Open Science Hardware & Space Research

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Wilson Center

Gathering for Open Science Hardware

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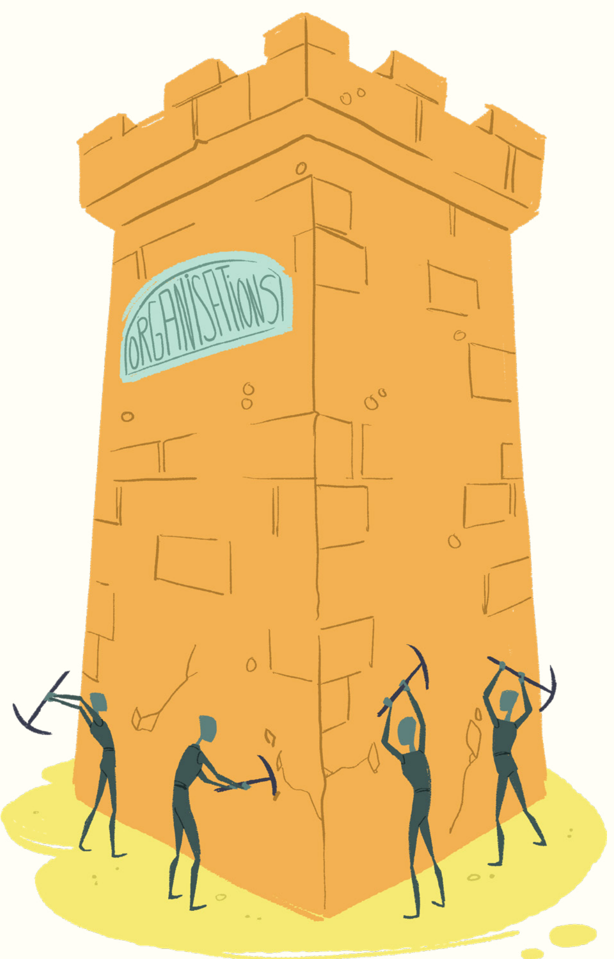
Executive Summary

Open source science hardware—that which enshrines downstream freedoms for reuse, study, modification, and dissemination—has seen growing adoption in various fields of research. However, the development and use of open source hardware for space research is currently limited.

Building on momentum towards open science on national and international levels, we convened key stakeholders to explore the role of open source hardware in space research. During an online workshop held in July 2023, 30 participants representing academia, citizen science, hardware makers and hackers, artists, and those from NASA and UNESCO laid out the landscape of space-related hardware development. Specifically, we identified the needs and opportunities for hardware in space research; barriers and challenges; and key actors who should be engaged.



We learned that a key benefit of open source hardware for space research is reduced barriers to access. It not only lowers cost but facilitates collaboration and innovation, especially on key technologies shared between different projects. For example, open source cubesat designs reduce duplication of effort, allowing different research teams to focus on adapting them for their purposes. The transparency and accountability afforded by open source hardware also improve security, an important consideration for some space-based applications. In addition to cubesat developers, early adopters of open source hardware also include educators and contributory citizen science projects conducting astronomy research.

In terms of barriers, some are common across research domains. For instance, academics face institutions which do not recognise or reward open research, including publishing open source hardware designs. In addition, even if open source hardware designs are published, there is a lack of standard open source file formats, bills of materials, metadata and measurements which would enable reproducibility, compatibility, and interoperability. Specific to space, there is a lack of inclusivity where non-institutional or non-"professional" participants are often left out of deliberations and their contributions unrecognised. The biggest barrier, however, is that export controls in some countries—especially the United States—prevent the sharing of information for international collaboration. Similarly, regulatory compliance and physical testing of hardware in development can be particularly difficult for space research hardware.

Those at the workshop enumerated nine categories of key actors who should be engaged to promote the adoption of open source hardware for space research. This includes policy makers, funding bodies, and research institutions, specifically their technology transfer offices which should recognise not only the various benefits of open source technologies, but also that they can be commercially successful. Crucially, participants stressed the need to involve non-institutional actors including makers, artists, and other creative communities. These groups have contributed to the development of open source hardware for space, and can provide a critical perspective on the role of science and technology in society.

We believe our workshop represents an important first step in representing the current state of open science hardware in space research, articulating a path towards wider adoption, and realising its full benefits for science and society.

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We also gratefully acknowledge all workshop participants for their valuable time and insights:

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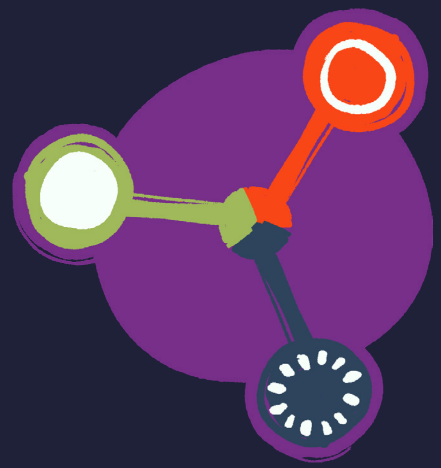
Vasileios Spanakis-Misirlis	PICTOR Telescope, University of Piraeus Research Center
Julian Stirling	Freelance/OpenFlexure/GitBuilding
Tiffany Straza	UNESCO
Miha Turšič	Waag Futurelab & Postgravityart
Fabian Uehleke	OpenAstroTech
Christian Villum	independent advisor and consultant (prior roles in OPENNEXT, Remodel, Open Knowledge Foundation, Creative Commons, etc.)
Makhan Virdi	NASA (SSAI)
Henry "Trae" Winter III	ARISA Lab, LLC, Eclipse Soundscapes Project

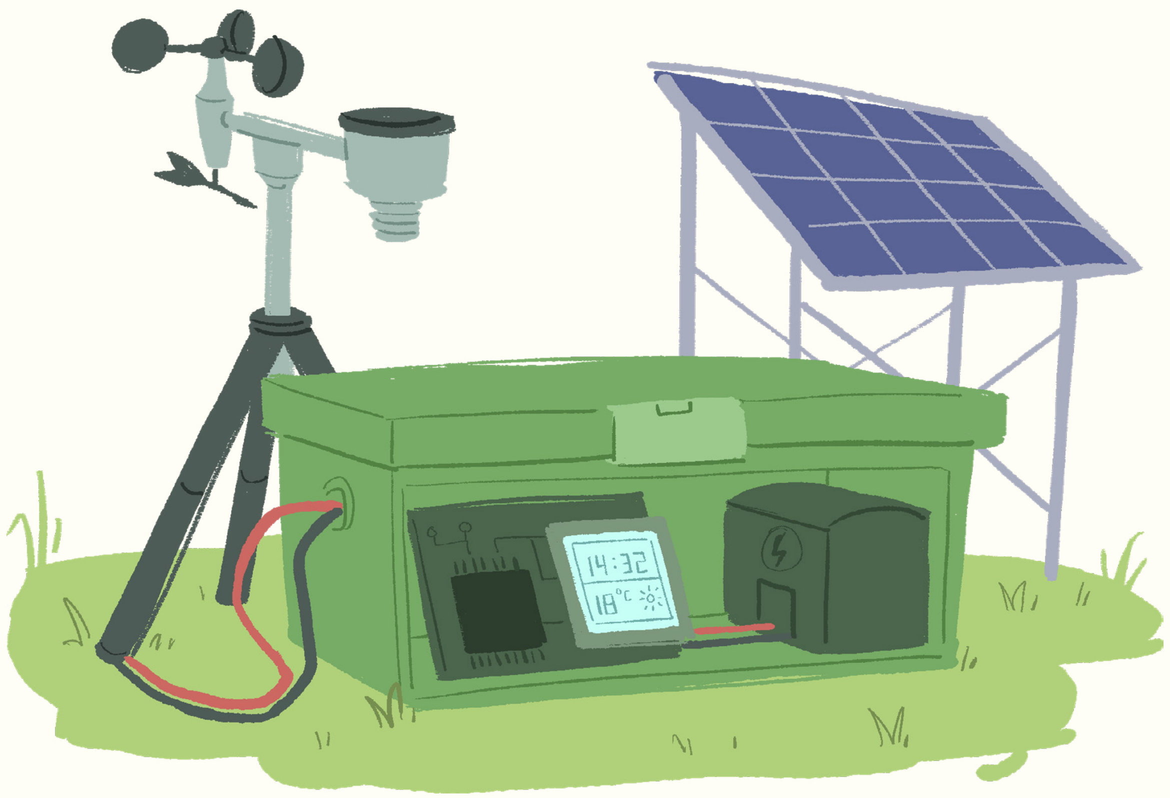
Introduction

In July 2023, the Gathering for Open Science Hardware (GOSH) community and the Woodrow Wilson International Center for Scholars (the Wilson Center) **organised a workshop to reflect on the role of open science hardware for space research and to chart a possible path towards wider adoption.** This document describes the origins of the workshop, the diversity of expertise represented during its proceedings, lessons learned, and a prospective look at next steps.



Defining open science hardware

Physical hardware underlies much of research. From computing devices, laboratory or field sensors, to remote sensing satellites, hardware forms the physical layer of research with which we can understand the world. In addition to data collection, various knowledge products and research processes are also facilitated by hardware.



Because of its fundamental role, open source hardware is becoming a key component of the open science discourse. As recognised in the UNESCO Recommendation on Open Science, open source hardware can enable more globally equitable scientific research[1]. In addition to respecting the iterative nature of scientific practice, open source hardware is necessary for realising benefits such as—but not limited to—reproducibility; reducing duplication of effort; environmental sustainability; lowering costs; faster innovation; and user rights. Importantly, open source hardware evens the playing field for development and manufacturing across the world, allowing more equitable access and adaptability to locally relevant research.

For this document, we will follow the Open Source Hardware Association (OSHWA) in defining open source hardware as:

> **"...hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design."[2].**

A closely related term is open science hardware, which refers to the emerging discipline and practice of using open source hardware in scientific research[3]. We will use the terms open source hardware and open science hardware interchangeably in this report, mindful of their meanings as defined here.

Open Science Hardware and Citizen Science

Citizen science is a broad umbrella term that involves a diverse array of participants in research, including those who are not professional scientists. Its complex meanings are also captured by related terms including community science and participatory science. These meanings span local community-driven research to global investigations in which participants act as contributors. In many ways, the goals of citizen science and open science hardware align; open science hardware and citizen science communities share the overarching objective of making scientific research more accessible and equitable.

