Building Blocks for Better Science:

Case Studies in Low-Cost and Open Tools for Science

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Wilson Center

Science and Technology Innovation Program

ALFRED P. SLOAN FOUNDATION

THING tank understanding low cost tools for science

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About the Authors

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Foreword

Foldable and 3D printed microscopes are broadening access to the life sciences, low-cost and open microprocessors are supporting research from cognitive neuroscience to oceanography, and low-cost sensors are measuring air quality in communities around the world. In these examples and beyond, the *things* of science – the physical tools that generate data or contribute to scientific processes – are becoming more inexpensive and more open.

As more tools become available at a price point that is do-able for non-professionals, the nature of access and use is changing. Like many consumer goods, innovation and competition are driving down price. The impact of dramatic decreases in cost are easily apparent in examples such as developer boards like Raspberry Pi and Arduino, and low-cost sensors for air quality such as Purple Air.[1] Many tools are incrementally more accessible simply due to decreased cost; others are sold at a cost so dramatically reduced that they may even be changing the nature of science itself (Appendix A).

As more people share designs openly or create do-it-yourself (DIY) tools as a substitute for expensive, proprietary equipment, the nature of tool design and production is also changing. The Open Source Hardware Association defines open source hardware (also known as open hardware, and including open science hardware) as "a term for tangible artifacts – machines, devices, or other physical things – whose design has been released to the public in such

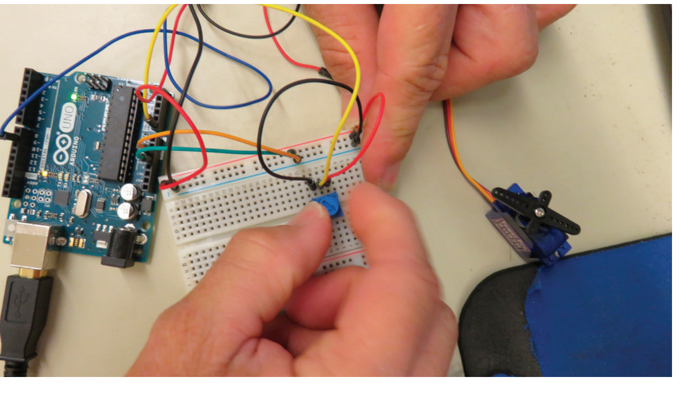


Image: "Make Your Own Arduino Project" by fabola is licensed under CC BY-SA 2.0

…the *things* of science – the physical tools that generate data or contribute to scientific processes – are becoming more inexpensive and more open.

a way that anyone can make, modify, distribute, and use those things." Open practices include *product openness*, or aspects of tools that allow for public sharing of documentation, and *process openness*, or "enabling participation of external people in the design process."[2,3] Open practices for hardware overlap extensively with those for software, including drawing on – and contributing to – Open Source Software (OSS) practices and licenses.

Moreover, many low-cost and open tools contribute to and intersect with open practices in scientific research. They often produce open data, and encourage its use. They can enable citizen science, community science, and other participatory approaches that seek to broaden public participation in, and access to, the scientific enterprise. Perhaps most importantly, tools – as well as the research they enable – are not just developed by and for the professional scientific research community, but by a wide range of commercial, academic, nonprofit, and community enterprises operating at a range of scales.

Image: Dave Bakker, PocketLab, all rights reserved, used with permission.

Introduction to the Case Studies

Here, we outline 16 tools for science that are causing us to rethink the boundaries of scientific research. We include both low-cost tools and open tools, recognizing that these categories often intersect; some low-cost tools are developed and shared using open practices, and open tools tend to be cheaper than proprietary alternatives.[4] Looking across these tools and their individual impact on science and society, we begin to ask questions about their collective impact. How do low-cost tools impact science? Do these tools accelerate scientific progress or expand access, and to what extent? Finally, is the impact – and potential impact – of these tools incremental, or potentially revolutionary?

We also begin to examine the unique value of open practices in this context. How important is openness? Do open practices accelerate progress or expand access, and to what extent? Finally, is the impact – and potential impact – of open tools incremental, or revolutionary?

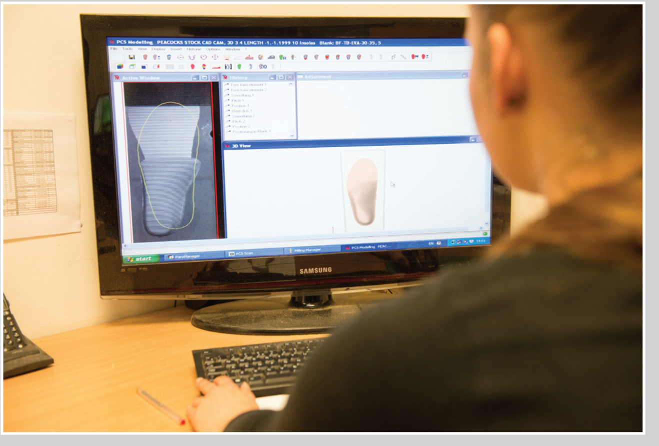
Image: "2012-12-07" by Taema is licensed under CC BY-NC-SA 2.0

A Note on Open Practices

Open practices describe practical ways that tool developers can enact ideals of openness including the right to "study, modify, make and sell" the design or tool. These open practices include making available and editable documentation files such as CAD files, assembly instructions, and bills of materials, and the use of open licenses, including those that allow for commercial use.[5] The Open Source Hardware Association (OSHWA) certifies products that include open documentation and have open licenses. Beyond product openness, process openness is often enacted via an open call for contributions or clearly stated guidelines for contributing to a tool's design or development.[6] Many tools also produce open data, and build communities around sharing and using open data.

In this publication, when we found evidence of these open practices, we include a check mark (☑) next to one or more of the following:

- ☑ Documentation available
- ☑ Documentation editable
- ☑ Open license
- ☑ Open process
- ☑ Open data



These elements of openness are adapted from those described by Bonvoisin and Mies, 2018, with the addition of open data.[7]

Importantly, we included a check mark when there was any indication of their use, even when the terms described by Bonvoison and Mies and others were not fully met.

Open licenses grant permission for the use of a work, and allow the creator to specify how they would like their intellectual property to be used, re-used, modified, and shared. Some open licenses can be used for a wide range of creative work (e.g. the Creative Commons suite of licenses). Others were created for use with open source software (e.g. the GNU General Public License, Apache). Still others were designed specifically for use with hardware (e.g. the CERN Open Hardware License). These licenses vary in whether they restrict or allow commercial use, sharing of modifications, and/or if they require that the same or similar license is applied to derivative work (i.e. share-alike, or copyleft). Licenses used by the tools documented in these case studies include: Creative Commons Attribution (versions 3.0 and 4.0, including ShareAlike and NonCommercial), the GNU General Public License (GPL), Apache 2.0, and the CERN Open Hardware License.

Image: "Young female textiles technician creating bespoke insoles for people with medical conditions" by This is Engineering image library is licensed under CC BY-NC-ND 2.0

1 Although some do not consider restrictions on commercial use (e.g. CC BY NC) to be fully "open", we include non-commercial licenses as open licenses here.[8,9]

Case Studies

1

Arduino

At a glance:

Field of application: Electronics, multidisciplinary

Year initially developed: 2005

Description: Arduino is a company that designs and manufactures low-cost, single-board microprocessor and microcontroller kits. These electronics can read inputs (e.g. a signal from a sensor) and transmit them into an output (e.g. turning on a light). The devices are easy to use and compatible with various operating systems. The electronics platforms can be purchased from Arduino as do-it-yourself (DIY) kits or full, pre-built products. Individuals can also make their own devices with the publically available design files.

Arduino is known for being one of the first widespread and successful open hardware projects. As a result, Arduino electronics platforms have been key to the maker movement and are used in a diverse range of projects, ranging from education to music to professional engineering.

Fun fact: Arduino was named after a bar named after an Ivrean King.

Website/contact: https://www.arduino

Analysis:

How was the tool developed? Who was and is involved? Arduino was initially developed as a master's student project at Interaction Design Institute Ivrea (IDII) in Italy. Arduino was designed for students who had little experience with electronics and programming, although now users have expanded beyond students to hobbyists, professionals, artists, and much more. The developers opened up the hardware and software to the public,

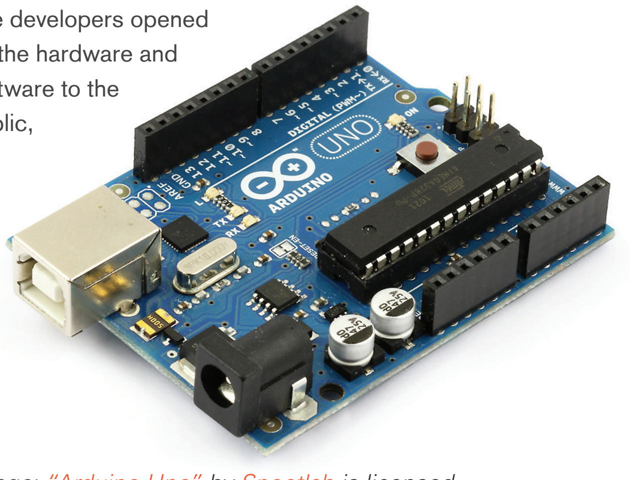


Image: "Arduino Uno" by Snootlab is licensed under CC BY 2.0 allowing for a large number of communities to debug codes, edit design files, create tutorials, and build community with other users.

Elements of Openness

- ☑ Documentation available
- ☑ Documentation editable
- ☑ Open license
- ☑ Open process

The hardware documentation can be found for each device in the store section of the Arduino website and under the documentation drop down. The hardware files are licensed under a Creative Commons Attribution Share Alike license. However, Arduino suggests only experienced makers create a device from scratch. The software documentation is found on GitHub and is licensed to be accessed, modified, and reproduced. There is also Arduino at Heart, a Brand License agreement for products that want to be recognized as an Arduino-based technology.

Arduino holds no patents. Contributions guidelines to code and hardware are highlighted on the website. Finally, Arduino has multiple open source platforms to share projects and tutorials, such as Project Hub, Arduino Forum, and an Arduino wiki.

What makes the tool low-cost?

Even pre-assembled Arduino boards cost less than $50.

In what ways is this tool accelerating science, enabling evidence-based decision making, or broadening participation in science?

Arduino was one of the first widespread open source hardware tools. By the founders' eagerness to collaborate with community members, Arduino demonstrated that the open source model can accelerate technological innovation and that low-cost and open source can be a profitable business model for hardware.[10] Due to its low-cost, ease of use, and compatibility, Arduino helped spark the maker movement and broadened participation in science by making electronics more accessible to non-engineers. With applications such as Complubot, a microprocessor robot designed by kids for STEM education purposes, aerial vehicles for bat research, and devices for water quality studies, Arduino is enabling science all over the world.

