licenses that reinforce the intent to share. Modularity, reflected in the "lego-like design style of some iconic projects," is an inherent property of open hardware, and a key enabler of openness and scale.[35, 36] Arduino's

Project Hub, which documents over 4,000 projects with applications ranging from Health and Fitness to Robotics, is just one testament to the foundational value of modular Arduino devices and kits.[37]

Concept and Business Model Development

Concept development determines whether a tool will actually work. In some low-cost and open source hardware, external communities participate in concept development by providing feedback on blueprints and design files. This is typically initiated through an open call for contributions led by the tool's developer. Platforms such as GitHub support concept development by providing a version control system that enables contributions, edits, and the creation of derivative products to be tracked. While GitHub is the most common groupware solution used, other platforms include MediaWiki, GrabCad, Wevolver, and WikiFactory.[38] Notably, in open source environments, concept development can be a distributed process, where one group of innovators focuses on the initial idea while others devote their attention to creating related yet derivative products.

Concept development often corresponds to the business model development. Often, as a hardware solution progresses through the innovation funnel, a founder or early leader will either acquire business development and marketing skills or bring in additional capacity.[39] Business model development–along with funding–is discussed in detail later on.

Engineering and Validation

During product development, tested concepts undergo iterative validation that include several iterations of failure modes and effects analysis (FMEA).[40] Engineering and validation help prepare a product for large scale production, including by taking relevant regulations and standards into account. This phase corresponds to a narrowing innovation funnel, as alternatives become progressively less feasible due to growing requirements.

Low-cost and open source tool developers rapidly prototype and test solutions in real world environments. Community participation allows developers to get feedback faster, and move through the innovation funnel more efficiently than would be possible through closed processes. Interestingly, in part because of the perceived value of IP, proprietary firms may be more motivated to apply lessons learned during external validation directly to a product line. Open engineering and validation–like open concept development–may also lead to the creation of derivative products that are taken forward in parallel to initial design and development goals.[41]

Scientific tools require calibration as well as documentation of specifications, and conformance to relevant standards. While all these steps are typically required before proprietary solutions can go to market, open source environments are more complex.[42] For example, because the designers of a tool are not necessarily the manufacturers or users, responsibility for calibration and conformance to standards is less clear.

Ignoring standards and regulatory specifications can be a barrier to adoption and trust, especially in highly regulated environments. For example, during the COVID-19 pandemic, personal protective equipment (PPE) manufactured by makerspaces were sometimes turned away from hospitals if adherence to regulatory standards could not be demonstrated.[43] Some groups, such as Make4COVID, developed their own, standards-based procedure for assessment and documentation.[44] Other groups, such as Helpful Engineering, leveraged partnerships with external groups including Veteren's Affairs (VA) agencies to ensure designs were manufactured in regulatory-grade environments.[45]

Production and Manufacturing

Early phases of production and manufacturing are iterative, and help determine error tolerance, batch production size, variance, and replicability. These processes also help identify opportunities for cost savings required for production to scale. Because low-cost, compex hardware solutions can often leverage a range of components, proprietary solutions may be vulnerable to supply chain disruptions. In contrast, open source hardware can quickly adapt thanks to transparency, modular design, and distributed manufacturing.

In open source hardware, transparency enables other supply chain innovations. If there was a shortage of a specific component, the use of transparent and modular designs would enable a tool to be redesigned around a more readily available component. Additive manufacturing, or 3D printing, is commonly used in the production of open hardware. 3D printing can help mitigate supply chain vulnerabilities by enabling the production of hardware components from plastic, resins, or other powdered raw materials.[46]