However, there are meaningful distinctions.

Open science hardware focuses on the design and dissemination of hardware tools, including a legal component that allows anyone to "study, modify, distribute, make, and sell" open science hardware designs and documentation. Citizen science is focused on, among other goals, civic engagement in science and does not necessarily require the creation or use of open science hardware. Therefore, some of the citizen science projects mentioned in this report might not exclusively utilise open source hardware.

That said, at the nexus of open science hardware and citizen science exist a variety of accessible hardware tools that are being used by citizen scientists to contribute to science. For example, PlanktoScope—a modular, open source hardware tool that allows for imaging of plankton samples—is used by hundreds of citizen scientists who upload their images to help classify aquatic taxa on the EcoTaxa platform. When used in tandem, open science hardware and citizen science can sustain a unique synergy of benefits: more accessible science, large-scale data collection, enhanced education in the sciences, and continuous improvements of the tools and instruments used for research. To this end, as both the open science hardware and citizen science communities grow, so will opportunities to integrate these practices to improve accessibility and scientific outcomes, especially in the context of space research.

A workshop on open science hardware and space research

Open science hardware has seen adoption in disciplines such as conservation, microscopy, or agricultural technologies, but to our knowledge there is a need to explore the benefits of open science hardware to space research. Here, we mean space research in a broad sense, that is making use of or studying outer space and not limited to research conducted in space.

To that end, we organised a workshop building on recent attention to open science at the United States National Aeronautics and Space Administration (NASA), which with the United States government declared 2023 the "Year of Open Science" and is championing its own Open Source Science Initiative and Transform to Open Science (TOPS) mission. The workshop convened open science hardware practitioners and space scientists to explore opportunities for the adoption of open source hardware by space research and make connections between the communities.

Space science has traditionally been carried out by government agencies and universities, with hardware going through strict regulatory procedures before use. Recently, there has been an increase in both public (e.g. open source small satellites) and commercial (e.g. private spaceflight technology) engagement with space hardware. By engaging with stakeholders from new and conventional space science communities, we hope to promote open science hardware by understanding the role and landscape in which open source hardware can co-exist with and benefit these diverse stakeholders. This will involve identifying what makes open science hardware relevant and valuable for space science, and what is needed for it to achieve its full impact. Furthermore, we hope this workshop will elevate the role of open science hardware in recent government open science initiatives, such as the NASA TOPS mission.

Organising team

The initial concept for this workshop began with a discussion between Pen-Yuan Hsing and Brianna Johns, community councillor and community manager, respectively, of the Gathering for Open Science Hardware (GOSH). GOSH is an international network of researchers and makers sharing a common interest in advancing open science hardware. It has organised four flagship in-person "Gatherings" (in 2016, 2017, 2019, and 2022), in addition to convening regular meetings, publications, activities, workshops, and providing a community forum. Most notably, the GOSH community has created a roadmap which documents the concrete actions that can be taken to make open science hardware ubiquitous.

The Wilson Center then led a proposal in collaboration with the GOSH community, which was funded by the Open Science Hardware Foundation (OSHF) via a grant from the Alfred P. Sloan Foundation. The Wilson Center is a Congressionally-chartered, federal trust instrumentality of the United States Government. Its mission is to unite the world of ideas and the world of policy. This workshop bridges two core portfolios of the Wilson Center's Science and Technology Innovation Program (STIP); from the Wilson Center, Alison Parker and Alexandra Novak contributed with an open science perspective and Sophie Goguichvili brought in space science expertise, with contributions from Richard He and Pranav Moudgalya.

To enable a more inclusive, stimulating, and productive workshop, we enlisted Allen Gunn of Aspiration, a non-profit technology organisation, to help structure and facilitate the event.

Workshop participants

During the planning phase, NASA agreed to send a representative from their TOPS team. Open space hardware projects, such as the Ore-sat open source cubesat project, also expressed interest. The workshop was also advertised in areas such as the GOSH community forum; the Wilson Center's THING Tank and Across Karman websites; and the NASA TOPS group on the Slack online chat platform. Additionally, we individually invited those with open science hardware or space research expertise among our professional networks.

In addition to the organisers and facilitator, 26 participants joined the workshop. They represented institutions such as the United Nations Education, Scientific, and Cultural Organisation (UNESCO), NASA, the Johns Hopkins University Applied Physics Laboratory, the Center for Open Science, and the Libre Space Foundation; academic institutions like Western University and the Technical University of Berlin; and relevant projects such as OreSat, Open Astro Tech, Radio JOVE, KISPE, Quetzal-1, Mach30, the PICTOR radio telescope, and OpenFlexure (see appendix for more information on each).

To facilitate participation by those without institutional support, we also offered an honorarium to all attendees.

Structure

The workshop was held online with the Zoom video conferencing software for two hours beginning 16:00 UTC on 20 July 2023.

The first half of the workshop explored a range of current projects relevant to the meeting scope, in a question-driven peer-learning format. The projects included OpenAstroTech, OpenFlexure microscope, and the Radio JOVE Project.

Then, we focused on exploring the present reality, possible collaborations, and potential future strategies at the nexus of open science hardware and space science. The group broke into three parallel working sessions to collaboratively discuss the following (which will be discussed in the next section).

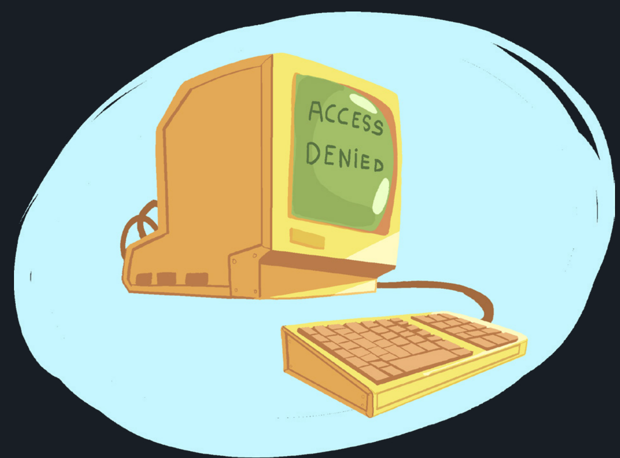
These sessions were shaped and informed by pre-event input we solicited from all participants, and they could choose to move between sessions throughout. Each session was facilitated by one of the organisers.

The workshop ended with each session facilitator summarising key takeaways, a discussing next steps and pending collaboration on the written report-out meeting to a close. The rest of this report will summarise those working session takeaways.

Mapping needs and opportunities for open science hardware in space science

Barriers and challenges to open science hardware in space science

Engaging key actors to consider open source hardware for space science

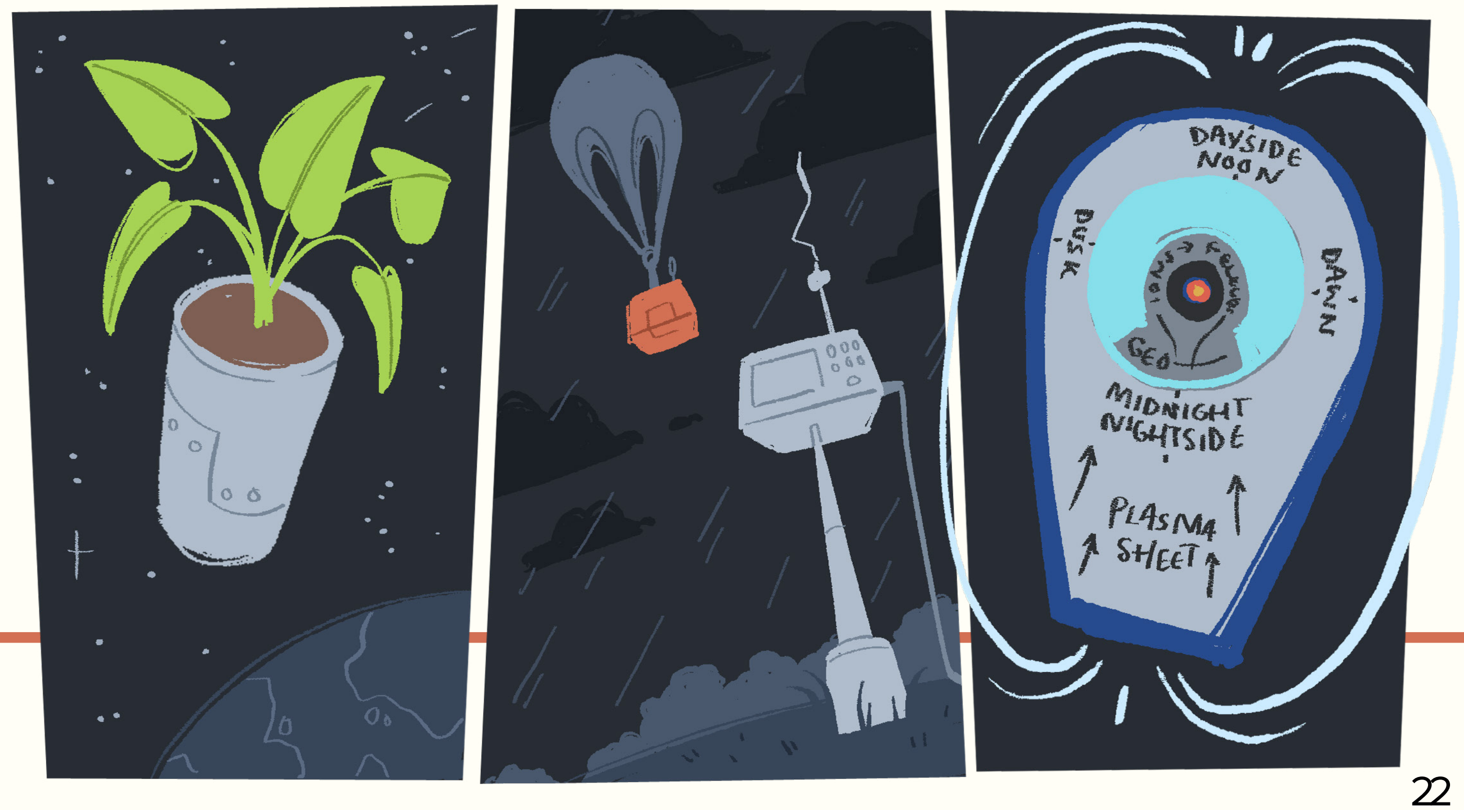


Workshop Outcomes

Needs and Opportunities

Open science hardware is already being deployed and used for a variety of space applications, particularly in the context of education, both formal and informal, and citizen science. In particular, examples from participants made it clear that the use of open science hardware in contributory citizen science is a thriving area of open science practice.