Plantower

At a glance:

Field of application: Sensors, environmental, health

Year initially developed: 2014

Description: Plantower is a company that creates low-cost air quality sensors that are commonly used in affordable air quality devices, such as Purple Air, Public Lab's Simple Air Sensor, and the Air Quality Egg. The sensors detect levels of particulate matter (PM), a type of harmful air pollution caused by small solid and liquid particles suspended in the air. Plantower uses laser scattering techniques to measure the sizes and concentration of particles. They also sell sensors for formaldehyde gas and carbon dioxide. The sensor can stream data in real-time and is compatible with various types of instruments. All sensors can be purchased online.

Website/contact: http://www.plantower.com/

Analysis:

How was the tool developed? Who was and is involved? The tool was developed by Beijing Plantower Co. They receive venture capital funding.

Elements of Openness

Basic schematics, technical specifications, and explanations of the particulate matter sensors can be found online. The hardware and software design files are not publicly available. It does not have an open hardware license.

What makes the tool low-cost? The tool has PM sensors (PMA003) that cost about $34 in 2018.[11] This is low cost compared to personal PM sensors such as PDR-1200 from Thermo Fisher Scientific ($6000) or the EPA approved MetOne BAM - 1020 ($12,000 to $21,000).[12]

In what ways is this tool accelerating science, enabling evidence-based decision making, or broadening participation in science?

The low cost and functionality of Plantower enables the development of accessible air quality sensors that provide quality data in real-time. By driving down the cost, Plantower is changing who can take part in the collection of air quality data and is increasing the availability of air quality data. For example, the Air Quality Egg, which uses Plantower sensors, is being used by citizen scientists in Colorado to figure out the source of air pollution in their community.[13] Plantower is also used by Purple Air to make air quality data publicly accessible on the online map. PocketLab illustrates how Plantower can be used to teach students about air quality and data analysis. Plantower's widespread use proves it is a key building block for air quality research and environmentally-informed communities around the world.

Image: "SCK 2.1 Particle Sensor" by smartcitizen is licensed under CC BY-NC-SA 2.0

RepRap

At a glance:

Field of application: Manufacturing tool, multidisciplinary

Year initially developed: 2004

Description: RepRap, which stands for **Rep**licating **Rap**id-Prototyper, was the first low-cost, open source 3D printer and has become the most widely used printer in maker communities across the globe. The small desktop 3D printer has the ability to replicate itself. Users can make the tool using the publicly available design files, or purchase a full kit or individual components. The original printers used plastic; newer versions have expanded the types of materials that can be used.

Fun fact: RepRap was inspired by mutualism, the symbiotic relationship where two species equally benefit from each other. In this case, people will build in return, the printer will print parts for the people. The names of different RepRap printers, such as "Darwin," "Mendel," and "Huxley," are named after famous biologists.

Website/contact: https://reprap.org/wiki/RepRap

Analysis:

How was the tool developed? Who was and is involved? RepRap was initially developed at the University of Bath, inspired by Dr. Adrian Bowyer's interest in self-replicating machines and by the versatility of 3D printers. Because patents would inhibit the

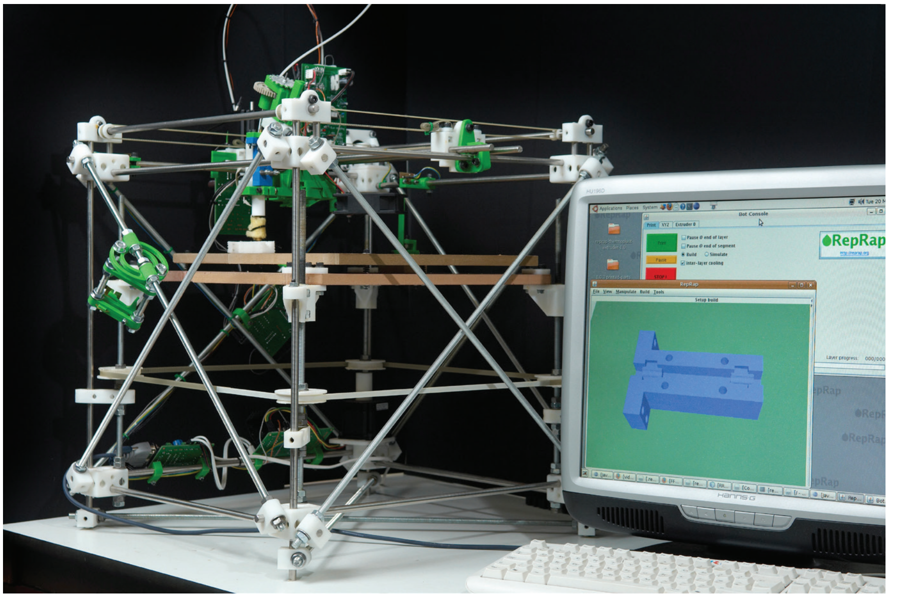


Image: Dr. Adrian Bowyer, all rights reserved, used with permission.

nature of self-replicating machines, the documentation for the tool was made publicly available from the start. The interest in the project skyrocketed and people began volunteering to help after the story of RepRap was covered by the press around the world. This led to a group of 16 principal collaborators as well as a broader global community of professionals and amateurs contributing their expertise to the tool's development. The community provided recommendations, resolved problems, and even created alternative designs, all under the single piece of guidance that everything be made open source. Despite "lots of failed experiments" in the development of the tool, Dr. Bowyer attributes the success of the tool to the support from the greater RepRap community. According to Dr. Bowyer, "There was never a point when we were stuck. If x didn't work we still had y and z to go back on".[15]

The tool development was supported with funding from the UK Engineering and Physical Sciences Council. Dr. Bowyer and collaborators developed and produced the RepRap machine for less than $40,000 - the full cost of a 3D printer at the time.[16]

Elements of Openness

- ☑ Documentation available
- ☑ Documentation editable
- ☑ Open license
- ☑ Open process

Hardware and software documentation can be found on the Build a RepRap page as well as GitHub along with instruction manuals, all clearly labelled and available. The software and hardware of RepRap are licensed under the GNU General Public License (GPL). Additionally, RepRap suggests that people license their hardware under the GPL or Creative Commons Licensing. The RepRap website clearly outlines the openness policies, missions, and best practices for contributing. All page activity is logged publicly for users to see. Finally, designs for printing certain projects can be uploaded onto the RepRap

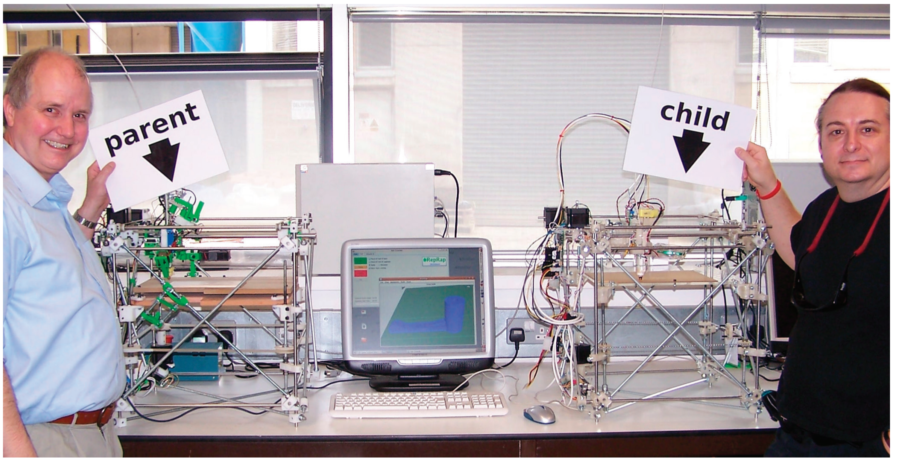


Image: Dr. Adrian Bowyer, all rights reserved, used with permission.

"In any sort of science, you need a physical kit of some kind. Suddenly there was the ability to have it, and in a customized way." — *Dr. Adrian Bowyer, RepRap*[14]

wiki for public access, and ideas can be shared in RepRap forum.

What makes the tool low-cost? The prices for RepRap range from $300 to $620 depending on what level of "DIY" the user wants. When first created, the cost of materials for one RepRap was 100 times lower than the price of 3D printers of similar quality at the time, which was approximately $40,000 USD (note, however, that the cost of materials does not include the cost of labor).[16] Once a printer is produced, another one can be printed essentially for free, with just a few low-cost parts and printing materials.

In what ways is this tool accelerating science, enabling evidence-based decision making, or broadening participation in science? RepRap was the first open source, desktop 3D printer. The price point and the tool's ability to self-replicate has made it one of the most widespread 3D printers, with over 30,000 printers purchased between 2004 to 2014.[17]

Many companies use RepRap printers, such as Prusa, one of the largest 3D printer producers in the world and a preferred brand of FabLabs, a large and impactful network of makerspaces. In addition to FabLabs, RepRap's accessibility has made it an integral tool to the broader broader maker community and DIY movement.

RepRap enables access to 3D printing in a large number of scientific labs around the world, including in low- and middle- income countries. RepRap allows researchers to produce customized lab equipment and tools that would not be commercially viable and low cost. For example, it has been used to 3D print laboratory research equipment such as low-cost microscopes (e.g. OpenFlexure) or a low-cost syringe pump which is used in a variety of research activities to administer precise amounts of liquids.

MakerBot

At a glance:

Field of application: Manufacturing tool, multidisciplinary

Year initially developed: 2009

Description: Inspired by the RepRap project, MakerBot was one of the first companies to make accessible and affordable desktop 3D printers. Currently, the MakerBot printers are designed for professional manufacturing, design, and educational applications and can be purchased as pre-built, full products. The original tool, however, was available as a DIY kit. The latest tools can print complex geometries with plastic along with advanced materials, such as carbon fibers and resin. Additionally, MakerBot created Thingiverse, the largest online 3D design community.

