Can Communities Produce Complex Technology? Looking Into Space for Insight

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Abstract
This article examines a community producing complex space technology. We attempt to highlight which aspects of the community’s activities can help democratize high-tech development while providing a context for similar cases involved in developing and manufacturing nonhigh-technological artefacts. We discuss how this has been made possible by using a technology-determined organizational approach based on the CubeSat open platform infrastructure, blending formal and hands-on education, open communication, specific recruitment and working practices, and a genuine passion for technology. We identify as critical enablers for community-based collaborative development of space technology the open-source architecture standard called CubeSat Design Specifications, the modularization of work in subsystems and between different organizations, and the open and participatory approach work tasks distribution and decision making. Moreover, we argue that the digital/informational aspect of this technology allows the community to implement organizational practices that resemble how open-source movements over the internet produce complex digital artefacts like Wikipedia or Linux. ESTCube can shed light on community-driven complex technology development, providing lessons on what a democratized version of high technology would resemble and how open and digitalized technology can help develop the capacities of a community.

Keywords
CubeSat, technology, democratization, complexity, open source, space

1. Introduction
In recent years, the myth of the lone innovator who, starting from their garage, has managed to build huge fortunes due to their ingenuity, and in the process carry society forward in its technological evolution, is beginning to be dispelled. Technological development is an iterative process and, as several studies have indicated, it is more often than not the outcome of publicly funded efforts instead of private initiative. This development is much needed too, since the decades of continuous attacks on the public sector have led to knowledge (and consequently technology) production with short-term financial gains rather than far-reaching economic development and social welfare (Archibugi & Filippetti, 2018). Scholars highlight that ubiquitous technologies, like electricity, enjoyed by everyone today are there thanks to public policy (Perez, 2002), while booming industries, like ICT and biotechnology, have greatly benefited from fundamental research in high-tech areas funded by public sources (Mazzucato, 2013). And it is the state which is typically willing to engage in the risky and low gains, in terms of immediate monetary benefits, research, which is necessary for future innovation rather than private actors in the markets. Ultimately however, whether publicly or privately funded, new technology is typically deployed through private applications, which seek to maximize profits and control over society for certain private entities rather than the public good.

Simultaneously, calls have been made for the democratization of technology. Meaning seizing control and reshaping technology to better serve its end users; society as a whole (Feenberg, 2002). Building on that imperative and inspired by the achievements of open-source movements, others have explored its radical potential for genuinely democratized technology in fields such as agriculture, energy production, ICTs, and so on. By examining communities which develop and freely disseminate technology, they highlight the capacity for alternative technological trajectories that promote openness, sustainability, user autonomy, and ultimately break from the incumbent framework of restrictive technologies. However, when it comes to highly sophisticated and complex novel technologies, these trajectories become significantly more difficult to envision.

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As opposed to creating a seeding tool with farmers or a small wind turbine, the processes and skills required to develop a highly sophisticated piece of technology cannot be simplified extensively in order for practically everyone to be able to participate. This article will examine how it is possible for a community to create such technology through the case of ESTCube, which produces space technology (both for exploration and monitoring earth). It will attempt to highlight which aspects of the community’s activities can help democratize high-tech development. In the next section, we will review the debate between state and privately developed basic and specialized technology and how that leaves much to be desired in terms of democratization of technology.

2. Private or Public?

During the past few decades, the rise of neoliberal economics pushing to minimize the public sector have had a devastating effect on publicly funded basic research (Judt, 2011). Meaning the research which has no direct commercial applications yet forms the foundation for future technological breakthroughs which in turn create new sectors of activity (think for instance the internet or green and nano technologies). Mazzucato (2013) in her influential work on the “entrepreneurial state” indicates that most of the innovative technologies that the iPhone uses were, in fact, drawn from publicly funded research on GPS technology, the internet, touch screens and others. And yet, the state is expected to have minimal involvement in the economy where market mechanisms are supposed to be appropriately handling technological advancement according to their imperatives. Worse still, institutions like universities, which traditionally engage in basic research, are increasingly geared towards research that produces new products or improves on existing ones (Archibugi & Filippetti, 2018).

This state of affairs has led to calls to socialize not only the risks and costs of developing basic technologies but also the rewards too. And while one may claim that the rewards are indeed socialized through taxation, rampant corporate tax evasion and global capital movements, sometimes hidden behind labels like the “sharing economy” (Baranowski, 2021), render this argument moot. There have been proposals for the state enjoying some benefit from the investments it makes in innovation, like adopting a portfolio approach (Rodrik, 2014) or “income-contingent loans” and retaining equity in the firms utilizing the publicly funded technology (Mazzucato, 2015).