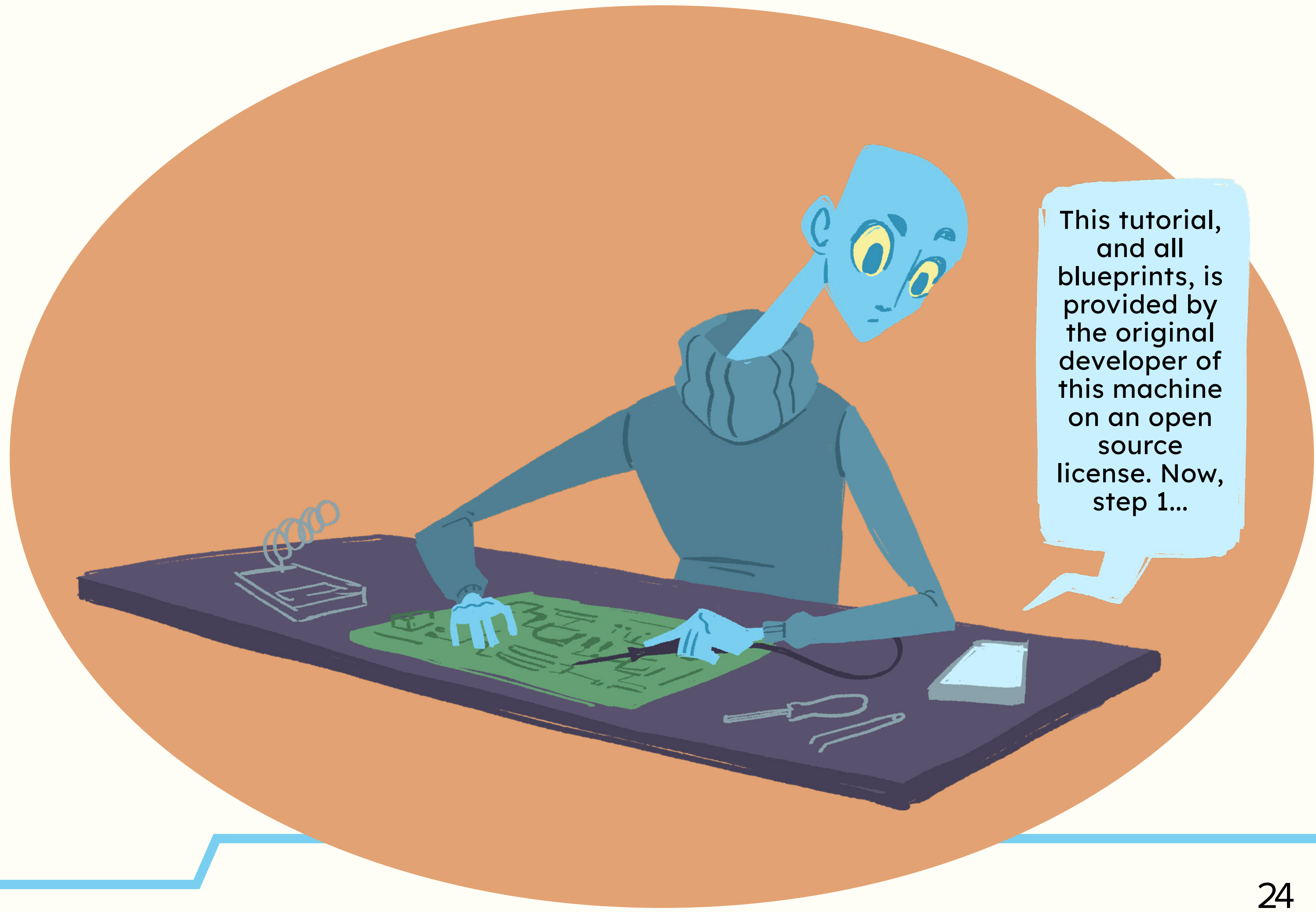
A prime example of access to essential research tools through open science hardware is the AstroPlant initiative, which equips citizen scientists with open source research kits to explore and experiment with life-supporting ecosystems. This perspective was also underscored by a participant from NASA, who highlighted the agency’s release of 3D printable designs for diverse citizen science projects. Other initiatives, like HamSci, RadioJOVE, eclipse projects (Eclipse Soundscapes, CitizenCate), projects like Aurorasaurus that rely on cameras for documentation, and EZIE-mag, also demonstrate the wide range of ways that open source hardware can be used for citizen science applications. Tools like PACKMAN, a portable instrument for space weather research, offer greater opportunities for participation. Many of these initiatives are coming together for the Heliophysics Big Year, which begins in October 2023 and extends through December 2024.



Reduced Barriers to Access

One key way in which open source hardware is helping to democratise space research is by reducing costs to access space. By using open source designs and specifications, space agencies and private companies can save money on research and development, as well as reduce the cost of procurement and production. Take cubesat missions, for example, which have benefited significantly from the use of open source hardware components for their success. Organisations like the CubeSat Laboratory at Cal Polytechnic Institute and initiatives like the CubeSat Kit have provided open source designs for CubeSat components, including satellite structures, power systems, and communication modules. These advancements have enabled universities and small teams to develop and launch their CubeSat missions cost-effectively and independently of well-resourced space agencies or companies.

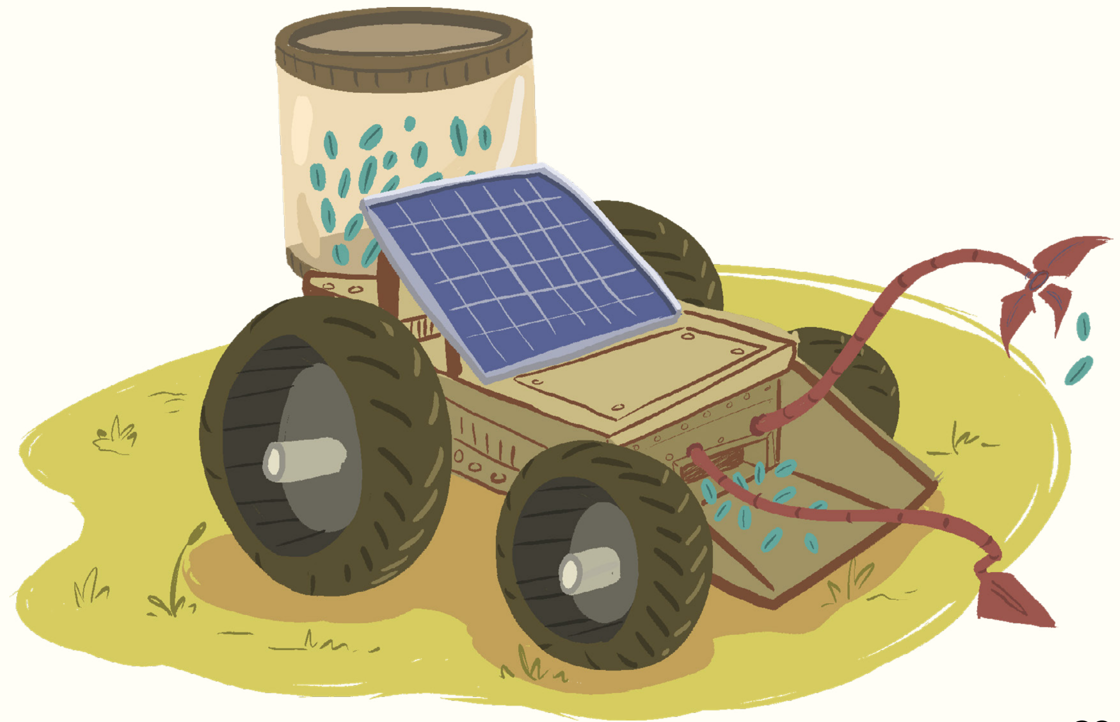
Open source hardware allows for a more rapid development of spacecraft and space-bound assets, as engineers can build upon existing designs and more easily collaborate with others in real-time. This can help to speed up the development process and get new technologies to market and be deployed on Earth or in orbit faster.