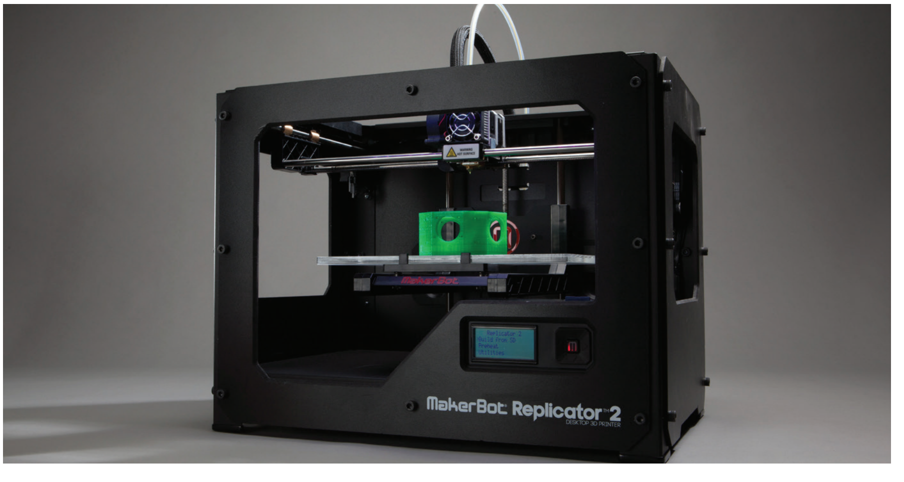
Website/contact: https://www.makerbot.com/

Analysis:

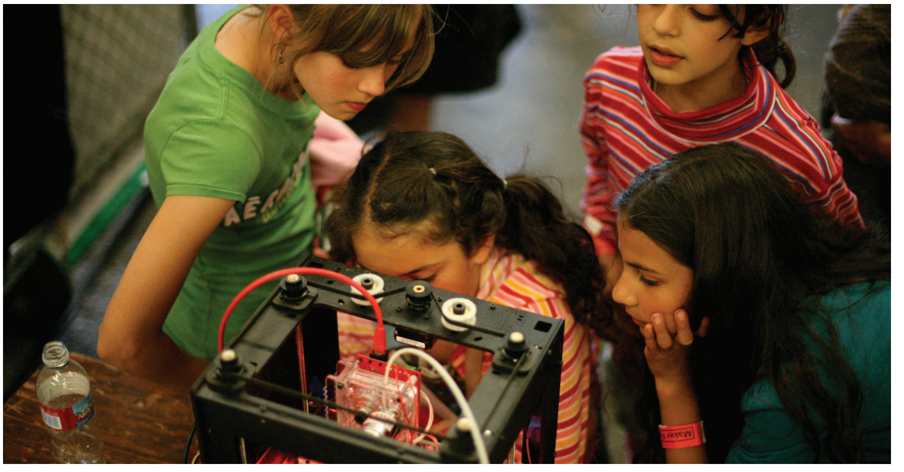
How was the tool developed? Who was and is involved? MakerBot's first 3D printer, the Cupcake CNC, was developed in the NYC Resistor Hackerspace. The founders were inspired to contribute to the RepRap team's mission to create a low-cost 3D printer for anyone. Seed funding came from private donations, including a $25,000 donation from the founder of RepRap. Cupcake CNC was sold as a DIY kit. Community members largely contributed to the development of this tool, even printing specific components for kits with their own MakerBots when consumer demand peaked. After MakerBot released its first pre-assembled, low-cost printer, the design was copied and almost sold under a different name. This incident led to MakerBot discontinuing its open source model.[19]

Elements of Openness

The early 3D printers from MakerBot were developed using open practices



Images: "Makerbot Industries - Replicator 2 - 3D-printer 05" by Creative Tools is licensed under CC BY 2.0



Images: "Chiildren checking out the MakerBot at Maker Faire." by bre pettis is licensed under CC BY-NC 2.0

and with participation from the community. In 2012, MakerBot no longer supported its open source model and the current models do not have an open source license but are patented.[20] MakerBot's design platform Thingiverse is open to the public so that people can create, share, provide feedback, and discover 3D printing designs. The website encourages the use of Creative Commons licenses for posted designs.

What makes the tool low-cost? The lowest cost professional desktop 3D printer is $3,499.30 and the lowest cost educational 3D printer is $1,799. Although there are desktop printers that are more affordable, the functionality of these printers at this price point make them a low-cost tool. Both of these printers sit on the lower end of professional/performance printer prices.

In what ways is this tool accelerating science, enabling evidence-based decision making, or broadening participation in science? MakerBot has contributed to a number of milestones in 3D printing. MakerBot broadened participation in innovation by creating some of the first affordable desktop 3D printers. These tools made the method of 3D printing a well known term, shifted the perception of 3D printing from an industry tool to a "household" tool, and was key in the development of the maker movement. The low-cost and modular features of the professional printers enable scientists to experiment with advanced printing materials in an accessible and customizable way, advancing the field of industrial grade printing. The education printers have encouraged early learning opportunities in design thinking and 3D printing. Finally, Thingiverse is one of the most widely used open design platforms by makers and the open source community, with over 8.5 million downloads between 2008-2012.[21]

Foldscope

At a glance:

Field of application: Laboratory equipment, education, multidisciplinary

Year initially developed: 2014

Description: Foldscope is an ultra-affordable, portable paper microscope that was developed to democratize science access. The tool can reach the magnification and resolution of conventional microscopes, but only costs $1 in parts to make. In addition to its low cost, these tools are lightweight and durable. In fact, the Foldscope can be dropped from a building and stepped on without breaking. Foldscope can be purchased as a DIY kit. These microscopes have been used by over 1 million people for many applications around the world, particularly in low- and middle- income countries. Some examples of applications include science education workshops in Peru, pest detection for local agriculture in India, and biodiversity monitoring in India.[22, 23, 24]

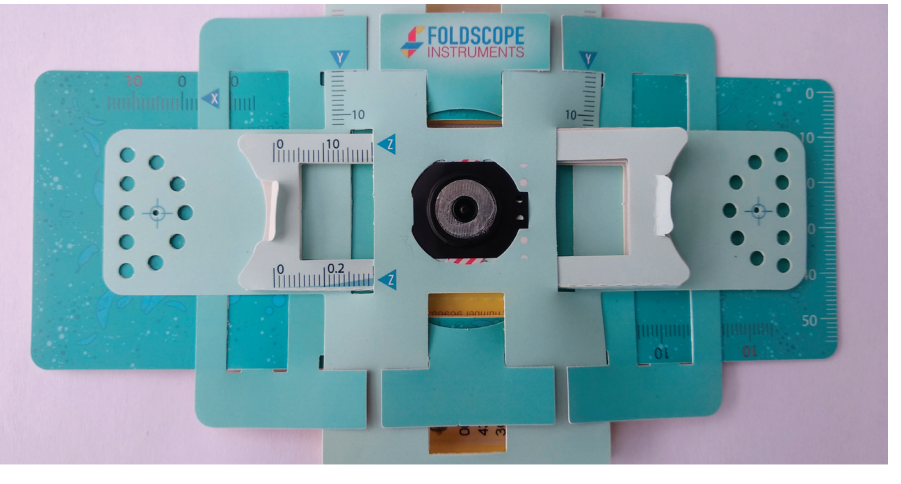
Website/contact: https://www.foldscope.com/

Analysis:

How was the tool developed? Who was and is involved? The tool was developed in the Department of Bioengineering at Stanford University, after researchers observed a lack of functional, affordable, and transportable microscopes during field work in low and middle income countries. They launched a pilot program, mailing 60,000 Foldscopes to 130 countries to test the prototypes, mostly on a volunteer basis. The pilot program was funded by the Gordon and Betty Moore Foundation and the Spectrum-Stanford Clinical and Translational Science Award from the National Institutes of Health.

Elements of Openness

- ☑ Documentation available
- ☑ Open process
- ☑ Open data



Images: "File:Aufgebautes Foldscope.jpg" by Sockenpaket is licensed under CC BY-SA 4.0

The academic papers are open access and include important design documentation and assembly instructions.[25] The tool itself is patented, however, Foldscope Inc. collaborates with a large number of industry, non-profit, and community organizations.[26] Foldscope's website has a large number of open access resources including user guides, tutorials, lesson plans, and workshops. Additionally, on the Microcosmos platform, Foldscope owners can collaborate and share ideas, observations, tutorials, and information about data collected with Foldscopes.

What makes the tool low-cost? The cheapest kit is $29.99, in comparison with microscopes with similar resolution that cost about $2,000.

In what ways is this tool accelerating science, enabling evidence-based decision making, or broadening participation in science? As "the pencil of microscopy," the Foldscope's price and portability broaden participation and accelerate science by making a microscope a tool that virtually anyone can own and carry around in their day to day activities. This is changing how and where microscopy is being done, as well as who is taking part. Reaching over 135 countries, the Foldscope is globally breaking down barriers in science education, healthcare, and research.

Images: "Foldscope India - A DBT-Prakash Labs initiative" by IndiaBioscience is licensed under CC BY-NC-SA 2.0

OpenFlexure

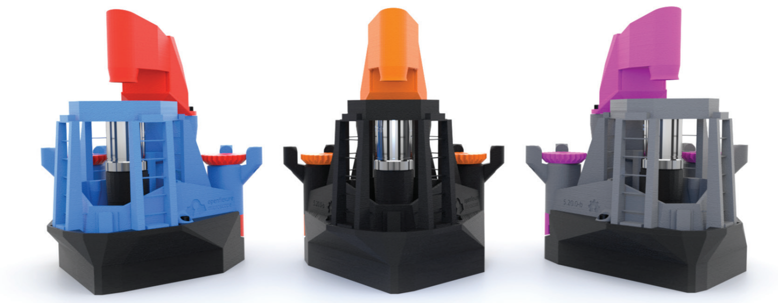


Image: OpenFlexure Microscope by the OpenFlexure Project is licensed CC BY

At a glance:

Field of application: Laboratory equipment, multidisciplinary

Year initially developed: 2016

Description: OpenFlexure is a 3D printed microscope with high precision mechanics, whose creation was inspired by the RepRap project. The tool can use either traditional microscope objectives or a Raspberry Pi camera as the optics lens. The tool can be built for a low cost from design files available to the public; the assembly uses a minimal number of parts. The tool is also easily modifiable. Achieving submicron stage precision and resolution of a conventional microscope, the microscope can be used for education or research, and is undergoing trials for use in healthcare.[28]

Website/contact: https://openflexure.org/

Analysis:

How was the tool developed? Who was and is involved? The idea for OpenFlexure was born when Dr. Richard Bowman at the University of Cambridge was shown a 3D printed microscope and thought "I could print more of a microscope than that!"[29] The development of a fully 3D printable microscope began then, with the goal to make microscopes more accessible to research institutions and schools in low- and middle- income countries. Since 2017, the tool has been co-designed by the University of Bath, STICLab, and SMEs in Tanzania. Other contributions have come from other research institutions, non-profits, and the wider open source community. The tool was funded by a variety of organizations, including the UK's Engineering and Physical Sciences Research Council, the University of Cambridge and Bath, The Royal Society, Royal Commission for the Exhibition of 1851, and the MRC Confidence in Concept award. OpenFlexure's tools are used in all parts of the world, with exploration into potential applications such as detecting bacteria contamination in water or diagnosing malaria.

Elements of Openness

- ☑ Documentation available
- ☑ Documentation editable
- ☑ Open license
- ☑ Open process

All the hardware and software files are clearly labelled and found on the OpenFlexure website. The hardware documentation is licensed with the CERN Open Hardware License. The software also has an open license so

“The frustration of needing to replicate an entire design to change one tiny little thing… how many times has the taxpayer paid to develop the microscope?” — *Dr. Julian Stirling, University of Bath and OpenFlexure Project*[27]

it can also be accessed, modified, and reproduced. Additionally, OpenFlexure’s forums and community page allow builders to collaborate “in an open, searchable way” that makes it easier to resolve problems and share ideas.[30] Contribution guidelines are clearly outlined.

What makes the tool low-cost? The cost of parts is estimated at $20 for an educational microscope, and $200 for a research grade version (note, however, that the cost of materials does not include the cost of labor). Research grade microscopes can cost £30,000 (approximately $39,000 USD).