While these are steps toward ameliorating this situation, we argue that such proposals are inadequate to address the issue of the broader society reaping the benefits of technological advancements or actively contributing to them. In the next section, we present a different path, which critically examines technology in society and seeks ways to democratize it. This sets the framework through which we explore the case of ESTCube in the section that follows.

3. Democratizing Technology

Parallel to discussions around public versus private technological innovation, technology studies scholars, and more specifically those engaging with critical theories of technology, have been attempting to “show the ordering, disciplining, rationalizing and modernizing processes that are associated with technology” (Misa, 2008, p. 372). In other words, through illustrative cases, they investigate the economic, social, political, and cultural values that motivate the production of technology in society and explore the development of technological trajectories which are more accessible, just, and inclusive. The concept of power plays a key role here since technology is, arguably, utilized to direct its distribution in society. It enables individuals or specific social groups to exercise power through certain technologies and systems. People are exposed to seduction, manipulation, coercion, or are simply expected to abide by certain authority through specific delegated technological artefacts (Brey, 2008).

It is the normative goal, then, of critical theories of technology to seek different ways for power to be distributed more proportionately in society through technologies. A version of technology that is more democratic, free and just is viewed as the necessary foundation (Brey, 2008). This democratized technology would be more inclusive in its development, dissemination and use. Andrew Feenberg’s body of work, arguably, offers the most concrete critique of technology developed in the capitalist system. He calls for the democratization of technology stemming from initiatives and movements at the micro and meso levels of activity through marginalized social groups who, initially acquire the conscious, and then the technology itself despite having to contend with structural obstacles as well as powerful private actors like global corporations (Feenberg, 2002).

Technological design is restricted by economic, political, and social imperatives often enforced by the powerful social actors to dominate over others. They form the underlying technological rationality in capitalism, which reinforces a hierarchical structure by prioritizing certain technical configurations over alternatives (Feenberg, 2002). Think of the assembly line. It illustrates how control is enforced via low-skill and repetitive tasks around machines, which is utilized to boost productivity and profits for the owners instead of improving the welfare of the workers (Braverman, 1974).

This is materialized by infusing the aforementioned social imperatives in the design, language and practices through a process Feenberg (2008) calls instrumentalization. Instrumentalization first breaks down technological artefacts into their basic components that decontextualizes them from their social environment. In the second phase of instrumentalization these components are recontextualized in the social world with values, goals, and meanings encoded within. These “technical codes” according to Feenberg (2002) “define the object in strictly technical terms in accordance
with the social meaning it has acquired” (p. 88). In other words, they define its design and manufacturing as well as the guidelines, standards, and processes to be followed. This may have a profound impact on how societies are organized, produce, and distribute the benefits of technology among citizens.

Critical theory of technology strives to expose this underlying technological rationality in society and seek out those initiatives that aim to produce radical new technologies. Feenberg (2002) offers “democratic rationalization” which questions basic, self-evident assumptions and values coded in technology and relevant institutions and structures. It posits that reappropriation of existing technological artefacts, collaborative development of new ones, but also social movements pushing for a shift in the technological paradigm can lead to more democratized technology. Building on that insight others have examined open-source technology initiatives as a potential source for such action.

Giotitassas (2019) has explored the development of agricultural tools by farmers and their allies which were better suited to their needs and values. Kostakis et al. (2013) similarly explored open-source artefacts developed for energy applications, while Söderberg (2010) delved into the processes of community building open-source telecommunication hardware. Feenberg (2002) himself offers the example of the Free Minitel as an example of reappropriation of technologies. The Minitel was first introduced as a telephone information distributor but was repurposed by users as an anonymous communication device. Such cases exemplify how a realization of the profound sociopolitical implications technologies hold in combination with the imbuing of suppressed values like openness, sustainability, user autonomy may lead to the development of structures and processes for more participation in the development and dissemination of technology that may better serve society as a whole rather than specific powerful social groups.

Such cases highlight a dynamic within this emerging phenomenon toward democratization of technology. At least democratization as described above, in terms of unrestricted access in all stages of the development and use of technology. However, when it comes to advanced technologies like the ones discussed in the previous section, then matters become significantly more complex. Access to specialized materials or equipment for such application is typically limited in few publicly or privately funded research facilities across the globe. The knowledge and know-how required for participation similarly is limited to those whose profession requires it or the truly passionate amateurs. And yet, this passion exists. Unlike other more accessible technologies, it cannot be claimed here that everyone may participate in the development of basic technologies thus making them wholly democratized.