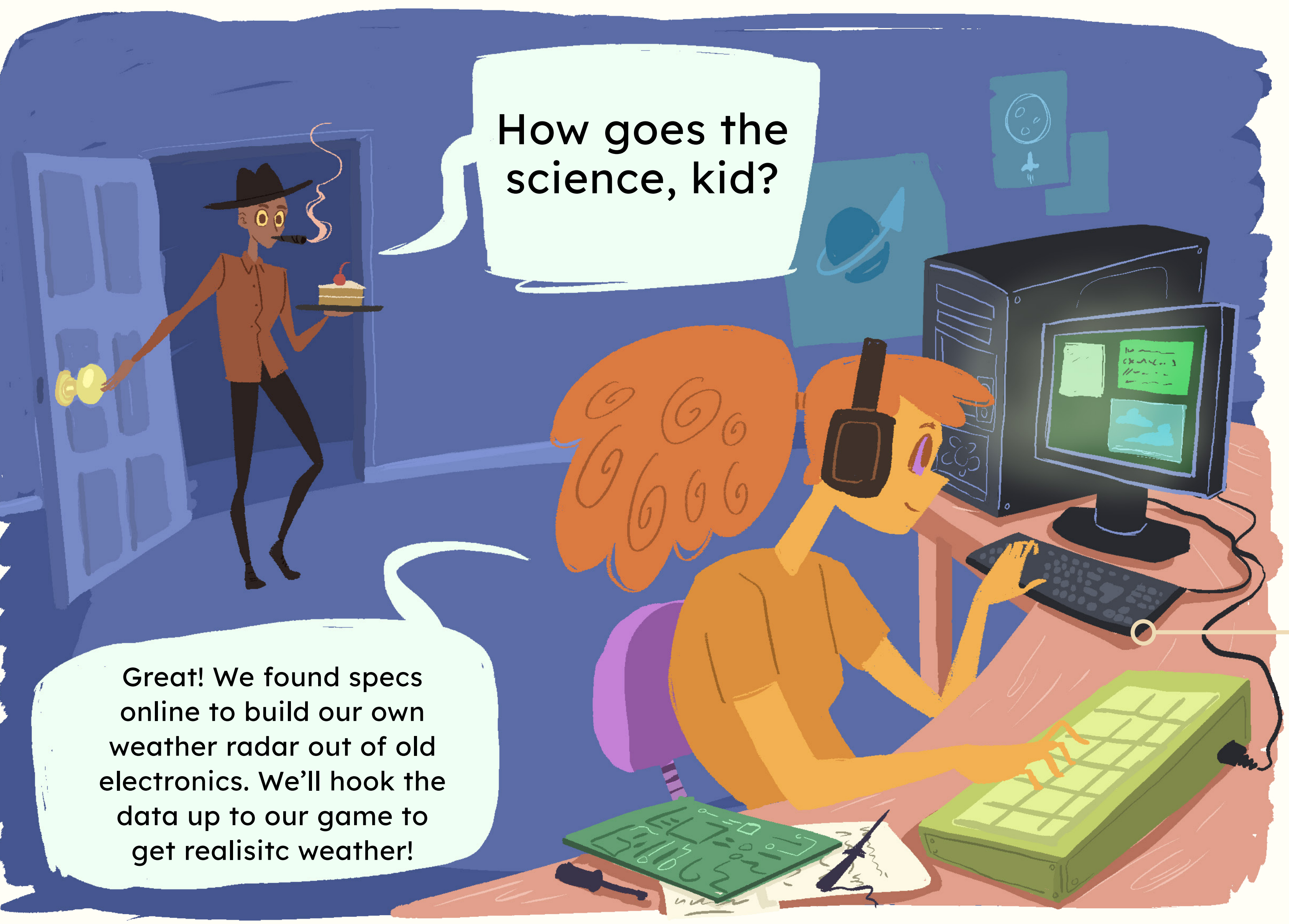


Enhanced Educational Opportunities

Open source hardware can provide valuable educational opportunities for students and professionals, helping to train the next generation of space engineers and scientists. The value of open science and open source hardware in space for educational opportunities has been recognized by many in the field, with NASA's Open-Source Science Initiative (OSSI) paving the way for an ecosystem of equitable, impactful, and efficient future. NASA's 5-year Transform to Open Science (TOPS) project calls for both a shift in the culture of space science and how we conduct research by ensuring scientific knowledge is not only accessible, but also reproducible and inclusive. This initiative, alongside other efforts to make open science more integrated into space research and development, plays a critical role in increasing participation in the field by historically excluded groups.

Another great example of how open source hardware is pushing the dial forward on inspiring the next generation of scientists, engineers, and roboticists is NASA Jet





"…highlighting the possibilities open science hardware unfolds for broadening participation and ensuring representation in space exploration and research."

Propulsion Laboratory's (JPL) Open Source Rover project. The Open Source Rover project is an open source, build it yourself, scaled down version of the 6 wheel rover design NASA uses to explore the surface of Mars. The Open Source Rover is designed entirely out of consumer off the shelf (COTS) parts with the intention of being a teaching and learning experience for those who want to get involved in mechanical engineering, software, electronics, robotics but is also an excellent research platform for rugged terrain.

Some applications of open science hardware already make a significant contribution in the context of museums and learning centres, generating significant engagement and benefit towards the missions of these institutions. These spaces are dynamic hubs for informal education, harnessing open science hardware, in its various forms, to foster public interest in space science. By making complex space technology accessible and relatable, open source hardware nurtures curiosity and understanding. This engagement plays a crucial role in transforming enthusiasts into active contributors within the field.

Beyond traditional educational environments, DIY (do-it-yourself) tools and open science hardware are fundamental in fostering education and engagement within the maker community. Initiatives like Libre Space and the AstroPlant project in collaboration with the ESA/Melissa project, along with 3D models such as the magnetosphere, available on NASA's 3D Resources, serve as accessible, tangible learning resources, demystifying space science and making it more inclusive and approachable. Platforms like the Federation Open Space Makers underscore the inclusivity and diversification of space science, highlighting the possibilities open science hardware unfolds for broadening participation and ensuring representation in space exploration and research. These initiatives are crucial in inspiring and transforming enthusiasts into active contributors and innovators in the field, driving forward a more inclusive and enriched future in space exploration.

Hardening Space Systems through Open Source Hardware

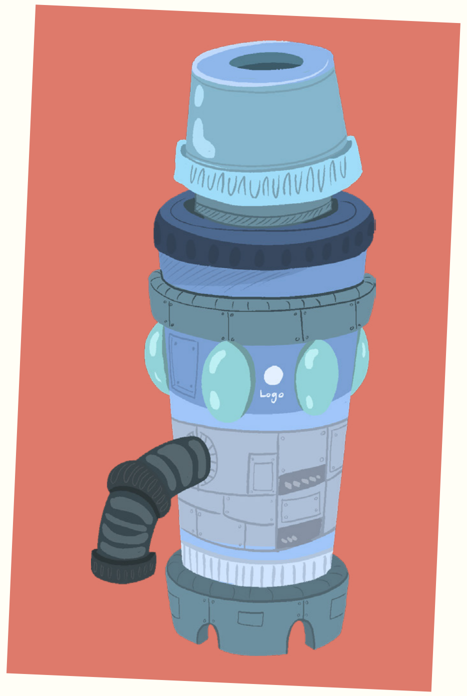
Insights from participants highlighted the range of ways that open science hardware can contribute to the broader science ecosystem, as it does for these other industries, beyond education, engagement, and citizen science. Citing examples in consumer hardware and electronics (Sodaq, Arduino, Prusa), automobile parts (SonoMotors), scientific instrumentation (PocketPCR, AudioMoth, WhiteRabbit, un0rick), drilling equipment and industrial tools (Thürmer Tools), power generation and distribution (Libre Solar), and agriculture (Farmbot), and healthcare (OSI²), participants emphasised the range of industries where open science hardware applications are making important contributions. They emphasised the potential of open source hardware to dismantle technological barriers between researchers, engineers, makers, and enthusiasts. A prevailing sentiment emerged: "The space industry is too closed and proprietary." In contrast to proprietary systems, open source hardware can avoid prohibitive licensing fees, fostering inclusivity.

"The space industry is too closed and proprietary."

The increased transparency and adaptability of open science hardware builds collaboration, trust, and collective progress. Participants emphasised the potential for open science hardware in space science particularly, in that there is significant potential for more robust connections between the space science community and commercial space industry.

Open source hardware offers a compelling approach to enhancing the security of space systems. Traditionally, spacecraft have relied heavily on proprietary, closed hardware systems, which have led to security vulnerabilities because of the limited insight operators have into their inner workings. The adoption of open source hardware in spacecraft—and other technological assets in space—reduces this dependence on closed systems, which gives operators greater control and visibility into potential risks and hence, the ability to act on them. The ability for operators to customise and harden hardware components based on their own unique specific security requirements is another advantage of using commercial off the shelf components for open source space systems.

Open source hardware is built on the foundation of transparency, and with transparency comes the ability to more thoroughly scrutinise and verify systems, since the design documents, test data, and other information are made public. Opening up these black boxes would help to ensure that spacecraft and their components are safe, reliable, and meet the necessary international and industry standards. In addition to reducing the risk of hidden vulnerabilities often found in closed space systems, the use of open source hardware in space also promotes robust supply chain security, allowing



Brand-name part.

Brand-name part breaks.

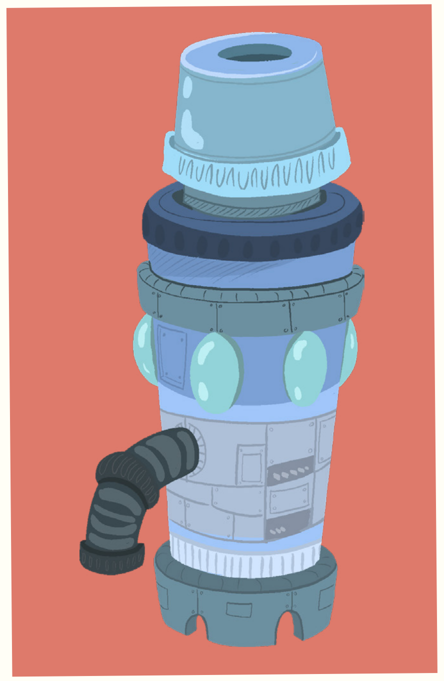
Brand-name part has a proprietary component.

organisations to trace and trust the sources of their hardware components.

Besides the security benefits that come with the open source hardware components themselves, the open science hardware community is a robust one – one where the diverse perspectives on security and collaborative engagement on security audits and peer reviews benefit the security of all parties. By allowing anyone to experiment with and improve upon existing designs, encourages security innovation and when paired with open source firmware and software, open source hardware can offer an even more comprehensive strategy to protect space systems against potential threats and vulnerabilities.

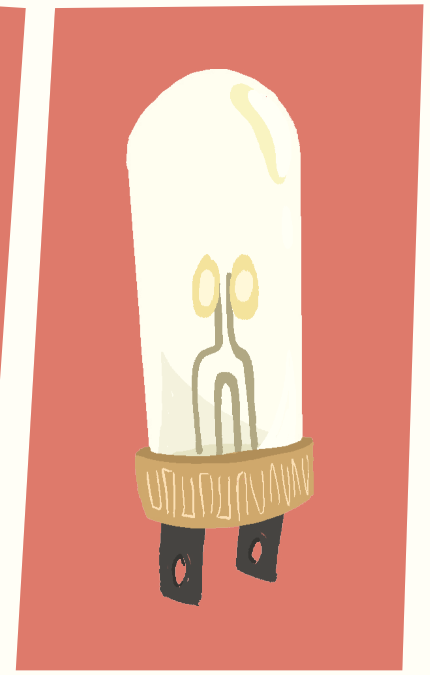
Collaboration is essential in the space industry, where complex missions require the coordination of multiple organisations and stakeholders. Open source hardware enables greater collaboration by providing a shared platform that anyone can access and contribute to. This can lead to new and creative solutions to engineering challenges, which can be critical in the fast-paced and rapidly evolving space industry.