In what ways is this tool accelerating science, enabling evidence-based decision making, or broadening participation in science? OpenFlexure allows scientists to easily build their own high-performance, low-cost microscopes, differing from other 3D printed microscopes that tend to be complicated to build and have low mechanical stability. As the design is open and modular, users can customize their tools, such as switching to a higher quality lens if higher resolution is needed. For example, the Public Lab platform hosts a microscope that is partially based on the OpenFlexure design but customized for environmental monitoring. Because most parts are 3D printed, “if you can build it locally, you can mend it locally,” avoiding the need for expensive service contracts.[31] OpenFlexure accelerates science by reducing financial and technical barriers to access high quality microscopes; OpenFlexure has been used on all continents including Antarctica, and has even been in low-earth orbit.

Image: OpenFlexure Microscope by the OpenFlexure Project is licensed CC BY

PyCubed

At a glance:

Field of application: Aerospace

Year initially developed: 2019

Description: PyCubed is a low cost, DIY CubeSat, a small satellite for low earth orbit. It can transmit radio signals back to earth, such as a personalized message or collected magnetic field data.[33,34] In the future, the tool could be used to carry sensors for the collection of distributed data on space weather.[35] PyCubed integrates complicated-to-build hardware to be easy to use, setting it apart from other DIY CubeSats. These tools are programmable using Python, the fastest growing coding language.[36] Though the tool is still a prototype, anyone can purchase parts to make their own. PyCubed's avionics were first used in the KickSat-2 spacecraft launch in early 2019. PyCubed is scheduled for two additional missions in December 2020.

Website/contact: http://pycubed.org

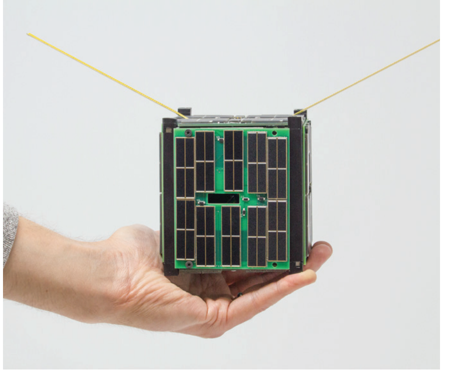


Image: Dr. Zac Manchester, all rights reserved, used with permission

Analysis:

How was the tool developed? Who was and is involved? The first generation of the PyCubed small satellite family, the KickSat, was a CubeSat that used ultra-small "cracker sized" satellite chips. It was developed at Cornell University with support from a Kickstarter campaign and collaborations with National Aeronautics and Space Administration (NASA) Ames and NASA's CubeSat ElaNa Launch Initiative. Due to the extremely small size of KickSat, further launches and development of the tool were restricted by Federal Communications Commission (FCC) regulations. An extension of the KickSat project, PyCubed was developed in the Aeronautics & Astronautics department at Stanford University. Adafruit Industries was a key collaborator in its development, helping PyCubed adapt their microcontrollers to Python.

PyCubed is used by students and researchers, and graduate students contribute to its continued development. Dr. Manchester describes how "You get a different level of engagement [from students] when the thing you build is going into space."[37] Hackathons, Maker Faires, and user suggested experiments were key in the development of both tools.

> **“If satellites were the price of a smartphone, what would it lead to?”**
> ***— Dr. Zac Manchester, PyCubed***[32]

The PyCubed platform has also been adapted to an emerging size-class of spacecraft: the PocketQubes. At $5cm^3$, PocketQubes are considered the smallest satellite ever. However, the PocketQube currently may not be flown from the US due to regulatory barriers.

Elements of Openness

- ☑ Documentation available
- ☑ Documentation editable
- ☑ Open license
- ☑ Open process

Hardware and software documentation can be easily found and is clearly labeled both on the website and GitHub. The software and hardware are licensed under the Creative Commons Attribution 4.0 International License. Additionally, instructions and troubleshooting forums to support building PyCubed are included in the resource page. The publications for PyCubed are also publicly accessible.[38]

What makes the tool low-cost?

The tool can be built by purchasing PyCubed parts for about \$200 to \$300 (note, however, that the cost of materials does not include the cost of labor). A typical DIY CubeSat can cost up to \$20,000. Non-DIY CubeSats can be purchased and launched for between \$50,000 to \$1,000,000.[39]

In what ways is this tool accelerating science, enabling evidence-based decision making, or broadening participation in science?

Most DIY CubeSats built from scratch have a 60% failure rate. By integrating complicated electronics and mechanical hardware, PyCubed provides an “off-the-shelf” CubeSat platform which addresses hardware failures and can take two years off of the usual build time. The use of Python to control the hardware is enabling, as Python is easy to set up and use compared to other software. By reducing the technical as well as cost barriers to CubeSats, PyCubed has expanded participation in space innovation and exploration from government organizations to universities to industry. PyCubed serves as an engaging education tool in more than 10 university groups, increasing interest in space and science. With the goal of carrying sensors in the future, PyCubed is promising to change how space data is being collected, in particular by expanding the ability to collect distributed, spatial information.

The impact of PyCubed has extended outside the field of aerospace. The device was reconfigured to serve as an IoT device for monitoring ammonium concentrations in water; the device won the grand prize at the Keysight Technologies' IoT Innovation Challenge. Max Alvarez Holliday explains how modularity can expand impact, commenting "If you have the hardware & tools around, you can use them to address any problem in front of you."[40]

Interorbital Systems (IOS) TubeSat Kits

At a glance:

Field of application: Aerospace

Year initially developed: 2009

Description: The TubeSat is the lowest cost professional grade SmallSat. Unlike a traditional CubeSat, the TubeSat 1.0 had a tubular hexadecagon shape and TubeSat 2.0 has an icosagon shape. The tool can be purchased as a DIY kit that comes with all circuits and components pre-soldered, making it easy to assemble. TubeSat also receives many requests and provides a great deal of support for customization. TubeSats, like CubeSats, can be used for Low Earth Orbit space exploration, experiments, spacecraft design lessons, the transmission of personal messages, monitoring migrating animals, and many other applications. IOS also provides a CubeSat 2.0 kit.

Website/contact: https://www.interorbital.com/Cubesat%20Kits

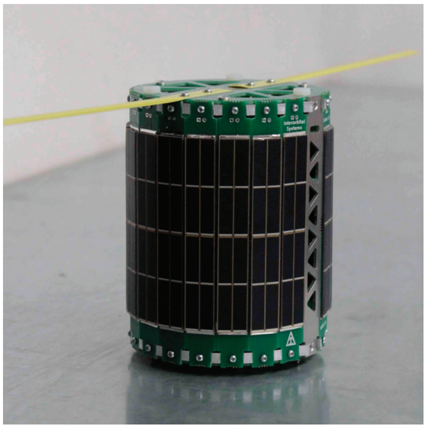


Image: Interorbital Systems, all rights reserved, used with permission

Analysis:

How was the tool developed? Who was and is involved? The concept of TubeSat was developed by two satellite scientists at Interorbital Systems (IOS). They were inspired to create a satellite kit that differed from a traditional CubeSat and that could populate IOS' rocket launches. TubeSat 2.0, the most recent version of the tool, was designed based on customer feedback from the original version, and is more accessible, easier to use, customizable, lighter, and stronger than TubeSat 1.0. IOS has received funding through commercial sales and awards such as the National Aeronautics and Space Administration (NASA) Small Business Innovation Research award.[42] The tool is used for numerous applications and by "customers ranging from students through professionals," including individuals, small labs and universities, NASA and research organizations, private entities, musicians and artists, advertising companies, and a cluster of small countries' space programs.[43]

Elements of Openness

When the kit is purchased, the customer receives all the necessary parts and instructions to build the spacecraft. Hardware and software files are not publically available, however, customers can have access to all design files,

> “We wanted to give satellite-makers an affordable space-rideshare opportunity that, before the emergence of our kit-and-launch program, was wildly expensive and extremely hard to find.” — *Randa Milliron, Interorbital Systems*[41]

schematics, and circuit details on request. They are free to modify it for their use as long as the core files are not distributed. The tool does not have an open hardware license. When TubeSat 1.0 was developed, IOS provided a forum for customers to ask questions and share ideas. Interorbital is creating a similar forum for TubeSat 2.0 and is considering adding an open satellite kit to its STEM-product line in the future.[44]

What makes the tool low-cost? The TubeSat 2.0 is the lowest-cost professional full-scale CubeSat Small-Sat kit. It costs $6,200 for a kit and $12,400 for a kit with launch included. Costs for typical CubeSats and launches can be $50,000 to $1,000,000.[45] When completed, these kits will fly on IOS's NEPTUNE Rocket – the core launch vehicle in the world's least expensive rocket and spacelaunch service.

In what ways is this tool accelerating science, enabling evidence-based decision making, or broadening participation in science?

TubeSat's low cost has made it "an entry point for people to begin to do space science".[46] In addition to its low cost, the use of pre-soldered circuit boards and the Arduino coding platform, TubeSat reduces technical barriers to building larger and more complex satellites. By providing access to the design files, builders and makers of the kit can learn the science behind the device, customize the tool to their own needs, and thereby build "not only a satellite, but also a more robust and better-educated Small-Sat community."

The modular, customizable rockets used to launch TubeSats decrease the cost of launch services, making it more financially feasible to launch what IOS calls 'the ultimate STEM tool.' The first TubeSat was built and launched by a group of middle-schoolers in rural Brazil. They launched their TubeSat on an H2 rocket in Japan and sent out a message of peace. It was the first TubeSat in orbit.

Quori

At a glance:

Field of application: Robotics, computer science, social sciences

Year initially developed: 2015

Description: Quori is an innovative, affordable, socially interactive robot platform for enabling non-contact human-robot interaction (HRI) research in both in-lab and field experimental settings. Quori's human-like, modular features allow for the customization of the hardware and its software is capable of programming various social behaviors. This robot can be used to study topics such as nonverbal communication, social robots for math education, mobility coaching for older adults, and infectious disease treatment. Quori will be used in ten different academic research groups and is currently in the prototype stage of development.

Website/contact: http://www.quori.org/

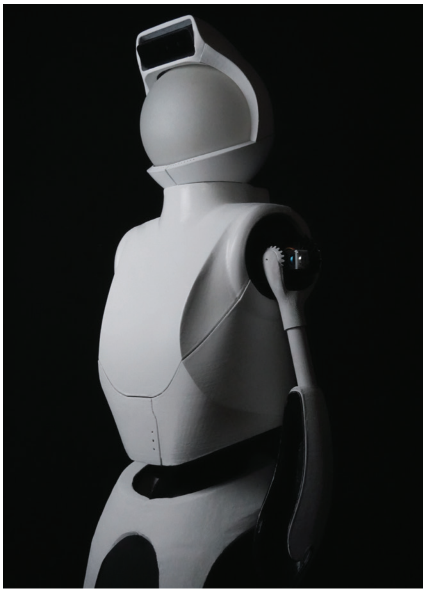


Image: Andrew Matia, all rights reserved, used with permission

Analysis:

How was the tool developed? Who was and is involved? The Quori project began in 2015 as a collaborative effort between research teams at the University of Pennsylvania and the University of Southern California. The research teams surveyed experts in the HRI and computing field as well as presented at workshops to get feedback from the research community. The teams also worked with their industry partner, Semio, to integrate high-level software packages that provide interoperable social behavior APIs and developer tools. The first recognizable Quori was finished in 2018 and had its debut at the Philadelphia Museum of Art in the fall of 2019. The National Science Foundation supports this work under Grant No. CNS-1513275 and CNS-1513108.