Certain steps can be taken further from the debate between state or private development into actually engaging with communities of people that can participate in the process. Others have explored ways for wider public engagement in biotechnologies (Delgado & Callén, 2017) and nanotechnologies (Selin & Hudson, 2010). Kera (2014) has examined community projects engaging in open-source technology research and development of nanotechnology and synthetic biology applications in an attempt to break down the barriers of the public’s involvement in novel scientific fields.

We will present another such community which, despite very obvious barriers, manages to participate in the development of space technology. We discuss how this has been made possible through specific recruitment practices, strategic partnerships, and genuine enthusiasm for the technology. Through this case we wish to distill certain lessons on what a democratized version of high technology would be possible.

We view ESTCube as an instrumental case study, selected to provide insight into community-driven high-technology development. Data were collected through extensive desk research which includes web sources (specialized online portals, grey publications, blogs, news reports), visual and audiovisual data, and other materials. Furthermore, structured and semistructured interviews with active members (both in individual and group settings), as well as field research, were employed to acquire a deep understanding of the community’s inner workings.

We received vital information on how the initiative is organized and how funding and logistics are determined by its connections and immediate context (national, Baltic sea area, European space research environment) during individual interviews with leading project members. They also enriched our understanding of how the organization of work is heavily determined by the intricacies of the technology (interdependence of software and hardware, use of unique materials, codesign of components, and the need to balance out decisions that may affect the whole artefact). During workshops and a visit to their working facilities, we had the opportunity to interact with team members and acquire a deeper understanding of the motivations and mode of working. Overall, fieldwork was paramount for understanding the big picture and building the narrative on the case that otherwise was dispersed over technical publications, media feeds, and reports. As such, the insight gained from these experiences is interwoven across Section 6, which provides a thick description of the case.

### 4. CubeSats

A CubeSat is a one unit (1U) 10-centimetre side cube-shaped satellite. By combining the volume of two or more 1U CubeSats, the size of the CubeSat can be arithmetically increased (2U, 3U, nU). CubeSats are based on an open-source architecture standard known as the CubeSat Design Specification (CDS; Mehrparvar et al., 2014; Swartwout, 2013; Toorian et al., 2008). CubeSats carry payloads—technological artefacts intended to be tested/demonstrated with the mission, like a camera or a propulsion system.
A CubeSat is like “a box” with two distinctive features. First, it ticks all the formal requirements to be loaded in a rocket launcher and safely deployed into orbit. Second, it is designed to operate in the extreme conditions of outer space, protecting its content. Besides the protective shield of the “space box” container, and its contained artefacts (payloads), a CubeSat needs to perform other functions to be operative. These operative functions (e.g., navigation, communication) are organized in different subsystems (e.g., attitude determination and control system, communications system) based on specific hardware (e.g., gyroscopic sensors, microstrip antenna; Ehrpais et al., 2016; Slavinskis et al., 2016).

As a means to safely launch the payloads that constitute the CubeSat mission objective (test/demonstrate technology artefacts), CDS provides a frugal platform for prototyping space technology. Its construction, development, and launching costs are relatively low, with shorter technology development periods (Selva & Krejci, 2012; Woellert et al., 2011). CDS is open to everyone, and it has been very beneficial to startups, universities, developing states, and communities (Woellert et al., 2011). In the next section, we are going to examine what makes technology complex, and how technology complexity can be conceptualized.

5. Complexity in technology development

Morin and Postel (2008) define complexity as a fabric “of heterogeneous constituents that are inseparably associated” (p. 5). He argues that in complex systems, knowledge should be used to tackle uncertainty and disorder (Morin & Postel, 2008). There are two main approaches to technology complexity: the complexity of knowledge and the complexity in industry.

The complexity of knowledge denotes nonlinearity, interdependencies of the parts, and intertwined chains of effects leading to uncertain outcomes (Yayavaram & Chen, 2014; Tani & Cimatti, 2008). In CubeSats, subsystems are interdependent, interconnected between themselves and with the payloads. Hardware is irreplaceable once the CubeSat is in orbit. Redundancies of functions are needed to back up possible failures and malfunctioning in the components. All CubeSat components should resist external factors like the thermal vacuum and intense vibration during the launch.