> **“The adoption of open source hardware in spacecraft—and other technological assets in space—reduces this dependence on closed systems, which gives operators greater control and visibility into potential risks and hence, the ability to act on them.”**

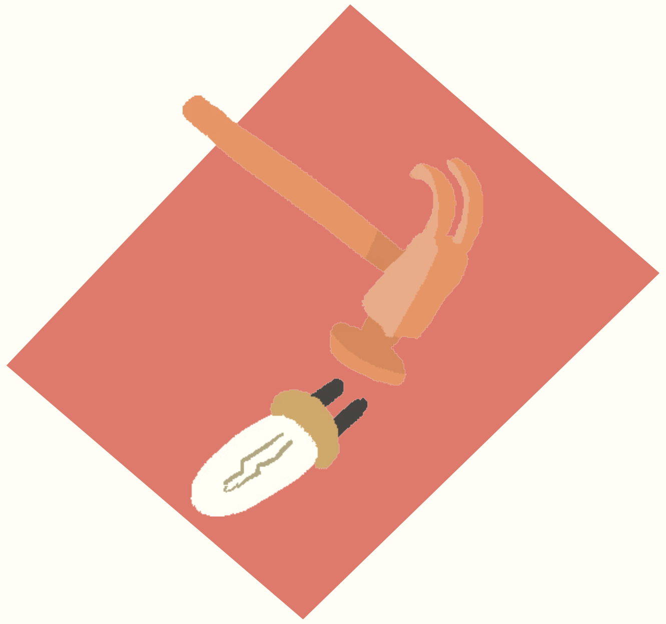


Open source part.

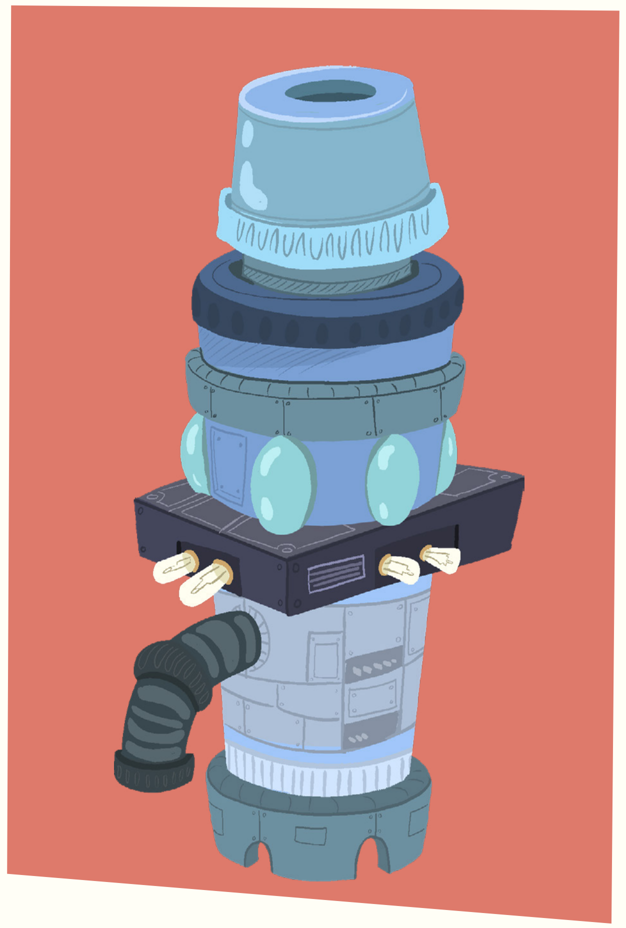
Open source part fails.



Part is made from common consumer components.



Component can be easily repaired with common tools.



Part has been improved and hardened to avoid common failure.

Barriers and Challenges

The workshop also tackled the barriers that need resolution for open source hardware to thrive in space research. Notably, many of these barriers correspond with those in open science hardware work in other scientific disciplines.

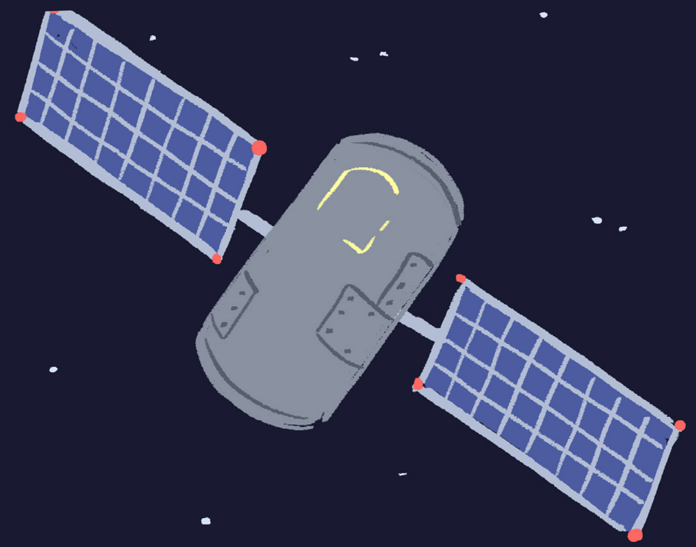
As in many fields of academic research, pressures for funding and tenure (or equivalent career progression chokepoints) work against sharing work openly prior to the publication of peer-reviewed articles. However, counterexamples are beginning to demonstrate the value of open science throughout the entire research process. As one notable example, the OpenFlexure microscope team found that sharing their work before publishing actually helped their review process. Another group shared their product design early and found it boosted their later publication efforts. These stories challenge the norm, suggesting that open science could facilitate publication. At a more landscape level, initiatives like the **San Francisco Declaration on Research Assessment** and **the Latin America Forum's CLACSO-FOLEC** aim to alter conventional academic assessment.

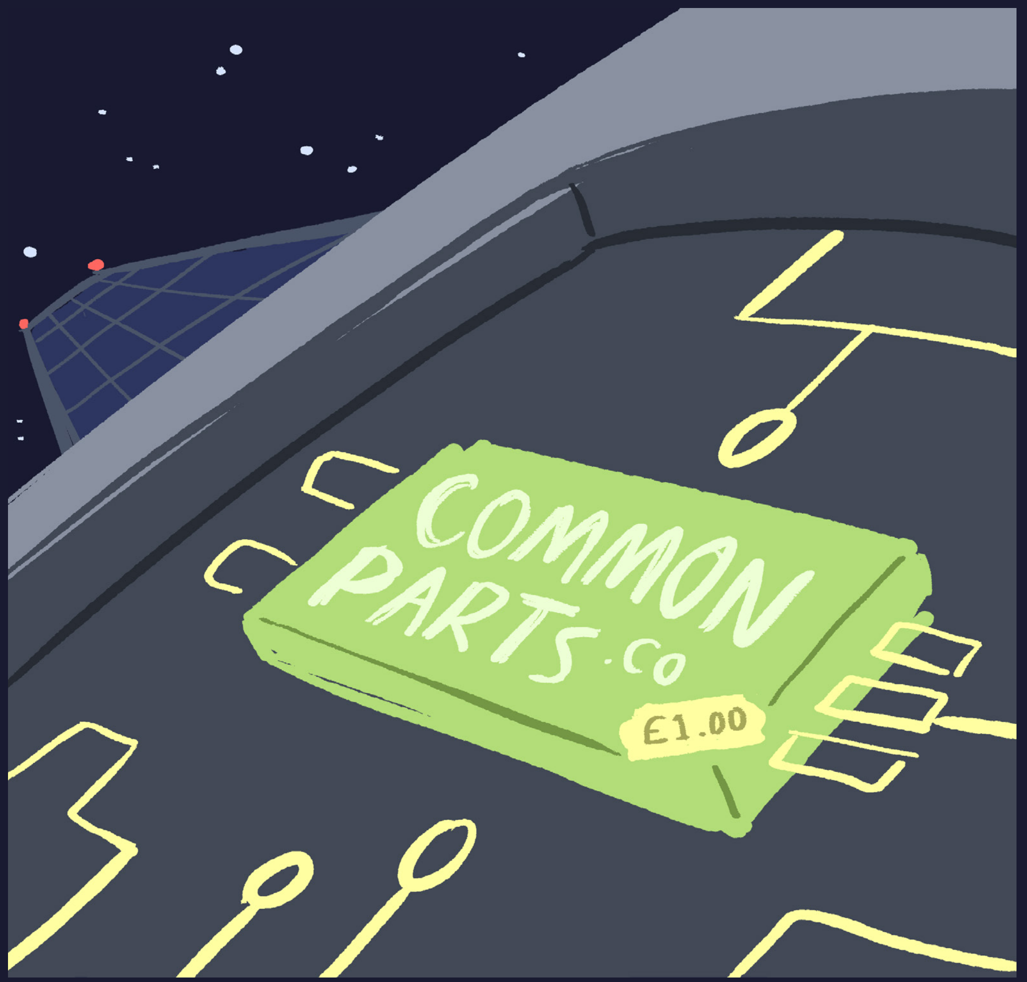
A second significant hurdle revolves around compatibility issues. These issues disrupt projects that use different open source platforms, especially concerning digital file formats. A panellist noted that "Collaboration in open hardware is hard as traditional CAD (computer-aided design) and Git-based platforms don't work well together - PDM (product data management systems) used in the industry is hard to scale due to licences and costs." This concern is echoed by others who face difficulties integrating files or data from different teams. To overcome this, as panellists suggested, increased standardisation for interoperability across the industry is vital. This should cover diverse aspects of open source hardware, like file formats, bills of materials, and measurements. Importantly, the ongoing process of standardisation must include voices from both the space science community and non-institutional contributors like citizen scientists. **Neglecting inclusivity could inadvertently create another closed system, which would in turn minimise the wider potential benefits of open source hardware in space science.**

A few of the key barriers identified are specific to space science, or more pronounced in the space science community. Among these, participants identified export controls as a significant challenge to the spread of open science hardware. These regulations particularly affect US contributors, preventing collaboration with the global community. With the status quo, even discussing ongoing projects with non-US citizens can be considered as an export, with the potential for negative legal consequences. Consequently, many space science projects, especially those related to federal agencies like NASA, are closed to international researchers. Similar restrictions are also

"Neglecting inclusivity could inadvertently create another closed system, which would in turn minimise the wider potential benefits of open source hardware in space science."