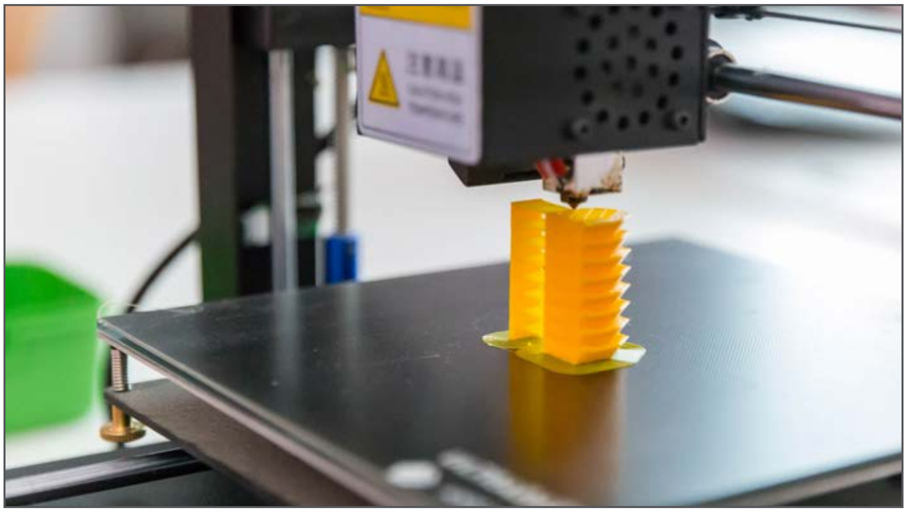

Figure 9. 3D printers enable the production of customized hardware components ("3D printer printing: Anycubic I3 Mega 3D Drucker" by marcoverch is licensed under CC BY 2.0).

Makerspaces and FabLabs enable distributed manufacturing by providing a community fabrication space. These spaces provide equipment such as 3D printers, as well as a space for individuals to assemble solutions, collaborate, and exchange ideas. Recognizing that 3D printing start-ups raised more than $1 billion in venture capital in 2019, and 29% of all additive manufacturing firms are headquartered in the US, 3D printing has support from federal authorities including Wilbur Ross, Secretary of the US Department of Commerce, among others.[47]

Market Introduction

In traditional manufacturing, market introduction tends to focus on a small, highly-targeted customer population. Once the product is introduced, demand drives further production, keeping available stock low and overhead cost down following lean manufacturing principles.

Low-cost and open source hardware, especially when developed through open processes, may have low market introduction costs. Many tools will already have a target customer base that participated in product development. Because of existing community ties, advertising is often done by word of mouth, and hardware developers rarely pay for digital marketing.[48] Instead, marketing goals are achieved with support from common community practices, such as showcasing the use of a tool (and spinoff designs) in community forums.

This noted, market introduction is not always a strong concept for open source. Although some open source hardware companies manufacture and sell tools or kits, these offerings are still developed through open processes. When openness and collaboration are prioritized from the earliest stages of ideation and discovery, products are arguably "introduced" to many potential markets on an ongoing basis. Offering users multiple pathways to access is an important aspect of open source hardware, and enables scale.

Market Factors Related to Scale

From a market perspective, at least two key considerations–funding and business models–transcend various phases of the innovation funnel.

Funding

For established companies, funding for new product development often comes from research and development (R&D) budgets, or is sponsored by an internal business unit. New companies and startups may lack access to these resources. But regardless of revenue model, startup costs include both the time required to design and prototype a solution, and resources including manufacturing equipment, raw materials, and other supplies.

Many low-cost and open source tools meet startup costs through crowdfunding. In addition to providing revenue, platforms like Kickstarter help build community around a tool. For example, the underwater exploration system Trident, previously known as OpenRov, launched their Kickstarter campaign with the articulated goals of incorporating user feedback into their designs and building a strong community.[49] The success of this campaign, which achieved its funding goal in three days, gave Trident the confidence required to continue their development work.

The production of open tools often begins in non-traditional settings to keep costs low. Purple Air was assembled in the tool developer's house before demand became overwhelming. Some tools also use group purchasing to fund small batch production. The open source acoustic sensor, AudioMoth, asks customers to place their orders through GroupGets, outsourcing manufacturing once sufficient demand is established to reduce cost and risk.[50]

In some cases, federal funding can help with startup costs. The pilot program that tested Foldscope was funded by the US National Institution of Health (NIH) (Figure 10). The US National Science Foundation (NSF) Small Business Innovation Award (SBIR) program has supported startup costs for both TubeSat, an open source satellite system, and PocketLab, a collection of laboratory tools.[51] Federal grants tend to provide more substantial support than crowdfunding, and add a layer of legitimacy. Additional sources of funding include venture capital, foundation grants, private donors, prizes and challenges, and self-funding.