Elements of Openness

- ☑ Documentation available
- ☑ Open process

The tool was designed with the participation of the HRI community in important design decisions, such as identifying important hardware functionalities and lowering the cost. Academic design papers are made publically available.[48]

> “[Quori] prevents researchers from reinventing the wheel, when they don’t have to.” — *Andrew Specian, Quori*[47]

Quori does not have an open hardware certification or license, however, some of its software has an open license and is in a repository.

What makes the tool low-cost? The materials cost for the Quori robot are approximately $5,000. Note, however, that the cost of materials does not include the cost of labor. The parts are modular, so the robots can be customized affordably. Other HRI robots on the market such as Nao or Pepper can cost up to $18,000 and are difficult to customize.[49]

In what ways is this tool accelerating science, enabling evidence-based decision making, or broadening participation in science? Current researchers studying HRI have to either spend time “designing a niche tool that is only used once or having to buy an expensive system.”[49] Quori is saving HRI researchers time and money by using low-cost parts and a robust design that allows anyone to customize the robot with a screwdriver. By removing these barriers to advanced HRI research, Quori permits algorithm testing and data collection for the HRI field to be done at a statistically significant level. Quori also provides a standard platform and tool for the HRI community, so that results can be more accurately compared between different research groups. Additionally, Quori is one of the first robots that is “neither generic nor has an intended gender identity”, which can help reduce gender bias for researchers investigating the jobs and roles of robots in the world.[50, 51]

Wearable Symptom Tracker

At a glance:

Field of application: Sensors, health, wearables

Year initially developed: 2020

Description: The University of California San Diego (UCSD) is developing a low-cost wearable device that can track an individual's temperature and respiration metrics, which can detect fever, shortness of breath, and coughing. The purpose for this device is to help people who are at high risk of COVID-19 self-identify their symptoms, in addition to aiding those who are infected monitor their recovery and health needs. The tool can be used to monitor other viral infectious diseases as well. Unlike other temperature and respiration devices, the UCSD's wearable symptom tracker is ultra-low powered, compact, disposable, and collects data in real time. The data is sent to a smartphone or smart watch for monitoring. Though the tool is still a prototype, the team of researchers plans to have the device fully developed by 2021.

Website/contact: http://efficiency.ucsd.edu/

Analysis:

How was the tool developed? Who was and is involved? The tool was developed by Dr. Patrick Mercier at UCSD. His lab studies low powered techniques that do not require batteries, such as wifi, bluetooth, and magnetic fields. In fact, Dr. Mercier holds the world record for the lowest powered temperature sensor in the world, requiring 100,000x less power than a basic

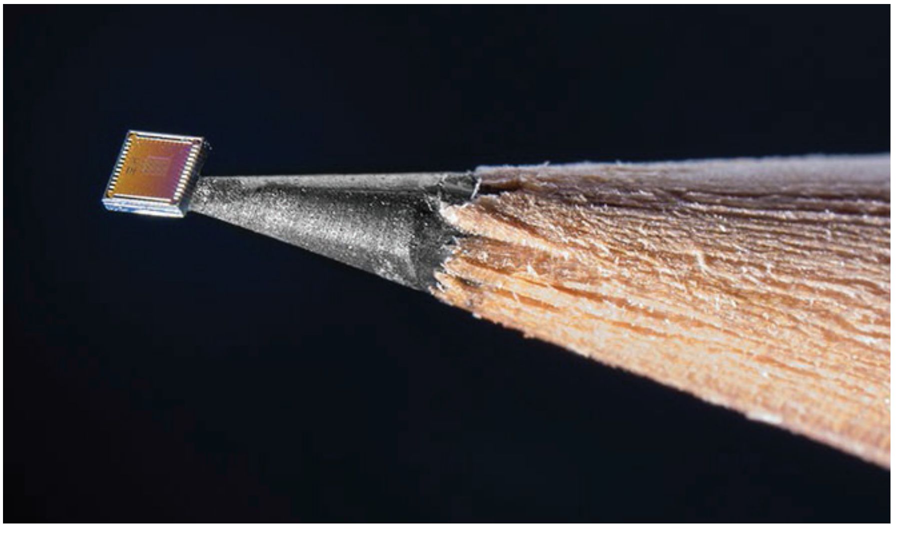


Image: Dr. Patrick Mercier, all rights reserved, used with permission digital watch. After relentless news headlines about COVID-19 testing shortages, Dr. Mercier was inspired to innovate "auxiliary ways to check for symptoms" by combining his low powered temperature sensor with a device to monitor breathing. Since receiving funding for the project from the National Science Foundation (NSF) Rapid Research Response Grant, the lab has developed prototypes of individual components and is working to integrate them.[52]

Elements of Openness

The tool does not use open practices or have an open hardware license. However, the developers are interested in building capacity for users to volunteer their anonymous data to be used in epidemiological research on infection rates.

What makes the tool low-cost? The tool will cost $0.10 per unit to manufacture, as the device does not require batteries. Antigen testing, which similarly provides fast (50 min) feedback, costs $100.

In what ways is this tool accelerating science, enabling evidence-based decision making, or broadening participation in science?

By allowing people to monitor their own symptoms, the wearable symptom tracker changes how infectious diseases "COVID-19 and beyond" can be monitored and provides individuals with data to understand their personal health.[53] The researchers intended the low cost to make the device accessible to those in limited resource settings and allow for the widespread monitoring of viral infections. With large quantities of data on infection rate from the device, this could improve epidemiology research. The success of the device is promising to enable broader adoption of battery-less wearable technologies.

Microplate Flange Replacement

At a glance:

Field of application: Biotechnology, medical, laboratory equipment

Year initially developed: 2014

Description: The Microplate Flange Replacement is a 3D printed replacement rim for a microplate. Hundreds of microplates are analyzed in a robotics system, in a technique called high-throughput screening (HTS), which is used in medical and pharmaceutical research to discover drugs and disease treatment research. The microplates are picked up by the robots at the flange, to be transported to the experiment site. If the flange on the microplates breaks, then the whole microplate holding the experiment and the expensive compounds it contains is discarded.[55] With the Microplate Flange Replacement, microplates can be repaired. This reduces experimental failure due to mechanical issues, avoids having to recreate or purchase expensive compounds, and decreases downtime.[56] This tool is one example among a set of very basic laboratory tools that can be 3D printed and have a huge impact on efficiency. The Microplate Flange Replacement can be made using the publicly available design files found on the National Institute of Health (NIH)'s 3D Printing Exchange.

Website/contact: https://3dprint.nih.gov/discover/3dpx-000368

Analysis:

How was the tool developed? Who was and is involved? The tools were developed at, and funded by, the National Center for Advancing Translational Science (NCATS). Flange breakage had been a problem for years; with access to 3D printing, engineers in the High-Throughput Screening lab invented a replacement flange using 3D printing within a few hours. Although this tool is specifically used by researchers conducting HTS, both general and niche 3D printed laboratory solutions have been invented such as 3D printed gel electropho-

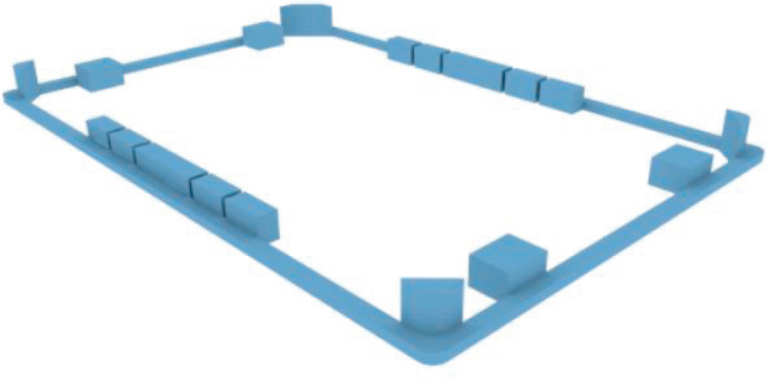


Image: Microplate Flage Replacement by Eric Jones is licensed CC BY NC.

"[It's] a minor piece that's very easy to overlook, but the entire system is contingent upon that working." — *Sam Michael, NCATS*[54]

resis combs, pipette holders, and spider holders.[57] The NIH 3D Print Exchange has been a key community involved in promoting 3D printed laboratory solutions.

Elements of Openness

- ☑ Documentation available
- ☑ Documentation editable
- ☑ Open license

The documentation for 3D prototyping and modeling can be downloaded from the NIH 3D Print Exchange. The tool has a Creative Commons Attribution-NonCommercial License.

What makes the tool low-cost? The compounds in the microplate library at NCATS cost a total of $3 million to produce and purchase. The Microplate Flange Replacement saves money that would be lost due to having to prepare new plates.[58]

In what ways is this tool accelerating science, enabling evidence-based decision making, or broadening participation in science?
The Microplate Flange Replacement is accelerating medical and pharmaceutical research by improving workflow and reducing failure costs of HTS. This enables projects such as discovering methods for treating rare diseases, which is often underfunded or lacks resources, or running preclinical trials on determining drug dosage. This tool also demonstrates how low-cost and open source tools can be customized and even produced on-demand to solve "everyday" science problems and have a lasting impact.

Sofar Ocean: Trident and Spotter

At a glance:

Field of application: Sensors, marine sciences

Year initially developed: Trident, originally known as OpenRov, was developed in 2012. Spoondrift's Spotter was developed in 2016. In 2019, the two organizations merged and became Sofar Ocean.

Description: Sofar Ocean is an organization with a mission to increase scientific knowledge and exploration of the ocean, through affordable and easy to use tools. Spotter is a real-time, solar powered weather sensor for marine environments, e.g. wind, wave, and temperature. All data collected by these sensors is shared using an API and used to model and predict ocean and global climate. Trident is an underwater drone that can be used to visualize the ocean floor, monitor water pollution, identify species, and much more. Both tools can be purchased as pre-built, full products; an older version of Trident can also be made using publicly available design files.