"Increased standardisation for interoperability across the industry is vital."

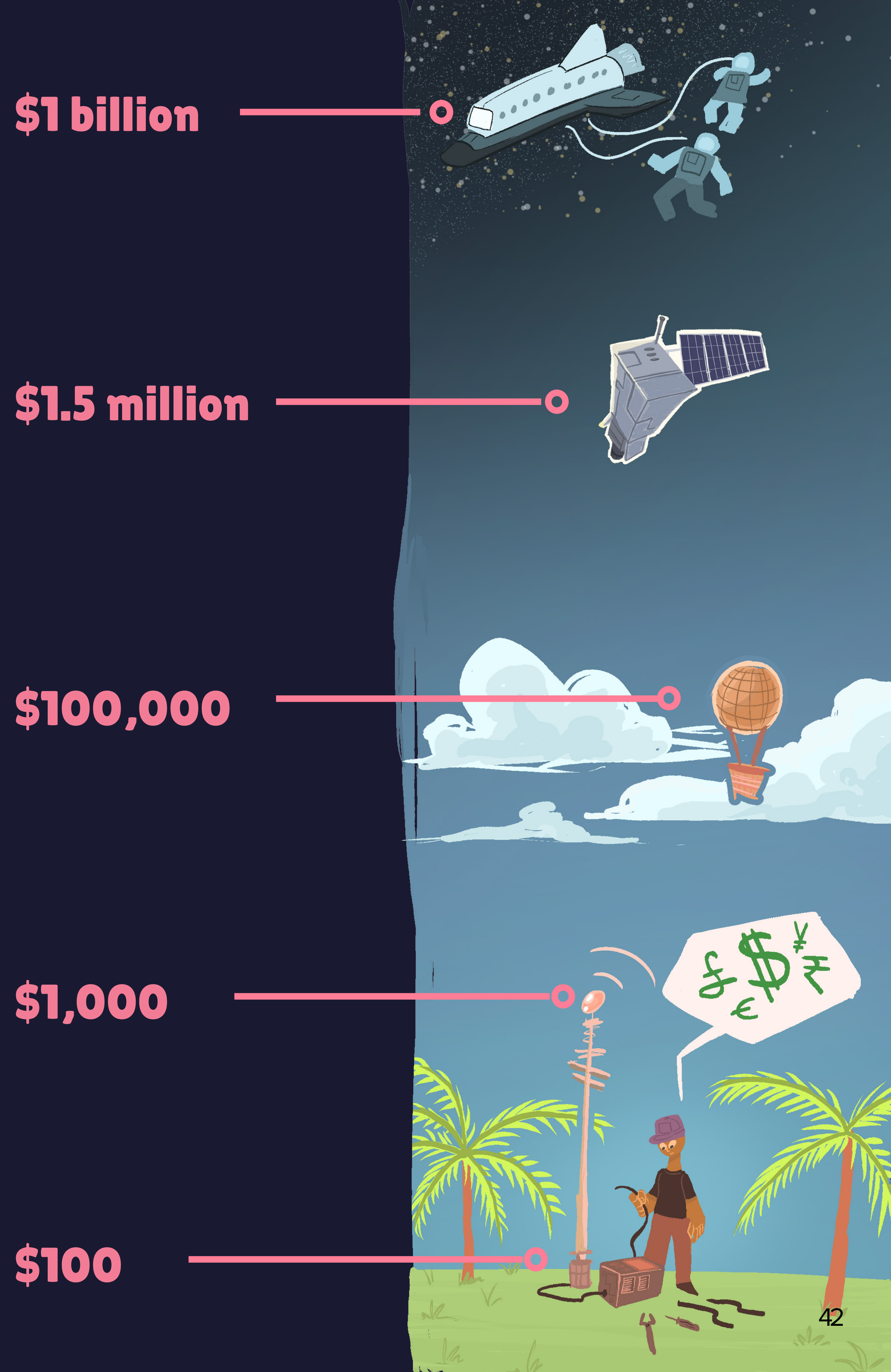




common in other countries, but there is a shared perception that they are particularly strong in the US. In this way, export controls work against the goals and values of an internationally collaborative and inclusive space science community.

Other barriers, participants noted, are particularly pronounced for space science despite being a common issue across open science hardware communities. One participant noted, **"Space is hard, hardware is harder." Testing hardware for space requires things like radiation hardening and mechanical endurance tests; vacuum, thermal and vibe testing, and systems testing is expensive.** The monetary costs and cross-border alignment required of space hardware add complications beyond those of open source software or open source hardware in other domains. In addition, understanding the relationship between regulatory compliance and open source is a continued challenge across the board.

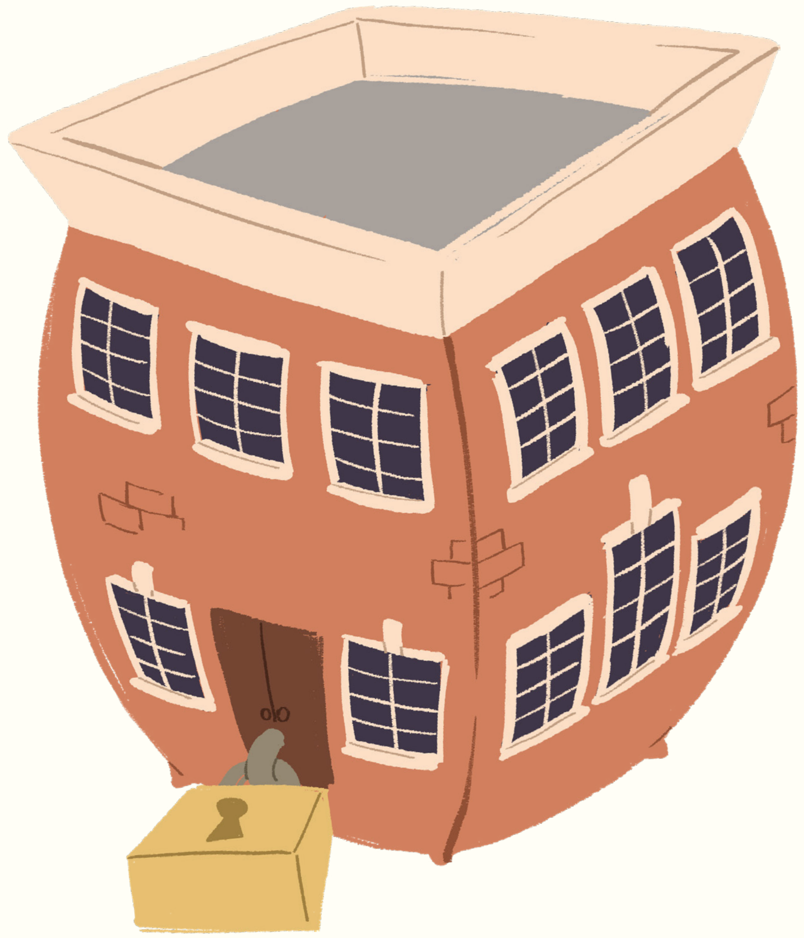
Lastly, the contributions of citizen scientists, makers, and creative communities are often undervalued in the space industry, and this is especially pronounced in space science despite the success of citizen science initiatives. During the workshop, presentations on OpenAstroTech, the Radio JOVE Project, and Oresat—projects all actively shaping space science—illustrated the potential of citizen science initiatives for innovation and for cultivating broader interest and engagement in space science. Despite this, their endeavours frequently remain overshadowed by traditional research institutions. This disparity in acknowledgment results in limited investment in and utilisation of their work. Addressing this challenge is imperative to ensure that the contributions of citizen scientists are recognized, granting them the pivotal role they deserve in propelling the frontiers of space science.



Engaging Key Actors

More than anything, this workshop highlighted the range of projects and organisations that are engaged in space-focused open science hardware and related practices. There is a need to bring them in and work together.

To foster greater inclusivity and enhance the impact of the open source community in space science, this workshop spotlighted key stakeholders for building capacity in open science hardware for space science, including higher education institutes, policymakers, research funders, and leading organisations. The full range of stakeholders documented by participants is listed in Appendix B. The group agreed that targeted outreach to these players could enhance the open science ecosystem and allow for increased application of open science hardware to space science. For example, one-page communications materials for a variety of audiences is an important tool for starting and continuing relationships across sectors.