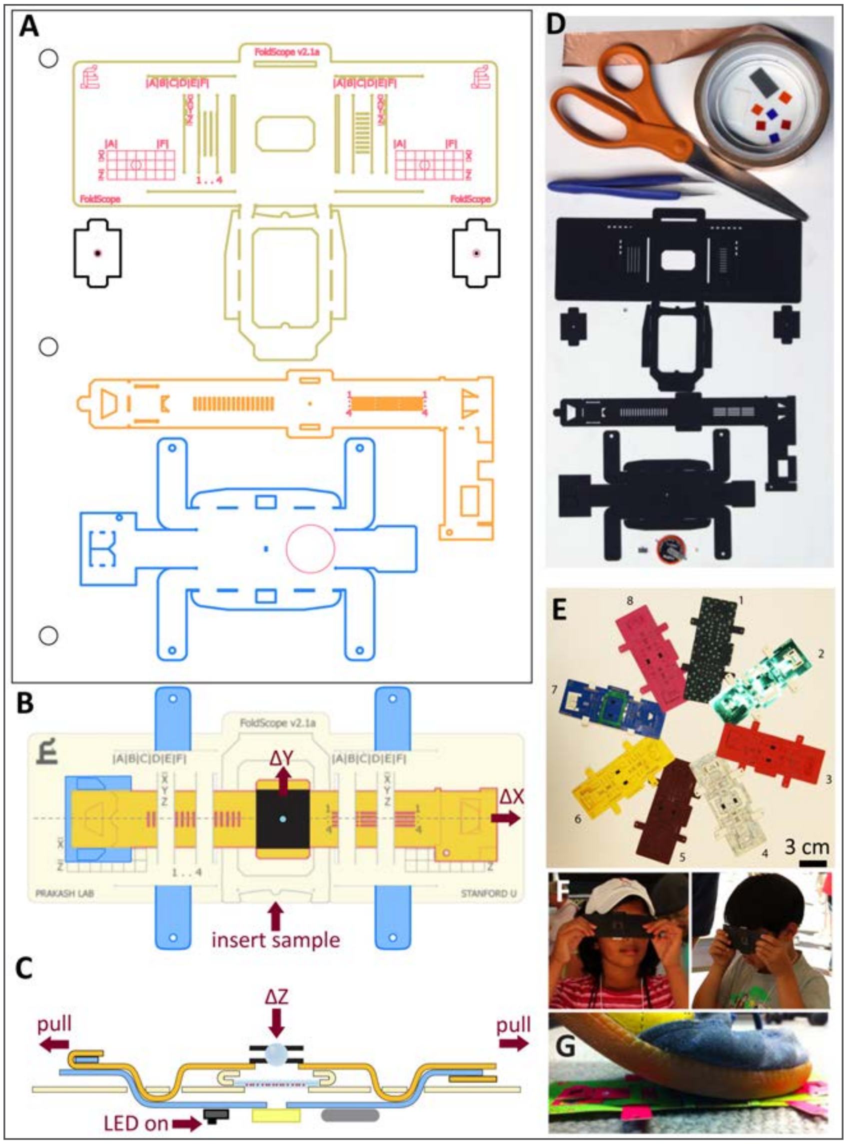

Figure 10. Many low-cost and open source tools, including Foldscope, were developed with support from federal funding (Foldscope design, components and usage" by Cybulski, J. Clements, & M. Prakash is licensed under CC BY 4.0).

For low-cost and open source hardware, funding for startup costs and sales revenue can be relatively easy to obtain. However, a gap often exists during the "in between" stages of tool development. Although this can sometimes be mitigated by revenue from other tools in a collection, challenges around finding funding to enable meaningful community involvement often remain.