Website/contact: https://www.sofar-ocean.com/

Analysis:

How was the tool developed? Who was and is involved? Spotter was developed by Spoondrift, a Bay Area start-up, in 2016. The development of the tool was funded by the Advanced

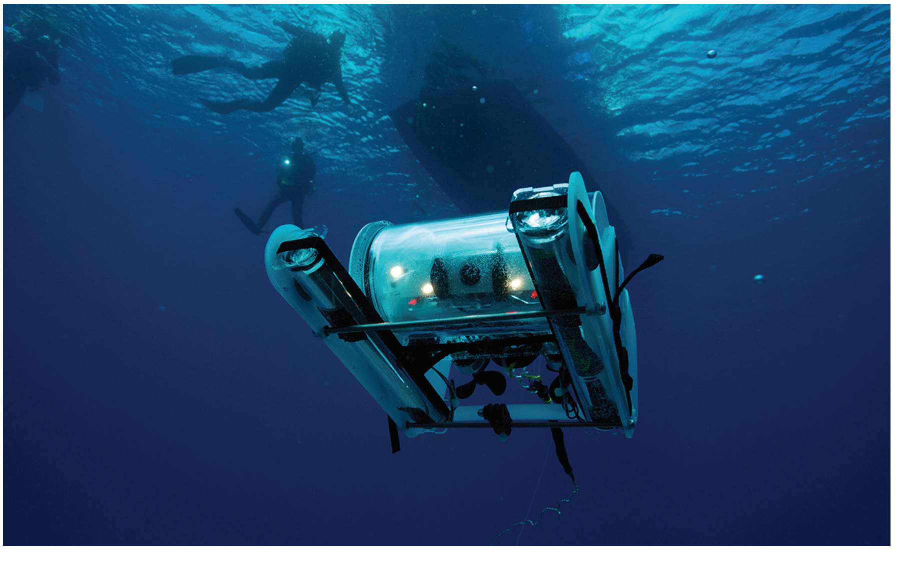


Image: Bristol openrov.jpg by the Octopus Foundation is licensed CC BY

Research Projects Agency - Energy, US Department of Energy.

Originally known as OpenRov, Trident was developed to search for treasure in a cave near its founder's home. Though no treasure was found, the original project quickly attracted an online community of contributors from over 50 countries who were interested in developing the tool. The original Kickstarter campaign was launched as the OpenRov DIY kit, targeted to people with a background in making and product development, as it required advanced skills to assemble.[59] A second Kickstarter campaign was launched with the name Trident with the ability to purchase the tool as a pre-built product.[60]

The two organizations merged to form Sofar in 2019 due to their same interest in open data and tools for the acceleration of ocean research. Both Trident and Spotter are currently used by scientists, engineers, and other ocean professionals. Trident is also targeted for education and hobbyists.

Elements of Openness

Trident:

- ☑ Documentation available
- ☑ Documentation editable
- ☑ Open license
- ☑ Open process
- ☑ Open data

Spotter:

- ☑ Open data

The software and hardware files of Trident's older version, OpenRov, are available on GitHub. The files are clearly labelled and are licensed under the Creative Commons Attribution Noncommercial Share Alike license. Documentation for the most recent versions of Trident are not easily available. On the OpenRov forum, tips and discussions on problem solving is available to the public. Additionally, the co-founders of OpenRov partnered with the National Geographic Society to create Open Explorer, an open platform for explorers of all levels to share their expeditions via digital storytelling. However, the platform is no longer active.

Spotter's hardware and software files are not available to the public, however, all the data collected from Spotter is available to anyone with a Sofar Ocean account. Additionally, tutorials and support for tool usage can be found on Sofar Ocean's community page.

What makes the tool low-cost?

The tools are designed for affordability. Trident costs $1,695 and Spotter costs $4,900, which are low prices for their niche functionality.

In what ways is this tool accelerating science, enabling evidence-based decision making, or broadening participation in science?

As a low-cost and low-maintenance device, Spotter is an accessible marine sensor. As a result, Sofar Ocean has the largest network of privately owned marine sensors, with almost 200 sensors in the network. Additionally, Sofar ocean has created its own data-driven modeling technique, which has proven to reduce wave forecast errors up to 50% in comparison to the statistical models used by the National Oceanic and Atmospheric Administration (NOAA) (see figure 2 on webpage). This allows for stronger evidence-based decision making regarding high energy storms. Since the data platform is open, it increases public knowledge and interest in the ocean.

The Trident's open source development shows how both amateurs and professionals can be involved in bringing a scientific tool to life. The affordability and strong community network have inspired professionals and citizen scientist communities alike to explore, monitor, and conduct research on the ocean. Some examples of Trident's use in science include monitoring non-native fish migration in Lake Michigan and at various high schools for STEM education.

PocketLab

At a glance:

Field of application: Education, multidisciplinary

Year initially developed: 2013

Description: PocketLabs are small, portable, and durable sensors for physics, weather, and air quality data collection. Designed to support STEM education for all ages, PocketLab sensors are low-cost, easy to use, and can be purchased as pre-built, complete products. These include PocketLab Voyager, PocketLab Air, PocketLab Weather and PocketLab Thermo. With the click of one button, the data collected from the wireless sensors can be live-streamed using Notebook, the PocketLab software, where students can analyze the data by making graphs, videos, lab reports, and compare to private or publicly available data. The software also allows educators to track students progress and create customized lessons and activities.

Website/contact: https://www.thepocketlab.com/

Analysis:

How was the tool developed? Who was and is involved? The idea for PocketLab began at Stanford University, by a graduate student inspired to provide an alternative to high-cost, difficult to use STEM sensors as well as enable open science exploration. In the prototype stage, the sensors were tested by over 100 middle school, high school, and university teachers as well as by hobbyists, homeschoolers, and makers. The PocketLab project received support and funding from its Kickstarter campaign, the National Science Foundation (NSF) Small Business Innovator Award as well as prizes from the Yale School of Management Education Leadership Conference and Stanford BASES.

Elements of Openness

☑ Open data

PocketLab has various open platforms and communities that are publicly available. On the website, anyone can access different lesson plans and lab activities as well as user guides and tutorials. PocketLab also has a popular ScIC "Science is Cool" virtual unconference and rapidly-growing Facebook community, where thousands of educators and industry partners can

> **"He was frustrated because he couldn't do simple measurements for less than $1000." — *Dave Bakker, PocketLab*[61]**

share ideas, connect, and collaborate. Additionally, anyone can create a PocketLab Notebook account in the PocketLab app, where lab reports, activities, data, and resources can be openly shared and accessed.

What makes the tool low-cost?

PocketLab devices range from $100 to $300. The devices have up to 12 sensors within them, many of these sensors would individually cost $2000 to $3000.[62] The sensors produce high quality data. Notebook Lite is free. Notebook Pro is $150/year.

In what ways is this tool accelerating science, enabling evidence-based decision making, or broadening participation in science?

PocketLab increases accessibility to hands-on and experimental STEM learning activities for students of all ages due to its low cost and ease of use. PocketLab has reached over 250,000 students in the US alone and is used in 60 different countries, including Antarctica. PocketLab's ease of use has made teaching science more accessible to teachers without a technical background. The openness of the platforms and education material developed by PocketLab and PocketLab users has also cultivated a large community of educators, increasing collaboration in education and exploratory science.

Because PocketLab encourages "open ended exploration," there is no limit to how they can be used.[63] They have been used for lab activities such as attaching a sensor to a wheel to understand the physics concepts of resistance, inertia, and rotational motion. The sensors are also used in citizen science projects such as as studying local air quality.

Images: Pocketlab, all rights reserved, used with permission.

Purple Air

At a glance:

Field of application: Sensors, environmental science, health

Year initially developed: 2015

Description: Purple Air is a low-cost air quality sensor that measures particulate matter pollution (PM), such as dust and smoke. The sensor only requires wifi and a power outlet, and the data is uploaded in real-time to a map that can be viewed on the website. From its start in 2015 - 2018, the network has expanded to over 3,000 sensors allowing individuals across the globe to crowdsource air quality data. The tool can be purchased on the website.

Website/contact: https://www.purpleair.com/

Analysis:

How was the tool developed? Who was and is involved? The idea for Purple Air started when the tool developer noticed large amounts of dust coming from the gravel mine near his house in Utah. He believed that the government air quality sensors were unable to detect the mine dust, so he decided to invent his own. After designing a laser particle counter particulate matter sensor and using it in his backyard, he gave out 80 sensors to people in the region for free. This sparked even more interest in the sensor, which consequently became commercially available. The tool is currently used by individuals, local government, industry, and schools/universities.

Image: Adrian Dybwad, all rights reserved, used with permission.

Elements of Openness

☑ Open data

The public can access the data collected on the map, download the data, and share data in the network. Thorough installation and sensor registration instructions can be found on the website as well.

What makes the tool low-cost?

The tool prices range from $179 to $259. The sensor produces data that is highly correlated to professional-grade EPA sensors which can cost between $15,000 to $50,000. Purple Air – and low-cost air quality sensors in general – are being evaluated for their potential use as complementary to professional-grade EPA sensors.[64]

In what ways is this tool accelerating science, enabling evidence-based decision making, or broadening participation in science?

Normally, air quality is monitored by government-owned sensors, however, there are typically only a few air quality sensors in a city. This may not give a comprehensive reading of a region's air quality. The low cost and high functionality of Purple Air allows individuals and community groups to purchase their own sensors, broadening who is able to collect air quality data. Purple Air and other low-cost sensors allow communities to better understand air quality issues, demonstrate environmental inequality, and investigate health impacts. For example, the Airkeepers program is working with local communities to document air pollution issues in Charlotte's West End. The map of sensor data allows people from around the globe to make evidenced-based decisions regarding the real-time air quality in their location. For example, Purple Air sensors are being widely used in regions impacted by massive wildfires in recent years, guiding individual choices and demonstrating community-level risk. Finally, low-cost sensors, including Purple Air, also allow scientists to better understand the spatial and temporal variability of air quality. For example, individuals in the National Aeronautics and Space Administration (NASA)'s Air Quality Citizen Science project use Purple Air Sensors to collect air quality data to validate satellite data collected by NASA scientists.

AudioMoth

At a glance:

Field of application: Sensors, conservation, ecology

Year initially developed: 2017

"We started as open source because… we wanted to get as many [devices] into the field as possible."
— Dr. Andrew Hill, Open Acoustic Devices[65]

Description: AudioMoth is a low-cost audio receiver that can be placed in the open environment for biodiversity research. Named after the species with the most sensitive hearing, AudioMoth can detect sounds from audible to ultrasonic frequencies. The tool is low-cost, small and low-powered so it can be used in large-scale, long-term deployments to detect certain acoustic events, such as the song of a species of interest. AudioMoth is principally used to monitor wildlife and record incidents of human exploitation of nature, such as monitoring the relationship between illegal activities and jaguar and puma populations in unprotected Mexican forests. The tool can be purchased or made individually using the publicly available design files.

Website/contact: https://www.openacousticdevices.info/

Analysis:

How was the tool developed? Who was and is involved? The idea for AudioMoth was inspired by a citizen science project that used smartphones to record and determine whether or not a rare cicada insect had gone extinct. The use of phones had the unintended effect of participants exploring off the path to collect data, disturbing forest habitats.[66] The Open Acoustic Devices research group, a collaboration between University of Southampton and Oxford University, created AudioMoth to solve this problem. Unlike a smartphone, this device could be left in the field over a period of time.

Upon hearing about the project, ecologists and biodiversity researchers expressed interest in AudioMoth and formed a community. The AudioMoth team collaborated with this community in the development of the device, using a user-centered approach.

Image: Dr. Andrew Hill, all rights reserved, used with permission.

The original research was funded by the Engineering and Physical Sciences Research Council and the Natural Environmental Research Council in the UK.[67] Open Acoustic Devices currently operates as a business. Though others have reproduced the tool, AudioMoth tries to remain a step ahead of competition in the development of acoustic devices while further advancing conservation technologies. Due to its low cost, the tool has been used in a variety of unexpected applications outside of conservation. For example, the tool is used to study the health risks associated with noise pollution that is inaudible to humans.