Complexity in industry postulates a correlation between maturity and simplicity of technology (Carbonell & Rodriguez, 2006; Vaesen & Houkes, 2017). Technology readiness for manufacture denotes the use of standards and modularity in design and production (Tani & Cimatti, 2008; Tsai & Wang, 1999). When the ESTCube initiative started, there were no recognized standards for components, subsystems, or payloads for CubeSats. ESTCube CubeSat’s payloads and subsystems are unique crafts mostly made of commercial off-the-shelf components. Complexity in industry further denotes a mature understanding of the technology. The complexity of knowledge should be mastered before attaining mature and simplified industrial processes. Mature specialized knowledge on a complex technology leads to the compartmentalization of knowledge, which allows modularization of the complexity and simplicity in production by standardized processes.

Kostakis (2019) sees modularity as the core feature of the digital. It describes the degree to which well-defined and limited modules couple with each other, where the highest degree of modularity entails each module performing only one specific function (Kostakis, 2019). CubeSat seems to be a highly modularized technology—each subsystem and payload performs one unique function and occupies a well-limited space in the structure. Moreover, modularity provides the possibility to work in each module independently if one condition is granted: each module should respect the common design rules (structure arrangement) that allows the modules to fit together as a system (Baldwin & Clark, 2003). Hence, if being digital is to be modular, and modularity is what ultimately unlocks complexity in technology, then the more digital technology is, the easiest to deal with its complexity.

Conversely, by labelling space technology over complex, a wall is raised between a small elite of space technology specialists and the rest of society. Until the arrival of CubeSats, space technology has been “nonappropriable.” However, building a CubeSat and launching it into space does not suffice to reappropriate space technology. Once in orbit, everything a CubeSat sends and receives is information. Communication with the CubeSat is critical to the success of the mission, and all the data retrieved from the satellite needs to be stored and analyzed. The CubeSat Program provides the infrastructure to carry out a CubeSat mission. Its technological infrastructure entails the CDS, a network of ground stations, and a mission control center (Toorian et al., 2008). Besides the technological infrastructure, the CubeSat Program requires a community of developers. In the next part, the salient characteristics of ESTCube’s community are presented.

6. The case of ESTCube

Estonia, a small European country with a population of one million, has prioritized ICT development in its national strategic plan since it regained its independence in 1991 (Kalvet, 2012). As a result, government, banking, education, taxation, and many other areas are highly digitized, featuring a wide array of online services: electronic voting (e-voting) has been implemented since 2005, making this small country a leader in such developments. Estonian society is often exposed to novel technologies, with Estonian institutions pioneering self-driving vehicles and delivery robots. In addition, technology is regularly part of the public debate, such
as the discussions around national regulation of artificial intelligence (Kerikmäe & Pärn-Lee, 2020).

This environment has, doubtlessly, provided favorable conditions for the conception and subsequent flourishing of the technological initiative, we will be discussing in this article. In 2008, a group of researchers and space enthusiasts from Estonia joined forces to develop the first Estonian spacecraft. From lacking proper national space technology infrastructure and expertise, this Estonian project tapped into open source technology and involved international cooperation from its conception.

6.1. Recruiting the Space Community

The Estonian Student Satellite Program (ESTCube Program) is a locally adapted version of the CubeSat Program. Through this program, a workforce of volunteers is recruited to work on ESTCube CubeSats (Noorma et al., 2013; Slavinskis, Reinkubjas, et al., 2015). Tartu Observatory (TO) and the University of Tartu (UT) have been the main hosts of the program. Since 2018, the former is an institute within the latter. They provide working space, labs, and testing facilities (Iakubivskyi et al., 2020).

Several ESTCube members have become department leaders, researchers, and engineers in these host institutions.

Typically, college-level students join the ESTCube Program, but the recruitment process starts earlier. To inform about space science and their work, ESTCube members organize and take part in several activities: workshops, presentations, and science outreach events. During summers, there are special activities to train high-school students. The Summer Academy brings together high school and university students to TO (Janson, 2018). There, students can participate in ESTCube activities through the Science Camp (Teaduslaager) and the Science Task Force (Teadusmalev).

The ESTCube Program provides hands-on education for students, complementing their formal education. Students work on goal-oriented tasks related to some aspect of the CubeSat. Responsibilities, the difficulty level of the work tasks, and other features are decided on aptitudes, capacities, experience, and disposibility of the students. Team leaders supervise and coordinate students, but students are expected to work independently on their work tasks. Recruits often write their theses (BSc, MSc, or PhD) on some aspect of the CubeSat. The first satellite produced by ESTCube, called ESTCube-1, has resulted in over 30 BSc, 20 MSc, and 2 PhD defended theses (Slavinskis, Reinkubjas, et al., 2015).