Business Models

Business models in traditional hardware production are rooted in intellectual property (IP) rights. In addition to securing IP, traditional business models rely on keeping costs low throughout manufacturing and distribution. While IP rights are critically important in low-cost proprietary production, this is not the case for open environments. Further, because the designers of a tool are not necessarily the manufacturers and distributors, a wider range of business models are needed to capture value.

Some researchers have analyzed how various "core competencies" of low-cost and open source hardware contribute to success and scale.[52] Some tools fill a niche market, controlling for quality and cost. For example, analysis of a historic "price war in the DIY 3D printing market" reveals that market value can be generated by producing the cheapest printer possible, a tactic utilized by numerous Chinese manufactures, or by producing a high-quality printer at a relatively low price point, a strategy exemplified by the open source competitor Lulzbot.[53]

The ability to innovate quickly, exemplified by the Shanzhai culture of Shenzhen, is a second core competency shared by proprietary low-cost and open source hardware designers. Rapid innovation is enabled by supply chain opportunities like 3D printing, and–in the case of open source–modular design. It is also enabled by open processes across the innovation funnel.

Some open source companies, like Arduino, generate community excellence and value by cultivating brand loyalty. Arduino offers the Arduino at Heart Brand License agreement for products that want to be recognized as an Arduino-based technology. In addition to legal permission to use a trademark, Arduino helps build value in partner brands through (for example) elevated attention on social media campaigns.[54] Beyond specific projects, the open source brand may have market value in itself: according to one researcher, "some have speculated it could be the next organic or fair trade." [55]

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These core competencies support a number of business models and market opportunities. Manufacturers sell low-cost and open source hardware on project websites or general eCommerce platforms such as Etsy.[56] In addition to selling final products, manufacturers also sell 3D printers, parts, or kits.[57, 58] Those who sell open source projects may rely on the emergence of complementary markets. For example, the Nitrate Elimination Corporation (NECi), a producer of enzymes for analytical chemistry, open sourced their photometer, a complementary research tool. Both NECi devices manufactured by open source communities, and copycat efforts from competitors, benefitted the corporation through an increase in enzyme demand.[59] Companies can also open source select offerings to meet diverse market values and needs.

Other business models include selling customized hardware, or selling hardware as a service. Companies leveraging the Thingiverse platform often manufacture custom projects for different businesses, or directly to consumers.[60] Some companies also sell services such as customer support or education and training. While similar business models are present in open source software companies like Red Hat, education services such as classroom packages explaining 3D printer use may be more unique to hardware environments.

Finally, some researchers have hypothesized that communities could outsource the process of science itself.[61] Similar business models have been explored in citizen science communities. Adventure Scientists, for example, will design and lead projects that involve the outdoor adventure community in a research project to help meet a sponsor's goals.[62]

DISCUSSION: SCALING LOW-COST AND OPEN SOURCE HARDWARE

Realizing the value proposition of low-cost and open source hardware–to advance research, accelerate discovery, and make science more participatory–requires attention to scale. One type of scale happens through production, which elevates research when more tools are designed, manufactured, and used. A second type of scale happens when the enhanced availability of tools enables new and more diverse audiences to contribute to science.

Figure 11. Scaling of low-cost and open source hardware can happen through increased production (Fab Machines Training July 2016 by Adafruit Industries is licensed under CC BY-NC-SA 2.0).

Figure 12. Scaling of low-cost and open source hardware can happen through increasing participation in science (K-12 STEM Education by Idaho National Laboratory is licensed under CC BY 2.0).

Recognizing how production can scale begins with understanding how low-cost and open source hardware for science moves through the innovation funnel, along with common funding and business models. Ultimately, scaling production requires finding the right balance between quality and cost. Market forces can play a critical role in this process, especially when the goal is to manufacture and distribute out-of-the-box solutions or kits. Fortunately, open source communities generally support commercialization, providing the product is sufficiently innovative or elegant to merit production.[63]

Scaling production also benefits from opening participation through open innovation or co-production. Open source communities expect product developers to contribute to the open source ecosystem when a product is based on open designs. This is reflected in part through the various standardization initiatives present in open source hardware. Although initial efforts focused on licenses or certification processes, recent attention has also focused on requirements for documentation and community assessment, including the DIN SPEC 3105, or metadata requirements to promote discovery, including the Open Know How Manifest Specification.[64] Such work re-enforces the value and importance of communities in low-cost and open source approaches by providing concrete mechanisms to promote sharing and re-use.