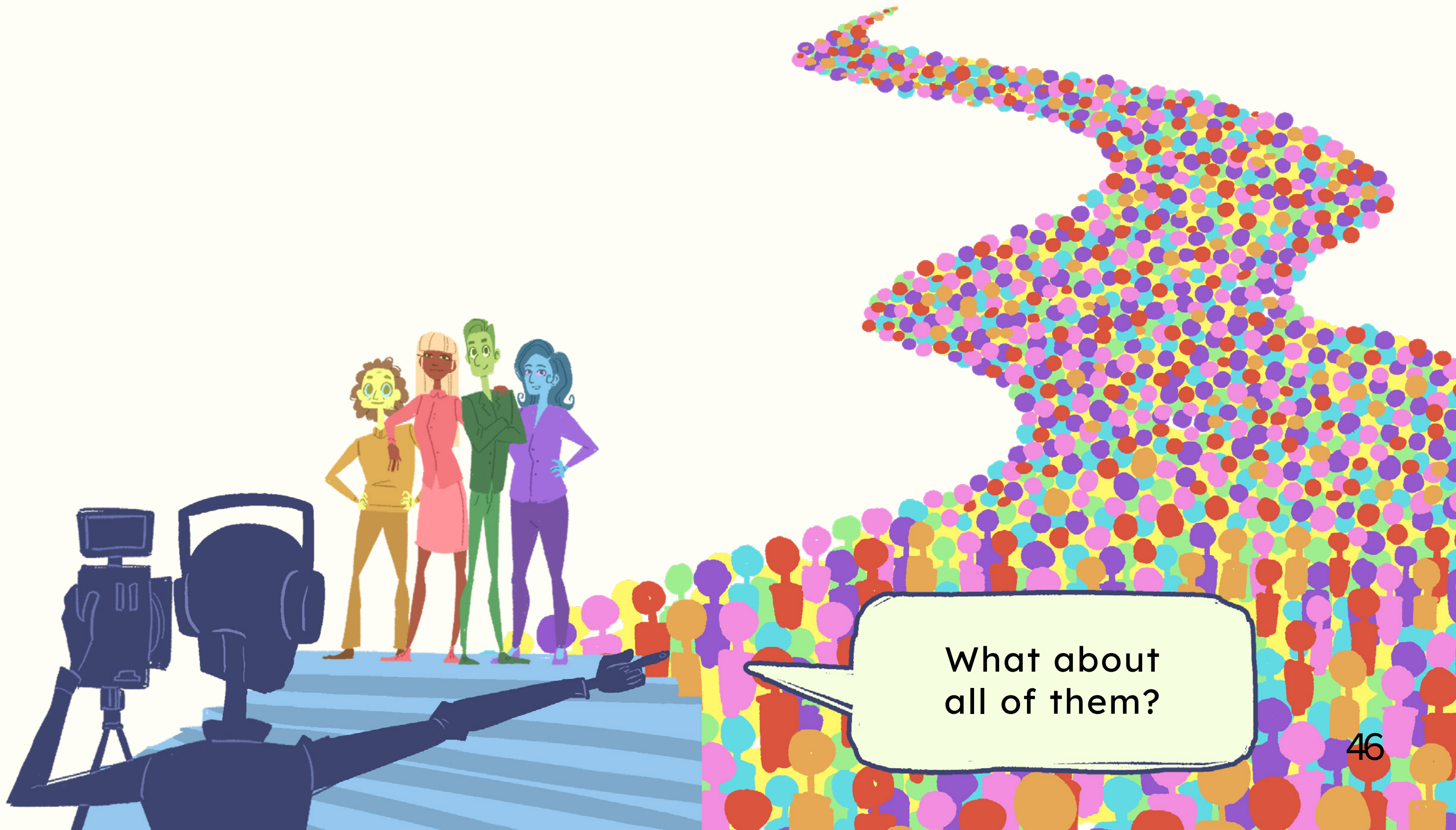
Throughout the discussion, panellists concurred that higher education institutions not only facilitate research but can also nurture openness. To cultivate a thriving open source research community, these institutions can initiate change by embracing open source solutions. For example, universities can facilitate the inclusion of open source options for researchers working with technology transfer offices. Policymakers were listed as powerful actors who can contribute to the open science community. They are able to yield significant top-down influence by issuing guidelines and enacting legislation that promote open source hardware practices in the space sector. In particular, policymakers can establish regulations that simplify the use of open source licences.

Another related target community are makers, creatives, and artists who are developing numerous space hardware-related projects, with some also realised in outer space. In the last decade, there were several art satellite projects developed and deployed, several art experiments realised through the Nanorack payload module, as well as some using open source satellite communications (Open-Weather community) and astronomy (A Sign in Space). Most of these projects essentially emerge from and contribute back to the open source hardware communities while addressing more cultural, creative, or even critical studies of outer space. With that, open source hardware acts as a key enabling technology for the democratisation of space technologies.

Given the need to secure adequate funding for researchers embarking on new projects, the workshop identified a more active role for science funders. A misconception that open source hardware lacks profitability has led to insufficient investment in these endeavours. Yet, multiple cases underscore that open source products not only drive more ethical and inclusive

innovation, but can also be commercially successful. This should also be made known to university technology transfer offices.

Many institutions at a variety of scales have already initiated efforts to facilitate global collaboration through open science. Leading organisations within the space science sector are taking leadership roles in championing open source principles and establishing standards for collaboration. For instance, the European Space Agency has nurtured various open source and citizen science space projects, while NASA actively engages with open source communities to facilitate communication, as evident in their participation in this workshop. Recognizing the contributions of these organisations, participants also identified that umbrella and intermediary institutions could play an essential role in signposting and advocating for open science for organisations within their immediate orbit. For example, disciplinary associations and regional university consortia could fill a gap between international and national agencies and organisations and individual institutions, and provide more direct context and meaning.



Conclusions

Exploring the role of open source hardware in space science reveals a landscape ripe with needs, opportunities, and transformative potential. The utilisation of open science hardware in space applications, particularly in education, citizen science, and public engagement, has already proven fruitful, where initiatives like AstroPlant and the NASA-led 3D printable designs have opened doors to individuals and communities that previously would have been unable to access space research.

Open source hardware's unique ability to reduce barriers to access and democratise space research is a pivotal development. It has and will continue to empower researchers within or outside of universities to undertake space missions in a cost-effective manner, in turn fostering a culture of innovation and collaboration. The rapid development cycle necessary for space science initiatives can be enabled by open science hardware, namely the adaptability of open source designs, which can play an important role in technological progress across both terrestrial and space applications.

Open source hardware has supported education and research in space, inspiring the next generation of scientists and engineers through initiatives like NASA's JPL Open Source Rover project. Besides bolstering educational and collaborative efforts, open source hardware offers advantages in enhancing space system security. By increasing transparency and encouraging innovation in security practices, it helps mitigate vulnerabilities and strengthens the space industry's collective resilience.

Another key advantage of open source hardware in space is that its compatibility and interoperability principles can trigger improved collaboration across diverse space science projects. The ability to host an open and shared platform for space science designs fosters creative solutions to engineering challenges, supporting the rapid evolution of the space industry. Open source hardware could enhance the longevity and sustainability of space systems because open source hardware has made it possible for space systems to be more easily modifiable and repairable. While repairing and modifying hardware operating in space are alternatively extremely costly, in energy, time, and financial resources, open source hardware could help negate these hurdles to the advancement of space science. On top of this, the standardisation of commercial off-the-shelf components (which can be open source) can streamline manufacturing and maintenance processes, in turn reducing waste and resource consumption.

Nonetheless, several barriers and challenges sit at the nexus of using open source hardware for space science, which include funding pressures, compatibility, export controls, and underrecognition of citizen scientists. Addressing these hurdles is crucial for unleashing the full potential of open source hardware in space research. Despite these historical and potential obstacles, open source hardware represents a pivotal paradigm shift in space science, one that opens doors to inclusivity, innovation, sustainability, and collaboration. Engaging key actors in higher education, policymaking, research funding, and leading organisations is, and will continue to be essential for harnessing the transformative power of open source hardware in space science, paving the way for a more equitable, open, and prosperous future in space exploration and research.

Appendices

The following are the projects relevant to the topic of this report represented at the workshop:

ARISA Lab, LLC

ARISA, or Advanced Research in STEAM Accessibility Lab, specialises in enhancing the scientific and educational value of technologies and products to support Science, Technology, Engineering, Art, and Mathematics (STEAM) and language learning in an accessible manner. They contribute to open science and hardware through the development of accessible technologies, such as mobile apps, smart speaker skills/services, and web platforms that align with clients' scientific and educational objectives. One of their notable projects, the Eclipse Soundscapes Mobile Application, provided an innovative, inclusive educational tool sharing NASA's resources in an engaging manner, especially for people who are blind or have low vision, highlighting ARISA's commitment to making space exploration accessible and inclusive. This focus on inclusivity and accessibility in technology solutions for education and science demonstrates ARISA's commitment to open science and expanding the reach of space exploration knowledge.

Aurorasaurus

Aurorasaurus is a revolutionary citizen science project designed to track auroras, utilising crowdsourced observations from a dedicated mobile app and widely used social media platforms like Twitter and Facebook. Developed by space physicist Liz MacDonald and supported by entities such as NASA and the National Science Foundation, the platform enables the creation of a real-time map displaying locations mentioned in aurora-related tweets with geolocation data, allowing users to verify sightings and providing valuable insights closer to real-world observations than models like OVATION Prime predict. This collaborative effort between NASA, Pennsylvania State University, the New Mexico Consortium, and Science Education Solutions, stands as an exemplary model of open source science, empowering citizens to contribute to scientific advancements and enhancing our collective understanding of auroral phenomena.

Citizen CATE

Citizen CATE (Continental-America Telescopic Eclipse) Experiment is an initiative designed to capture high-resolution, rapid cadence images of the inner solar corona, focusing on making advancements in open source space science. The experiment involves a network of more than 60 telescopes, equipped with identical hardware and software, operated by a diverse group including citizen scientists, high schools, and universities. The project employs off-the-shelf components for telescopes, cameras, and other necessary hardware, requiring assembly and modifications, thus allowing a broader range of individuals to engage in space science, fostering hardware accessibility and contributing to the democratisation of space exploration and scientific research. The images and data obtained from the telescopes, contributed to by numerous volunteers and sponsors, provide unique insights into solar phenomena and are invaluable in enhancing our understanding of the sun's corona, thus promoting open source space science.

Eclipse Soundscapes Project

The Eclipse Soundscapes project, under NASA's Citizen Science initiative, studies the impact of solar eclipses on Earth's ecology, focusing particularly on animal and insect behaviour, by leveraging multi-sensory observations and sound data collected from the public during solar eclipses. This innovative project is notable for its emphasis on the accessibility of data collection processes and tools, incorporating features like tactile cues to the AudioMoth recording device. Furthermore, Eclipse Soundscapes is committed to open source principles and free data sharing; it makes available all its raw soundscape data and developed software to the public through platforms like NASA's Solar Data Analysis Center (SDAC), Rainforest Connection, and GitHub.

HamSCI

HamSCI, or Ham Radio Science Citizen Investigation, is a collaborative platform aimed at advancing scientific research and understanding through amateur radio activities. The organisation focuses on projects that use data generated by amateur radio operators (ham radio operators) to study upper atmospheric and space physics, providing a unique perspective on the ionosphere and related systems. HamSCI is a substantial contributor to open source science, especially in open source hardware, by fostering collaborations between professional researchers and amateur radio operators, enabling the development of new technologies, and making scientific observations and insights openly available to the wider community. Through projects like the Personal Space Weather Station and initiatives around solar eclipses, HamSCI empowers individuals with tools and knowledge, allowing them to contribute valuable data and observations to the scientific community.