ESTCube members are also involved in other peripheral activities, often as amateurs. Passion for science and technology is their core intrinsic motivation, along with meeting like-minded people. Their areas of interest include radio communication, robotics, science Olympiads, hackathons, programming, game development, or desktop fabrication. For example, an ESTCube member has created an online database on nanosatellites (nanosats.eu). This database was originally supported by an EU grant, but since 2014 it is regularly updated every 2 or 3 months.

During the development of their ESTCube-1 (2008-2013), the ESTCube community did not formalize the initiative into any legal form. ESTCube members were tied by shared values, having a common goal: to produce and launch a CubeSat, making Estonia a space nation (Noorma et al., 2013). They envision space exploration as an activity that should benefit humanity as a whole. Membership is open for everyone who shares their vision and their values and is willing to contribute to the project with inclusive community development prioritized over efficiency.

Community building on shared values is crucial for ESTCube community persistence through the long CubeSat development periods. The principal stress factor came from working with an accelerated schedule after accepting an earlier-than-expected launch opportunity from Ariane space (Slavinskis, Pajusalu, et al., 2015). The iterative prototyping of satellites is only possible through successive prototypes and models of the flight-ready satellite. Once a CubeSat is in orbit, there is no possibility to bring it down to Earth for hardware improvements or reparations. Simulations (digital models) and physical tests in testing facilities (e.g., testing functions, systems integration tests, and environmental tests) are performed to test the technology. ESTCube members report strong life-long bonds with other team members, developed through years of close collaboration—especially during the latest stages of development of ESTCube-1.

6.2. Funding and Logistics

In the case of ESTCube, researchers, engineers, and space enthusiasts were the instigators. ESTCube is “a combination of various initiatives—education, science, technology, as well as student and volunteer organizations” (Kalnina et al., 2018, p. 2). The ESTCube community does not own fixed assets or property: the host organizations provide working space and lab access.

To this day, ESTCube does not have one principal source of funding. Several outlets are used to finance the costs of manufacturing technology for the CubeSats, the launching costs, and to financially support its members. The European Commission, The European Space Agency (ESA), and Estonian grants and scholarships (Lätt et al., 2014), a crowdfunding campaign (Kalnina et al., 2018), donors, or sponsorships, are some of the funding sources that ESTCube has been tapping through the years.

The complexity of ESTCube’s organizational model gradually expanded. Having an international network of partners, over 200 students divided into a larger number of working tasks, involvement in international regulatory bodies, partnering with ESA, among other areas of activity, become an administrative burden. The organization could not operate much longer without a formal legal structure. At
Table 1. List of ESTCube-1 sub-systems and their functionalities. Elaborated by the authors from https://www.estcube.eu/en/subsystems

| Subsystem                  | Function                                                                                |
|----------------------------|-----------------------------------------------------------------------------------------|
| ADCS: Attitude determination and control system | Determines and modifies the satellite's orientation                                     |
| CAM: Onboard Camera         | For taking images of the Earth and the main payload                                     |
| CDHS: Command and data handling system | The satellite's main onboard computer                                                   |
| COM: Communications system  | For up- and downlinks                                                                   |
| EPS: Electrical power system| Provides electrical power for the satellite                                             |
| PL: Payload                 | The satellite's experiment module, that contains the tether and everything else related to the experiment |
| STR: Satellite's structure  | The containing structure as specified in different CDS versions                         |
| GS: Ground station          | A radio station on the ground which is used to communicate with the satellite           |
| MCS: Mission control system | It is the mission control software enabling monitoring, sending commands and viewing received data from the satellite |

the beginning of 2017, 32 new and old members of ESTCube founded the Estonian Student Satellite Foundation.

The initial objective of ESTCube was to build one CubeSat and launch it into orbit. The mission was accomplished in 2013, when ESTCube-1 was launched into Earth's orbit. The initiative was redirected after launching ESTCube-1. The transition period from ESTCube senior leaders to the new generation leading ESTCube-2 satellite took approximately 2 years. Currently, the second CubeSat (ESTCube-2) is in an advanced development phase under the guidance of the Estonian Student Satellite Foundation.

ESTCube-1 provided Estonia with the space technology proficiency needed to attain permanent membership status in the ESA. The status of Estonia as a member in ESA brought new opportunities for ESTCube and its host organizations to expand their involvement in new activities, both locally and internationally. The same year that Estonia joined ESA, ESTCube-1 micro-camera was selected to be a payload of the European Student Earth Orbiter satellite (the third mission within ESA’s Education Satellite Program; Noorma, 2016). Also, in 2019 Estonia was invited to participate in ESA’s “Comet Interceptor” mission. ESTCube also influences some decisions of its hosting institutions. Acquisition of lab testing machinery, rearrangement of departments and academic curricula, selection of grants and project proposals take into consideration the ESTCube needs and outcomes.