This noted, not all hardware developers try to scale through production (Box 3). 3D printing, whether conducted in university labs or community makerspaces, is not always effective at supporting production at scale–but it is adept at meeting small batch production needs for low-cost and open source tools, including for custom equipment and repairs.

Box 3: Scale: Two Drivers of Demand

Recent examples demonstrate how demand for low-cost and open source hardware is increasing, including for materials research and disaster response during the COVID-19 pandemic, and at the nexus of research and education in universities.

Supporting Innovation During Disaster Response

Times of crisis often require informal institutions to partner with established authorities.[65] Recent examples of support from low-cost and open source hardware communities in disaster response include the Deepwater Horizon Oil Spill of 2010, the Fukushima Daiichi nuclear disaster in 2011, and the COVID-19 pandemic.

During COVID-19, traditional supply chains and business models were unable to meet hospital demands for personal protection equipment (PPE). The open source hardware community rapidly prototyped open source design files for medical supplies, such as face shields and ventilators. Large numbers of decentralized volunteers also manufactured and distributed PPE to hospitals, sometimes working with partners like Veteren's Affairs (VA) groups. Impact is shown in the numbers: Helpful Engineering volunteers spent 3 million hours making and distributing PPE, while Open Source Medical Supplies delivered 16 million PPE, as just two examples.[66,67]

Advancing Research in the University Sector

Over the past decade, open source hardware has gained prominence in education, with one important source of demand stemming from universities. Driving forces include changes in teaching methods; a lower price point; and, the ability of hardware to generate data for analysis.[68] For advanced students, low-cost and open source hardware offers access to tools that would otherwise be prohibitively expensive. iCub, an open humanoid robot platform designed to emulate a 2.5 year-old child, was used in one undergraduate's award-winning thesis on face and emotion recognition.[69] University administrators, as well as those procuring and maintaining laboratory equipment, are also drawn to affordances of open hardware that make it easier to fix devices, secure replacement parts, and avoid vendor lock-in.[70]

Although the scale of production in university settings may be smaller than in examples like PPE during COVID-19, the link to traditional academic processes may be stronger. Further, students who encounter these tools during their education may utilize them, or embrace complementary open science agendas, throughout their careers.

For example, companies such as Arduino, Raspberry Pi, and Seed Studio provide platforms for individuals or organizations to create derivative tools. These platforms are then embedded in devices created for niche applications, such as a sensor for plant water management. Such building block solutions are designed primarily to support small scale, as opposed to mainstream production, and support communities that wish to showcase the diversity of derivative tools and applications.

Some 3D printing solutions can be found in general-purpose platforms like Thingiverse, which host blueprints and other documentation for science and hobbyist products alike. Domain-specific repositories such as the NIH 3D Print Exchange, which contains blueprints for tools ranging from customized test tube holders to replacement parts for syringe pumps, can be helpful for supporting a particular type of research.[71] In addition to supporting scale through custom, small-batch production, 3D printing also broadens participation in tool design and science, and helps extend the life of an existing tool through the right to repair.

Scaling by broadening participation in tool design, development, and ultimately use requires moving beyond cost considerations to find additional ways to lower barriers to entry. Emerging infrastructures of people and technologies create the scaffolding required for interested newcomers to learn, find inspiration, and ultimately create their own science solutions.

CONCLUSION

What is the true potential for low-cost and open source hardware to accelerate and democratize scientific research?