Elements of Openness

- ☑ Documentation available
- ☑ Documentation editable
- ☑ Open license
- ☑ Open process

All software and hardware documentation can be found, clearly labeled in the resource section of the webpage. The hardware is licensed with a Creative Commons Attribution license. The software is also licensed so it can be accessed, modified, and reproduced. The webpage also has additional publically available user support materials, such as user guides, help forums, and publications.

What makes the tool low-cost? The device can be purchased for about $70. Acoustic recording devices can cost up to $5000.[68] CircuitHub and GroupGets, companies which allow for the small scale production of open devices, were key to driving down AudioMoth's price and scaling the business.

In what ways is this tool accelerating science, enabling evidence-based decision making, or broadening participation in science? AudioMoth is a more energy efficient device than current acoustic monitors, which have too short a battery life. This allows for useful data to be collected over a longer period of time. Additionally, the size and durability of the device makes it easy to transport over long distances and the plan to add wireless connectivity to the device will permit data collection in more remote areas. The tool is low-cost, making it more financially accessible to broad audiences. Because of the tool's accessibility, it has been used to conduct impactful conservation research around the world, even leading to the discovery of new species.[69] AudioMoth hopes to further expand into underwater acoustic monitoring.

Image: Dr. Andrew Hill, all rights reserved, used with permission.

Safecast – bGeigie

Image: bGeigie nano by Safecast is licensed CC BY NC.

At a glance:

Field of application: Sensors, environmental, health

Year initially developed: 2011

Description: Safecast is a non-profit organization that was founded as a response to the 2011 Fukushima Daiichi Nuclear Power Plant disaster. The organization developed various low-cost radiation sensors, including the portable bGeigie. This device is easily attached to a car, bike, or another mode of transportation, where it can collect radiation and GPS location data in real time. In 2012, the organization expanded their tools to low-cost air quality devices for monitoring particulate matter. The data collected using Safecast's devices by a global community of volunteers is uploaded to the Safecast dataset, where anyone can access and download the data or easily visualize the radiation risk levels on a map. The tool can be purchased as a DIY kit, a full product, as well as made by individuals using the publicly available design files.

Website/contact: https://safecast.org/devices/bgeigie-nano/

Analysis:

How was the tool developed? Who was and is involved? After the Fukushima Daiichi Nuclear Power Plant disaster, a group of entrepreneurs, activists, and innovators noticed a lack of supplies for Geiger counters and that those accessible to the public produced low-quality data. Through communication over social media and open source tools, the idea for bGeigie and it's open data platform was born. The device itself was designed at the Tokyo Hackerspace through volunteer-based hackathons. A Kickstarter campaign was launched to crowdfund the project. In addition, Safecast was funded by the Knight Foundation and some smaller grants.[70] Though the tool was originally developed for people of Fukushima after the nuclear accident, Safecast devices are used globally by citizen scientists as well as at larger institutions.

Elements of Openness

- ☑ Documentation available
- ☑ Documentation editable
- ☑ Open license
- ☑ Open process
- ☑ Open data

The hardware and software documentation can be publicly accessed on the Safecast website. The hardware is free to "open, manipulate, hack, break, and improve" under a Creative Commons Attribution Share Alike license. The software is licensed to be accessed, modified and reproduced. Furthermore, the page has additional links to discussion groups and an owner user group list, where users can ask for help and receive updates about the device. The list of tasks needed to be accomplished in device development are also listed on the volunteer page, with detailed instructions on how people can participate and how their contribution will be licensed. The Safecast iOS application can be downloaded by anyone, giving open access to nearby radiation data as well as access to data from the US EPA and other institutions. Instructions on how to use and and create an open API for for data collected by devices can be easily found on the website. All the data uploaded to the Safecast dataset can be downloaded and used by anyone, with no licensing requirement.

What makes the tool low-cost?

The DIY kit costs $600 and the fully assembled device is $1,500. This is low cost for a device with the accuracy and GPS logging features of the radiation sensor.

In what ways is this tool accelerating science, enabling evidence-based decision making, or broadening participation in science? Safecast is an initiative where communities have been at the center of each part of the process, from design to data collection. Instead of relying on the government to collect data and take action, with bGeigie, anyone can collect and view "mobile" radiation data, empowering individuals to assess their own environmental safety and make informed decisions. As a result, the strong global community fostered by Safecast has created the largest radiation dataset in the world.

Observations

2

The review of case studies and our conversations with tool creators led to many observations about "the state of the field" for low-cost and open tools for science. These observations provide insight on tool development and use, the challenges and opportunities for low-cost and open tools, and the potential for low-cost and open tools to accelerate science and broaden participation.

Observation 1. Low-cost tools enable diverse scientists (professional and not) to conduct research across a wide range of domains.

The tools profiled here span scientific disciplines, from theoretical physics to human-robot interaction research. They have a huge variety of uses, from DIY creativity and entrepreneurship, to education and learning (e.g. PocketLab), to lab research (e.g. OpenFlexure) and large scale data collection (e.g. Purple Air and Safecast). They are used by individuals, by communities, and by global networks; they are developed and used by people with a variety of backgrounds and educational experiences. The context for initial development of these tools varies greatly as well, with most of the tools presented here developed in an academic setting (e.g. OpenFlexure, RepRap, AudioMoth), and others developed in makerspaces (e.g. MakerBot), by a non-governmental organization (e.g. Safecast), by a for-profit company (e.g. TubeSat), by individuals (e.g. Purple Air), and some through a combination (e.g. Safecast, Arduino).

Observation 2. Federal funding plays an important role in tool development.

Although we did not gather comprehensive information on funding sources for all tools included here, it is clear that federal funding is important. Of the 16 tools highlighted here, eight had funding sources that included US federal agencies, including the National Aeronautics and Space Administration (NASA), the National Institute of Health (NIH), the National Science Foundation (NSF), and the Department of Energy (DOE). Federal grant programs providing funding included the NASA Small Business Innovation Research award (TubeSat) and the NSF Small Business Innovator award (PocketLab). Another three were funded by government agencies

Image: Dr. Adrian Bowyer, all rights reserved, used with permission

abroad (e.g. from the UK Engineering and Physical Sciences Council). Other significant funding sources include venture capital, foundation grants, private donors, prizes and challenges, and self-funding. Interestingly, at least five tools (e.g. PocketLab, Safecast, OpenRov/Trident, and KickSat, the PyCubed predecessor) generated revenue via crowdfunding on Kickstarter; for these tools, the use of Kickstarter likely contributed to the twin goals of generating support and developing community.

Observation 3. The impact of low-cost tools is not incremental.

A few of the tools profiled here have a broad user base and demonstrate the potential for low-cost tools to revolutionize science by allowing new solutions to scale. The Arduino microcontroller, for example, produced 700,000 boards by 2014 and has catalyzed countless projects and, arguably, the maker movement itself. The RepRap 3D printer inspired MakerBot and OpenFlexure, motivating the creation of more tools and ideas in the broader movement. These tools are foundational and have had extraordinary impact within certain disciplines and communities.

However, our review of these tools and the broader field of low-cost and open tools has highlighted that there are a huge variety of smaller-scale low-cost tools developed and used in lower numbers. For example, while AudioMoth had manufactured approximately 4,000 devices by 2019), it has contributed to scientific discoveries including the discovery of new animal species. These tools have had a large impact directly in specific research, hobbyist, or other communities (e.g. Trident and Spotter),

Six of the tools profiled here use Arduino in some way, and six are 3D printed or contain 3D printed parts, enabled by 3D printers like RepRap and MakerBot.

and have made unique contributions to scientific practices.

Observation 4. "Building block" tools enable other tools.

Low-cost and open tools are uniquely suited to enable innovation in other tools. Open tools, in particular, provide opportunities to create modifications and derivatives to support customization. Some foundational tools, like the Arduino (and other microcontrollers) and 3D printers, provide the "building blocks" for countless new tools. OpenFlexure was originally designed to be 3D printed by RepRap 3D printers.[71] This enabling is additive; OpenFlexure itself inspired other microscope designs, such as the ones included in Public Lab kits. Although bespoke tools do exist, the prevalence of reusable solutions is an important accelerator for research.

Some proprietary tools act as "building blocks" as well. The Plantower sensor is a component of many of the most popular low-cost air quality sensors, including Purple Air and PocketLab.

Many tool creators are surprised in the ways in which their tool is ultimately used; tools not designed to be "building block" tools end up serving as a basis, or inspiration, for other creative uses. PyCubed, for example, was used to monitor the health of yeast and for water quality monitoring, among other unexpected projects. AudioMoth, designed for cicada research, was later used to discover a new species of bush cricket, and for noise pollution and underwater monitoring.

Observation 5. Modularity and customization are key features for low-cost and open tools.

For some tools, emphasizing modularity was the key to making the use of tools for science less technically tedious; Quori and AudioMoth emphasize modularity and customization to reduce technical barriers but allow for customized use. "Researchers were frustrated by spending the time to design a niche tool that is only used once, or having to buy an expensive system to meet their specific needs… [Quori] prevents them from reinventing the wheel when they don't have to. The design is made so it

“Because of the cost and the size, anyone can do science.” — *Dr. Andrew Hill, Open Acoustic Devices*[75]

is easy to use and robust. You can use a screwdriver to take it apart.”[72] As with the prevalence of “building block” tools, modular and reusable components allow for a wide range of tools to be designed quickly, and enable a level of customization that supports evolving scientific research needs.

Observation 6. “Low-cost” tools are significantly lower cost than those traditionally used.

The tools profiled here are low-cost relative to traditional tools; they range in cost from less than $50 (e.g. Foldscope, Plantower, Arduino) to multiple thousands (e.g. TubeSat, Quori). Although these tools were chosen due to their low cost, the extent of their cost difference is extraordinary (Appendix A). These tools for science are not exactly the same or equivalent to traditional, more expensive alternatives, and sometimes, the cited cost does not include the labor needed to build or assemble the tool; however, the difference in cost is often an order of magnitude – or multiple orders of magnitude – between low-cost tools and the tools alternatively used. Dr. Adrian Bowyer, creator of the RepRap 3D printer, noted that at the time of its invention in 2007, the only available 3D printers were more than $40,000; the RepRap was a few

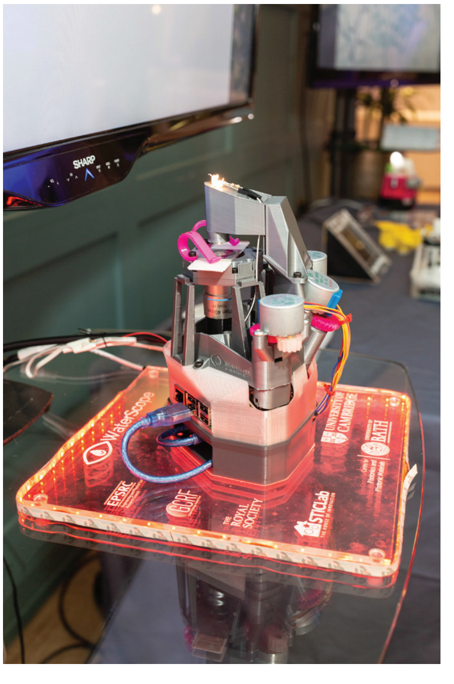


Image: The OpenFlexure Project, licensed CC BY

Image: "Creator of the Foldscope" by NIH-NCATS is marked with CC PDM 1.0

hundred dollars to build.[73] Other tools decrease costs to a significant degree. For example, the 3D printed microflange plate prevents approximately $3 million in lost samples.[74] Although more expensive but still low-cost solutions do exist, the availability of tools at this price point suggests tremendous potential for low-cost tools to democratize research by enabling a far greater range of scientists and innovators to contribute.