Producing knowledge and technology in-house is one of the priorities of ESTCube and its hosting organizations. However, procuring the machinery to manufacture space technology was never an option. Instead, a network of external partners is used to produce components designed and developed by ESTCube members.

6.3. Technology-Determined Organizational Structure

CubeSat technology greatly determines the organization of work. ESTCube-1 consisted of seven subsystems and two ground support systems (Table 1). The communication and interrelations between subsystems must be well-defined and effectively executed. Each subsystem has a team leader who coordinates the work tasks inside the subsystem team. Also, team leaders coordinate tasks among themselves. All subsystem teams engage in discussing the main choices from the early stages of design. All issues are open for discussion, and all members are involved in making crucial decisions, like choosing a launch provider (Slavinskis, Pajusalu, et al., 2015). Team leaders use transversal groups created on the spot to deal with newfound coordination needs. In areas of limited impact or requiring specific expertise, the discussion and decision making are entrusted to task-force groups. Students are usually involved in developing more than one subsystem to gain practical multidisciplinary collaborative working skills.

ESTCube outreach efforts resulted in more than 15 academic journal articles (and several conference papers and posters) documenting the technology, the design, the results, and the know-how of the project. Payloads and subsystems and thoroughly described from functions to hardware, and from technical specifications to the justification of design choices. These academic publications appeared mostly during condensed periods—especially right after the development of ESTCube-1, and we could split them into two areas. First, publications connected with the CubeSat technology (design and flight results), including areas like the main payloads (Iakubivskyi et al., 2020; Lätt et al., 2014); the electrical power system (Pajusalu et al., 2014); or the command and data handling subsystem (CDHS) and its firmware (Laizans et al., 2014; Sünter et al., 2016). Second, publications dealing with the project and the community (know-how), including a compilation of lessons learnt (Slavinskis, Pajusalu, et al., 2015); the working processes and the funding (Klinina et al., 2018); and the management of the community (Noorma et al., 2013; Slavinskis, Reinkubjas, et al., 2015). We can say that, in the case of ESTCube, technology determines their organizational model, and their academic outcomes reflect the impact of technology determinations over how they organize themselves. These academic
publications follow the same modular structures (payloads, subsystems) of the CubeSat. ESTCube uses a network of partners to develop and manufacture CubeSat’s technology. Often, companies agree to provide services or discounts to support ESTCube. During the development of ESTCube-1, the preference was to use customized components off-the-shelf (Slavinskis, Pajusalu, et al., 2015). However, not all components are available in Estonia, and in some cases, they were shipped from the United Kingdom, Germany, or the United States. Hardware components are provided with different—primarily closed—licenses. Students usually utilize proprietary software provided by the universities to students and academic staff. This tendency is shifting as the advantages of working with open-source software become more evident to ESTCube members. The ESTCube-1 CubeSat incorporated open-source software. The mission control system of ESTCube-1 used open-source software “Hummingbird” codeveloped with an Estonian company (ESTCube, 2020). The open-source “FreeRTOS” operating system was used on the satellite’s main onboard computer (CDHS) and the camera, while the also open-source TinyOS operating system was used on the communication module. As part of the results and lessons learnt from ESTCube-1 experience, the use of an operating system that “provides most of the needed functionality, for example, a form of embedded Linux” (Slavinskis, Pajusalu, et al., 2015, p. 18) is recommended.

It is, however, during the development of ESTCube-2 that open-source software becomes widely used. The open-source “tech stack” (a set of technologies used to build a single application) of ESTCube-2 developers consists of nearly 20 digital technologies including languages (Python, Go, Apache Groovy), databases (PostgreSQL, SQLite) and satellite specific software like Skyfield (see Table 2). Besides, the development setup (Microsoft Visual Studio Code), and the repositories (Git) used are open source. To provide quality assurance, open-source coding standards (Python 3, Docker, React JS) are used, data exchange standards are followed when possible (XTCETM, C2MS), and compliance with international standards is followed (European Space Components Coordination, European Cooperation for Space Standardization, Consultative Committee for Space Data Systems, and others).

During the final stages of ESTCube-1, a difficult period marked the core design decisions for ESTCube-2. The launcher provider offered an earlier launching date. The ESTCube team decided to speed up the development time to make it into the new launching date —the CDS version of ESTCube-1 was selected to fit into Arianespace’s Vega rocket. In the end, everything went well except for one thing: the tether of the main payload failed to deploy on orbit, and the principal experiment did not take place.