Evidence suggests that the potential for low-cost and open source hardware to accelerate and democratize scientific research is significant. First, looking at scale as measured by numbers alone, Arduino produced 700,000 boards within its first 10 years of development.[72] MakerBot sold 10,000 3D printers worldwide in 7 years.[73]

Scaling production requires balancing price and quality, and benefits from opportunities for open participation, as well as community excellence and support. While different drivers of demand are associated with large or small-batch manufacturing priorities, the benefits of low-cost and open source are enjoyed across academic and community-based environments, in a wide range of research and application domains.

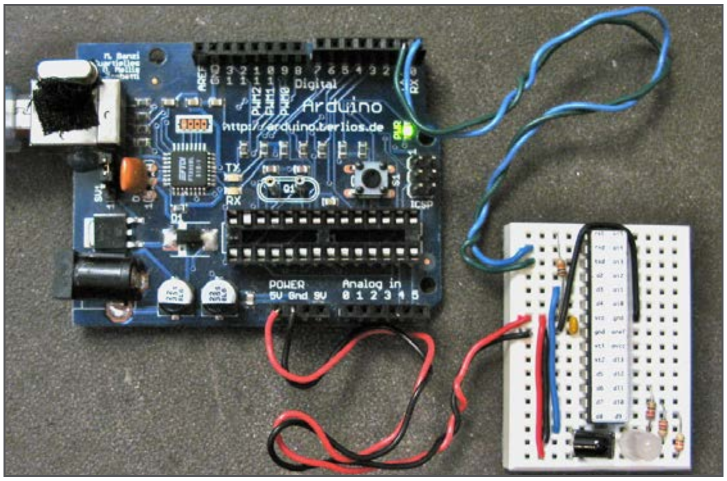

Figure 13. Arduino, one of the first open source hardware companies, has successfully achieved both scale in numbers and in broadened participation ("Minimal Arduino" by todbot is licensed under CC BY-NC 2.0).

Second, low-cost and open source hardware can help scale science by enabling different types of research. Even when low-cost and open source tools produce data at a different quality than traditional devices, they can support distributed and more representative data collection. For example, the use of low-cost, lower sensitivity air quality sensors can produce high resolution pollution exposure maps when sensors are simultaneously deployed in many locations.[74] One National Aeronautics and Space Administration (NASA) supported air quality citizen science project leverages a large network of Purple Air sensors deployed in three regions to validate and interpret satellite observations.[75] Low-cost devices can also serve as early detection or early warning systems, identifying general trends that can be explored more comprehensively by researchers with access to higher-price point tools.

Third, low-cost and open source hardware can enable research and broaden participation through citizen science. The price point of low-cost and open source tools enable individuals and community groups to monitor their environment, while the ability to design and create open source hardware enables ownership, agency, and control. This noted, data quality is an often-articulated concern that has arguably limited progress in certain research and public policy communities.[76] A well-executed strategy of balancing quality and price can help mitigate similar concerns in open hardware for scientific research, along with well-documented calibration strategies, specifications, and adherence to regulatory standards (if any).

Fourth, hardware can offer deep engagement in science and technology. In general, participation in science or technology through low-cost or open source hardware will engage a smaller absolute number of people than software-based approaches like open code or mobile applications. This is due to the increased complexity, level of effort, and cost inherent to the physicality of hardware. But complexity also creates value through deeper engagement in both research and technology development processes.[77,78] The complexity of hardware often requires scientists to learn relevant skills outside their primary field.[79] For example, a neuroscientist may gain skills in electrical engineering and physics while building a sensor to support their research.

Fifth, the unique affordances of open source hardware have additional benefits. The ability to quickly and easily create new tools, including by leveraging building block solutions, promotes new ways of thinking and enables new research questions. Open source tools can be tweaked to support a series of studies approaching a research question from slightly different angles as a research program evolves. Open blueprints give tool owners agency over fixing broken devices.

The transparency associated with open tools also helps scientists understand a tool's capabilities and limitations, thus helping researchers assess the feasibility of various experiments and the implications of different results.[80] Transparency also enables external assessment and supports replicability, thus increasing rigor when similar findings are repeated.