Observation 7. Many tools thrive on community, and communities coalesce around tools.

Many tools offer not just a product, but also access to a broad community of tool designers and users. Across the board, tool creators invest in cultivating community; this takes many forms, including online forums and other methods for sharing how individuals interact with tools. Many tools are known for their platform (e.g. MakerBot is known for Thingiverse, its platform of 3D designs), and links between tools and communities appear to be a central feature of business models. For example, PocketLab has filled a need for a community of educators that use hands-on science tools in the classroom.[76] For tools including Arduino, Makerbot, Trident, and Safecast, the community was key in both the development and use of final products. Some tool creators cited their communities as essential to their business model, as their contributions allowed them to innovate faster and stay one step ahead of any competition (e.g. AudioMoth, PyCubed). These communities are also part of the reason why "building block" tools and modular approaches to development are important: there are engaged audiences ready to test and use these creatively.

Other tools, such as Arduino, Trident, and Safecast, have cultivated strong platform-level user communities, and a significant presence in broader communities such as the maker movement

“It’s quite difficult to make this easy.” — *Dave Bakker, PocketLab*[81]

and citizen and community science. For example, Public Lab brings together tools created and used within a community of people committed to environmental justice and community science. These communities share expertise and multiply impact for advancing scientific discovery and broadening participation.

Observation 8. Low-cost and open tools cause us to rethink expertise; at the same time, tool creators struggle to make their tools technically accessible to broad audiences.

All of the tools profiled here broaden who is able to design, create, and use tools for science. For example, although previously “government and the Department of Defense are the ones flying and innovating satellites,” with PyCubed, “you can be up and running in minutes.”[77, 78] PocketLab allows teachers and students to use the types of sensors traditionally reserved for professionals, and Purple Air does the same for community members and individuals wanting to understand local air quality, health, and exposure.

“Most people want to buy a thing, they don’t want to make it… the biggest thing [for open hardware] is moving from something you can make to something you can buy.” — *Dr. Julian Stirling, University of Bath and OpenFlexure Project*[79]

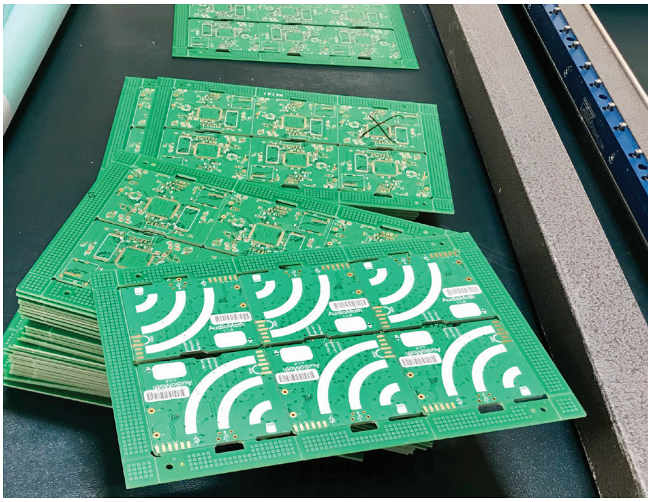
However, the extent to which the user base is broadened varies greatly. Open tools in particular are “very focused on people who have the know-how.”[80] Many tools (e.g. OpenFlexure, RepRap, PyCubed) use a do-it-yourself (DIY) approach; they require some level of technical expertise to build, and a time commitment for climbing the hardware learning curve. A common barrier for tool developers is creating a tool that is accessible not just to other expert users or those with technical skills, but to broad audiences.

Image: "US-LS Science Lab" by Kentucky Country Day is licensed under CC BY-NC 2.0

Despite this, the collection of tools included here demonstrate that low-cost and open tools can be designed for, and accessed by, a variety of users. Some tools are sold in the form of a kit for users to assemble (e.g. TubeSat). More and more tools – including open tools – are available "off the shelf" and come with the "unboxing experience" of a ready-to-use tool that many users seek out. Examples of this include Arduino, which – in addition to emphasizing open practices in their business model – provide users with an experience very similar to that of many proprietary tools. More work is needed to explore how off-the-shelf tools broaden participation beyond those that require more technical expertise.

Observation 9. Scaling tools is a key barrier.

Low-cost tools, and particularly open tools, challenge traditional production practices. Because open tools do not (by definition) occupy an exclusive market niche, demand is often uncertain. In some cases, minimum quantity batch manufacturing is supported by crowdfunding.[82] Other tool creators (e.g. RepRap) left commercial production entirely to external groups. Tool creators who begin with small-scale production may soon find themselves in an in-between stage, with production needs higher than what can be accomplished on their own, but not large enough to



Adafruit Industries

Adafruit Industries was founded by Limor Fried, also known as Ladyada, who started making and selling her own DIY electronics kits as a student at MIT. Since, the company has grown to be one of the largest and most influential open hardware communities, without ever accepting funding from venture capital. Adafruit's platform contains thousands of tutorials and DIY projects and has about 14 million website views with over 2 million new visitors per month. The company, which is a certified Minority and Women-owned Business, has over 100 open source products, ranging from wearable fashion electronics to high speed microchips.

Image: 2016_Limor_PnP_Machine_02 by Adafruit Industries is licensed CC BY NC SA.

accommodate standard production methods. For example, the creator of Purple Air was manufacturing sensors in his house until he could no longer keep up with production; the AudioMoth team struggled to find a manufacturer that could produce a small number of tools at a reasonable cost. The MakerBot team even relied on volunteers to fill orders for the Cupcake CNC while they navigated this in-between stage. Companies such as GroupGets and CircuitHub have emerged to support small batch manufacturing and help communities like AudioMoth meet their needs. In many cases (e.g. PyCubed), external communities (like Adafruit Industries, described in text box) provided essential support and know-how for navigating issues related to scaling. Similarly, there tends to be a funding gap between the creation of a new tool and the next stage of its development that results in something more fully developed and broadly useful.[83]

Observation 10. "Openness" exists on a spectrum.

Current labeling of tools as "open hardware" or "open source hardware" may lead to a general understanding of openness as binary; either a tool is open, or it's not. The case studies presented here demonstrate that openness exists on a spectrum, and that tool developers often choose to demonstrate openness in inconsistent ways (as also reported by researchers like Bonvoisin et al., 2017).[85] These tools also show a range in openness in both process and product. Some tools, such as OpenFlexure and RepRap, demonstrate a high level of openness by including documentation and clearly marking licenses that allow others to

“All of this would not be possible without companies like Adafruit.” — *Max Alvarez Holliday, PyCubed*[84]

“study, modify, make and sell” the tools. Others demonstrate the intention to be open through providing the necessary documentation, but have limited accessibility or ease of use. Others emphasize the openness of the data platform in tool materials (e.g. Safecast), while still others provide a data platform limited by membership (e.g. Spotter). In some cases, tools not generally perceived as open contain elements of openness; for example, Purple Air air sensors make their data publicly available. Some tools use open practices but contain proprietary parts. Other tools began as fully open but transitioned, at least partially, to a proprietary business model (e.g. MakerBot). In still other cases, some tools appear to be fully proprietary (e.g. Plantower), with no indication of open practices.

Image: “Safecast Hackathon” by seanbonner is licensed under CC BY-NC-SA 2.0

Conclusion

3

As these tools demonstrate, the *things* of science are changing the way science happens. Low-cost and open tools are accelerating scientific progress and expanding access to science, from enabling custom tools to broadening what is possible in science classrooms. The success of low-cost and open tools may be due to the extent to which open practices, such as open documentation, editable documentation, open processes, open licenses, and open data enable innovation and enhance impact. It may be due to the modularity and the customization that they make possible, or the way that they spur the development of additional tools. Above all, the success of low-cost tools may be as simple as the extent to which they are low-cost, allowing more scientists (both professional and not) to experiment with something new, build off of others' work, or simply build or purchase tools they otherwise would not.

These tools also demonstrate that their impact extends far beyond the use of the tools themselves. The resulting communities enhance users' experience, helping solve common problems and expanding their impact on science and society. They also demonstrate a changing notion of expertise, and who is able to participate in the scientific process.

Finally, this close look at low-cost and open tools for science hints at common barriers and opportunities, such as the challenge of designing technically accessible tools, the barriers creators face when trying to scale, and the importance of diverse funding sources, including federal investment. More analysis is needed to explore and demonstrate the value of these tools, understand common barriers, and evaluate practices and business models. If barriers could be overcome or ameliorated, would these tools revolutionize science? Does the future hold a new way of doing science that is faster, more actionable, and more inclusive, and will low-cost and open tools drive that change?

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Appendix A

Cost Comparison Chart

The following chart compares the current cost of tools to tools of similar use (referred to as "traditional tools"). There are important caveats here: sometimes, the costs are estimates or from an unknown date; other times, the cost of the low-cost tool does not include the labor needed to build or assemble the tool because it is built by the user. In still other cases, the low-cost tool may not be exactly comparable to the traditional tool. However, these cost comparisons demonstrate the magnitude of the difference in cost between low-cost and traditional tools.

Tool	Cost	Comparison to Traditional Tool
Arduino	All microcontrollers less than $50	N/A
AudioMoth	$70	$500[86] (2020)
COVID-19 Symptom Tracker	$0.10/Device	N/A
Foldscope	$29.99	$2,000 (2018)
MakerBot	Professional -- $3,499 Education -- $1,799	$1000 to $10,000 (2020)
Microplate Flange	N/A	$3,000,000 loss (2014)
OpenFlexure	$200	$40,000 (2020)
Plantower	$34 (2019)	$12,000 - $21,000[87] (2019)
PocketLab	Devices -- $100 to $300 Notebook lite -- $150/yr	Individual sensors -- $2000 to $3000[88] (2020)
Purple Air	$179 to $259	$15,000 to $50,000 (2018)
PyCubed	$200 to $300	$50,000 to $1,000,000[89] (2014)
Quori	$5,000 without labor	$18,000[90]
RepRap	$300 to $620	$40,000[91] (2004)
Safecast	DIY Kit -- $600 Fully Assembled Device --$1,500	N/A
Spotter	$4,900	N/A
Trident	$1,695	N/A
TubeSat	Without launch -- $6,200 With launch -- $12,400	$50,000 to $1,000,000[92] (2014)

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