As a consequence of the shortcomings detected in the ESTCube-1 subsystems organization and the critical failure on the principal payload, ESTCube-2 follows a unified organizational structure. It aims to maximize the use of common components, allowing reusability and “facilitat[ing] mobility of team members between subsystems” (Slavinskis, Pajusalu, et al., 2015). This integrated-system approach reduces the number of subsystems and improves the resilience and stoutness of the hardware. Building all subsystems as independent

### Table 2. ESTCube-2 open-source tech stack (November 2020).

| Name              | Role                        | Description                                      |
|-------------------|-----------------------------|--------------------------------------------------|
| Docker            | Infrastructure              | Platform-as-a-service                            |
| Kubernetes        | Container management        | Computer application management                  |
| Python (FastAPI)  | Front-end language. API     | Self-documenting API                             |
| React, Next.js    | Front-end library           | Application developer                            |
| Grafana           | Analytics Platform          | Dashboards                                       |
| Swagger           | API specification           | Usually bundled in with FastAPI                  |
| Graylog           | Logging Platform            | Machine data analysis                           |
| PostgreSQL        | Database                    | Datasets management                              |
| RabbitMQ          | Message Queue               | Message-broker Protocol                          |
| Groovy            | Scripting language          | Scripting Engine                                 |
| Giffy             | Diagramming                 | Real-time collaborative tool                     |
| Jenkins           | Continuous Integration      | Automation Server                                |
| NodeJS            | Infrastructure              | JavaScript runtime environment                   |
| Skyfield          | Satellite orbit propagator  | Computing orbit positions                        |
| TLE Fetcher       | Downloads TLE(s) from SpaceTrack | Orbital elements datasets                        |
| Go (Golang)       | Back-end language           | Safe and simple                                  |
| Java (Spring framework) | Back-end language         | Platform                                          |
| SQLite            | Database                    | End-program embedded library                     |
| MarvelApp         | UI mockups                  | Live inventories                                 |

Source. Compiled by Andris Slavinskis.
components connected only by cables resulted in an overall weak system structure in ESTCube-1. The ESTCube-2 organization of work is the same as ESTCube-1: the satellite platform is developed in Tartu, while the payloads (one in ESTCube-1) are developed in specific places. The main difference is that ESTCube-2 is a 3U (three-unit) CubeSat and can carry more payloads. ESTCube-2 teams are based on different academic institutions (TO, UT Institute of Physics, Aalto University, Dresden University of Technology, Ventspils University of Applied Sciences and the Finnish Meteorological Institute). Each team focuses on a single payload. Each payload is related to the expertise of the academic institution in which each team is based.

This technology-determined organization of work resulted in one more important defining trait of ESTCube: open and efficient personal communication skills. Different subsystems demand expertise from different scientific and technical fields. Most ESTCube members tended to use jargon and technical terminology when communicating their work and findings, which complicated both the coordination between subsystem teams and the communication with external parties. To solve this issue, ESTCube members take communication skills training and are generally encouraged to publicly talk and write about their work (Olesk, 2019). For internal communication, like task coordination or decision making, ESTCube first adopted an Estonian communication platform called Fleep (Liibert, 2017) and later moved into the open-source oriented Discord platform. Using channel lists to organize working tasks and topics, every member can find the relevant information and documentation and take part in the conversations at any time in the same domain.

7. Discussion

The previous section provides an overview of the various elements that define the initiative. Certain insights emerge. First and foremost the initiative is made possible due to the activity of open-source movements that creates and promotes technology and knowledge without restrictions in terms of intellectual properties. This appears as a prerequisite for any discussion around the democratization of technology. At the same time, due to the lack of structural funding for this type of initiative, its model for technology development faces significant challenges in the context of an economy based on competitive market interactions. For those that utilize and, in turn, develop open-source technology for a living to secure personal sustainability, creative solutions need to be achieved. ESTCube manages to do so through strategic partnerships and a mix of research grants, private donations and crowdfunding endeavors.

While this approach does seem to work, it leads to significant concessions too. Some of the components procured are not under released open-source licenses. Furthermore, students and engineers are utilizing closed source software as the public institutions that provided their training and employment do not use open-source alternatives. These form barriers in the wider dissemination of the technology and know-how of the project. A community aiming to produce highly complex technology needs to find access to expensive materials and costly machinery. The ESTCube strategy to produce space technology is twofold. First, in-sourcing the key production capacities like knowledge, know-how, and design. Second, outsourcing manufacturing capacities through a network of partners. Building key capacities in-house is necessary to secure the community’s long-term sustainability.