Lastly, open environments are enhanced by shared values and norms. Diverse, well-moderated community platforms can foster interdisciplinary collaboration and interconnectedness between professional and non-professional scientists. Community values and norms around shared innovation and mutual education can help support more socially aware, accountable, and ultimately meaningful science.

Recommendations for Elevating Impact

There are a number of opportunities for taking concrete steps to enable more low-cost and open source hardware for science, and a wide range of stakeholders that can support scaling this emerging research paradigm.

1. **Invest in virtual infrastructure for community collaboration**. Open hardware communities require groupware for tasks including communication and coordination; sharing and commenting; forking and versioning; documenting, and collaborative work. One recent review of five groupware solutions found that, while existing platforms have various strengths and weaknesses, "will create a growing market for new groupware solutions."[81] Such solutions should adhere to common open source hardware norms like transparency, but also meet relevant privacy and security expectations.

2. **Make more commercially-available products available as kits or off-the-shelf solutions**. Although some designers are motivated by the creative challenges of ideation and concept development, others, including scientists, may wish to invest more of their time in using tools. For this reason, scaling open hardware through production requires moving from a primarily Do-It-Yourself (DIY) model to make more commercially-available products available as kits or off-the-shelf solutions. Kits offer an interesting middle ground, and ensure that certain audiences, such as those operating in educational environments, can avoid supply chain limitations while still experiencing opportunities for creativity, self-expression, and learning. Tools such as Arduino that offer blueprints, toolkits, and finished products help ensure that people with different interests and skill sets can access tools in ways that appeal to them.

Figure 14. Open hardware can be scaled through commercially available kits and off-the-shelf products, such as the Balloon Mapping Kit pictured in this image which can be purchased from Public Lab (Image by Public Lab is licensed under CC BY-SA 3.0)

3. **Bridge the gap between ideation and production by fostering partnerships at all stages of innovation**. Many tool designers are unlikely to manufacture at scale due to production costs. Bridging the gap between ideation and production requires understanding and fostering partnerships between funders, designers, and developers on one hand, and manufacturers on the other. Some success stories involve platforms for small batch, on-demand manufacturing like GroupGets. These may be particularly valuable when standards or regulations are not critical concerns. Other success stories include partnerships with organizations like Veteren's Affairs (VA) groups that can manufacture in regulatory grade environments.

4. **Create training around legal issues and IP, as well as funds that specifically target supporting the commercialization of these tools**. Funding gaps exist for tools seeking to move from ideation or concept development to production. Open source tools may especially struggle with funding scale and commercialization as their lack of IP is viewed as risky by investors. Training funders, tech transfer offices, and other key stakeholders on IP and legal implications of the commercial scaling of open source products can help them understand the value of open source tools and better support their commercialization logistically and financially.

5. **Create professional development opportunities for low-cost and open source entrepreneurs**. Many tool designers and developers have ample expertise in creative and technical aspects of design and manufacturing, but lack the business and marketing skills required to successfully bring a tool to market. Programs such as NSF's Innovation Corps (I-Corps) program--which seeks to bridge this gap by offering existing grantees entrepreneurial education, mentoring and funding to further develop their products and attract third-party investments--would be useful for low-cost and open source entrepreneurs.

6. **Advance work on standards, including standards and certifications for open source hardware, and guidelines specific to different research domains**. One limitation of small batch production is that custom or DIY tools may align most closely with the concept development phase of the innovation funnel. This means that engineering and validation have not been completed, and alignment with regulatory requirements and standards cannot be assumed. Developing easily accessible guidelines on the approaches and standards relevant to a particular research area will help designers and manufacturers ensure that the desired impacts of a tool can be achieved. Attention to open standards and certification processes can also help assess, and amplify, the value of uniquely open source hardware approaches.

Through these recommendations and others, the value of low-cost and open source hardware may be more fully realized, in its capacity to both accelerate scientific progress and democratize research by broadening who can participate. By taking opportunities to support the scale of low-cost and open source hardware, ranging from IP to infrastructure, the true potential of these scientific tools to reach a larger and more diverse, participatory audience can be realized, innovating a more inclusive, impactful, and efficient paradigm along the way.

ENDNOTES

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