JHU/APL EZIE-Mag

EZIE-Mag is an important program aimed at bridging the gap between scientific exploration and community involvement, particularly focusing on citizen science magnetometer programs. It empowers students and communities, especially those underrepresented, with kits enabling them to capture and upload mission science data, similar to that obtained by the EZIE mission, thereby contributing critical scientific insights from a terrestrial perspective. With a commitment to cultural humility and reciprocity, EZIE-Mag engages in meaningful intercultural dialogues, especially with indigenous communities, to understand diverse scientific approaches to auroras and to foster a deeper connection with diverse communities and our planet. The program's future vision is to make kit contents and software open source, allowing any community to build, contribute, and integrate their voices into larger global discussions on United Nations priorities, including climate change and access to clean water.

KISPE

KISPE is a project engineering, system design, and implementation company specialising in space, telecommunications, and electronics fields. With a focus on open science hardware, KISPE initiated the Open Source Satellite Programme to develop a Next Generation Microsatellite Platform (NGMP), with the aim to make space technology more affordable, accessible, and sustainable. The design of the NGMP will be made open source and freely available, serving as a hub to connect teams developing open source space capabilities and stimulating innovation in the small satellite industry. The NGMP is designed to address the need for improved affordability, accessibility, and sustainability in space technology, intending to fill the performance and robustness gaps presented by current small satellites and cubesats. Through this programme, KISPE is endeavouring to foster an Open Source Space ecosystem and community, allowing a collective effort to develop and improve space systems and technologies.

Libre Space Foundation

The Libre Space Foundation is a non-profit organisation established in 2015, focusing on the development and promotion of open source technologies and knowledge for space exploration and utilisation. One of their notable projects is SatNOGS, a global network of satellite ground stations designed as a participatory, open source project, providing infrastructure for space communication. Additionally, they have developed UPSat, the world's first open source hardware and software satellite, and are involved in numerous other projects such as QUBIK missions, PHASMA for spectrum monitoring and space-based situational awareness, and Cronos, a hybrid-fueled sounding rocket developed in collaboration with university student-led teams. Through their diverse range of projects, the Libre Space Foundation is fostering innovation and accessibility in space technologies and exploration.

Mach30

Mach 30, a non-profit organisation, is a hub of innovation focusing on the creation and development of open source hardware projects aimed at making space exploration more accessible. They have initiated projects such as the Shepard Test Stand, designed for testing Estes rocket motors and envisioned as a precursor to developing test stands for full-scale liquid rocket engines for orbital launch systems. Another notable project is the Ground Sphere CubeSat Ground Station, Mach 30's inaugural endeavour to facilitate ground-based reception of messages from orbiting satellites, enabling advancements in space-bound communication systems. These projects exemplify Mach 30's commitment to leveraging open source hardware for developing practical, community-driven solutions in the realm of space technology and exploration.

Oresat

OreSat, managed by the Portland State Aerospace Society (PSAS), is an innovative project that brings open source space technology to the forefront, enabling a variety of scientific missions and educational outreach. It operates with a firm commitment to open source principles, allowing broad accessibility to its hardware and software, which are licensed under the CERN Open Hardware License and the GNU General Public License, respectively. OreSat's missions include "OreSat Live," focusing on STEM outreach by letting students build ground stations to receive live feeds from space, providing a hands-on approach to learning and engaging with space technology. Another mission, utilising the Cirrus Flux Camera, aims to enhance the understanding of cirrus clouds and their impact on global climate models by mapping their global distribution, which is crucial for space and atmospheric exploration. This project's open source approach promotes collaboration and knowledge sharing in space science, making it an essential initiative in democratising space exploration and study.

OpenAstroTech

OpenAstroTech is a platform dedicated to providing open source astronomy equipment, focusing on making astrophotography more accessible through 3D printable equipment. They have developed several open source hardware projects like the OpenAstroTracker, a DIY star tracker built from affordable and 3D printed parts, and the OpenAstroGuider, an affordable autoguiding solution with integrated imaging sensor and 50mm optics. Another notable project is the OpenAstroMount, designed for larger telescopes, featuring built-in autoPA and extremely low backlash due to its belt-driven RA and DEC. These projects aim to lower the entry barrier to astrophotography by leveraging community innovation and avoiding locking progress behind paywalls or strict licensing.

OpenFlexure microscope

OpenFlexure develops laboratory-grade open source, customizable optical microscopes, designed to be assembled by individuals using 3D printed components and simple, widely available hardware, maximising accessibility and adaptability. The OpenFlexure Microscope utilises inverted geometry and can achieve high-precision movements, essential for high-magnification studies, and can be motorised using low-cost motors. The OpenFlexure Block Stage is another innovative project enabling fine, sub-micron mechanical positioning with impressive stability, designed for applications like fibre alignment stages. The OpenFlexure Delta Stage addresses the need for static optics and expanded range of travel, enhancing the capabilities of the original microscope design. The microscope has been built or used by its community in over 50 countries and on all seven continents.

Although not directly applied to space science, this project is a prominent example of well-documented and highly reproducible open source hardware.

OpenNEXT and OpenMAKE

Open Make is a multidisciplinary project focused on creating open and FAIR (Findable, Accessible, Interoperable, and Reusable) hardware strategies in academia, with an emphasis on enhancing hardware documentation and publication. It is fueled by the collaboration of researchers from three Berlin universities and is funded by the Federal Ministry of Education and Research (BMBF) and the state of Berlin. The project operates in several phases, including the investigation of current hardware documentation practices, consultation with different communities to define open and FAIR principles for hardware, and the prototyping of a hardware peer review, certification, and publication system. This initiative aims to cultivate an ecosystem for hardware publication, which includes a peer review system to recognize the efforts of hardware makers and to drive the acceptance and adoption of developed workflows and FAIR hardware in the research community. They are actively involved in the GOSH community.

PICTOR Telescope

PICTOR, stationed in Athens, Greece, stands as a significant entity in the open source hardware domain, providing a fully open source radio telescope equipped with a 1.5-meter parabolic antenna. This facility enables users to conduct free continuous and spectral drift-scan observations of the radio sky in the 1300~1700 MHz range. Designed to democratise radio astronomy education, PICTOR allows students, educators, astronomers, and other enthusiasts to delve into the wonders of the radio sky without constructing large and expensive antennas. The project's comprehensive approach in offering open access to radio astronomy knowledge is pivotal, with all the software and hardware details openly available on GitHub for educational and developmental purposes.

Radio JOVE Project

The NASA Radio Jove project is a stellar example of leveraging open source hardware for space exploration, enabling enthusiasts and students to construct their radio telescopes to observe natural radio emissions of Jupiter, the Sun, and the galaxy. By providing access to open source hardware designs and guides, Radio Jove fosters a global community of amateur astronomers and educators who can contribute to the collective understanding of celestial bodies. The project not only democratises space exploration by making it more accessible to the public but also encourages scientific learning and curiosity, creating a broader base of participation in astronomy and space science.

SunRISE Ground Radio Lab

SunRISE Ground Radio Lab (GRL) is an innovative initiative that works in tandem with the University of Michigan and NASA's Sun Radio Interferometer Space Experiment (SunRISE) mission, engaging high schools across the United States in radio science campaigns. The GRL promotes citizen science by employing a multi-frequency radio telescope to observe various radio emissions from celestial bodies like Jupiter and the Sun, as well as from the Milky Way Galaxy and Earth, fostering a deeper understanding of radio astronomy among high school students. This project stands as a commendable effort in the field of open source science, as it not only provides hands-on experience and increases science literacy but also facilitates the exchange of data and ideas among participants, allowing students and staff to access online observatories and real data, hence contributing to the broader scientific community. Through this, SunRISE GRL is pivotal in inspiring and educating the next generations of Science, Technology, Engineering, Arts, and Math (STEAM) scholars.

Waag Futurelab

Waag Futurelab is at the forefront of creating innovative solutions through open source hardware at the intersection of technology and space. As a public research organisation, Waag empowers citizens as designers of environmental sensing devices and provides training through its Waag Academy programme. In the context of outer space research, Waag's Space Lab developed a Planetary Public Stack as an open method for the development of planetary imaginaries inclusive of citizens, creatives, and artists. Through such projects, Waag emphasises the crucial role of open source hardware in fostering collaborative, community-driven solutions to pressing environmental and spatial issues.

Engaging various actors in open science hardware for space science

Stakeholder Category	Specific Stakeholders	Roles/ Responsibilities	Impact
Policy and Regulation	Policymakers for R&D, Regulatory bodies	Setting open preferences for R&D, making regulations open-friendly and encouraging competition, addressing ethical considerations	Fostering an enabling environment for open science hardware, managing export control issues, ensuring equitable open science practices
Funding Entities	Research donors, philanthropy	Setting open preferences for R&D, making regulations open-friendly and encouraging competition, addressing ethical considerations	Ensuring lowest costs, fastest innovation, and minimising duplication of effort
Institutional Leaders	Higher education institutions, NASA administration	Ensuring long-term success and use of open projects, advocating for accessibility and transparency	Providing leadership and direction, building culture and institutional frameworks for open science hardware
Industry and Business	Industry partners, specialised business coaches, OEMs (licensing and intellectual property)	Licensing out intellectual property and manufacturing, testing open science hardware products and providing feedback	Bringing commercial perspective and expertise, ensuring product viability and performance
Education and Training	Educators and students, academic mentors	Engaging with hardware builders and users, mentoring students/young scientists	Training and developing skill sets, ensuring diverse and informed participation in open science hardware
Publication and Com-munication	Scientific publications, popular science journals	Providing open access, updating and completing open source design, facilitating outreach and engagement with broader communities	Disseminating information and knowledge, accessing expertise from outside of conventional institutions and communities,
Technical Providers	ICT infrastructure providers, standardisation bodies	Providing tools and infrastructure, sharing hardware sources from requirements	Supporting the technical needs of open science hardware projects, ensuring standardisation and interoperability
Culture and Creative Industries	Makers, creatives and artists	Engaging and developing new hardware, facilitating outreach and engagement with broader communities	Contributing diversity and democratisation of space research, providing expertise outside of space domain
Community and Wider Public	Diverse communities	Creating access to sites or resources for scientific purposes, engaging for an open, equitable science system	Offering diverse perspectives and resources, meeting global needs and fostering inclusivity

Citations

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[4] Bureaud, Annick. (2021) It's a Beautiful Name for a Satellite: Paradoxical Art Objects Somewhere between Politics and Poetics. Leonardo 54 (1): 79–91.

Thank you for reading.