ESTCube’s approach to producing complex technology resembles the approach employed by open-source movements producing complex digital artefacts, like Wikipedia or Linux. In the latter, wide-spread access to the Internet and the use of privately owned tools for producing digital information (computers) allow distributed networks of collaborators to coordinate their efforts. Hence, such initiatives are producing highly complex digital systems and technology without appropriating the material infrastructure that makes their endeavors possible.

Following Benkler (2006), the production of information depends on three main inputs: already existing information; the mechanical means to sense, process, and communicate information; and human communicative capacity. Regarding digital information, Benkler posits that human communicative capacity “becomes the primary scarce resource in the networked information economy” (Benkler, 2006, p. 52), thus the most valuable asset in information production. In the case of ESTCube, the 6-year-long period of development of the ESTCube-1 CubeSat is mainly a digital information process. The manufacturing of ESTCube-1 technology was the material output of a collaborative intellectual process. It entailed over 100 people coordinating their work tasks through the Internet, using software programs installed on their personal computers to produce a 10-centimetre cube-shaped artefact.

Using an analogy between the production of digital information and the production of technology, we can adapt Benkler’s categories to suit the ESTCube case:

- The CubeSat open platform (CDS) and current space scientific knowledge would correspond to Benkler’s first input (existing information).
- The manufacturing capacities, like specialized machinery, and the CubeSat’s components would belong to the second category (mechanical means).
- The ESTCube members’ communicative capacities and the ESTCube Program (know-how) would correspond to the third category (human communicative capacity).

Moreover, there are certain similarities on how open-source movements through the Internet are democratizing knowledge, and how a grassroots initiative like ESTCube is
approaching the production of highly digitized complex technology. In the former, a collective consciousness was developed to pursue the democratization of information digitally. In the latter, a similar awareness process may be taking place through groups of space enthusiasts having access to outer space through the CDS open technology platform. The core concept allowing such initiatives to democratize and reappropriate information technology is the digital/modular. Two aspects align it to what open-source movements have been doing to democratize information. A digital-oriented organization of work, and the decreasing costs of technology manufacturing in its mature phase.

First, a CubeSat is “mostly digital.” The largest part of its production is related to manipulating digital information. Open-source movements produce specific practices and organizational models well suited for peer-to-peer networks. Likewise, a community of space enthusiasts can use similar organizational patterns producing a CubeSat. Second, the closer the CubeSat industry gets to its maturity phase, the simplest and more cost-efficient the manufacturing of its components should become. In the case of open-source movements, the ubiquity of personal computers and affordable wide-spread access to the Internet was necessary to reach a critical mass of participants. Outsourcing manufacturing capacities also frees ESTCube from the limitations and financial burdens of risky fixed capital investment in the nonstandardized-yet CubeSat industry.

It appears that, in the case of ESTCube, the appropriation of complex technology seems to be a highly digitized process that entails certain organization forms adapted from the open-source movements to the technological demands of CubeSats. The organizational structure of the community is flexible and adapted around the needs of the technological development processes. These processes are complex and interdependent, thus they are compartmentalized in nonrigid structures that follow the evolving needs around the project.

Furthermore, the community uses what we identify as a three-fold strategy to produce complex technology that helps overcome the disadvantages of using closed tools and closed manufacturing capacities. First, by using an open-source platform (CDS) as the base to produce the artefact, along with a community organizational model (CubeSat Program). Second, by using open-source software to develop the technology. This is highly relevant as most of the software is produced and transmitted to the CubeSat after it is in orbit. Third, by producing open knowledge academic publications documenting (a) the design of the CubeSat, payloads, and subsystems; (b) the results of the space mission, including the technology’s performance; (c) the know-how (lessons learnt, the ESTCube Program, the experience).

Open communication, both internally and externally, is one of the configuring aspects of ESTCube’s open-source approach. It allows them to partially overcome some of the limitations imposed by restrictive hardware and software licenses they use. The closed-licensed hardware manufactured by their partners can be, up to a point, “opened” by documenting the technology design, results, and know-how.

Expanding the communication skills of the members to “open” the initiative was fundamental to connect the project with the general public, making space science more accessible. The role of technology-related hobbies and enthusiastic amateur involvement of ESTCube members in other activities provided a shared sense of belonging for the community and opportunities for recruitment, funding, promotion, and establishing partnerships. The long term viability of the initiative depends on transmitting and nurturing the shared values of the community, generating tight bonds between its members, building the resilience needed for the initiative to not disband after long years of hard work and unpaid contributions. Wide and early recruitment events are utilized to attract interest. Indeed, as opposed to more accessible types of technology development, special effort is required when it comes to sophisticated technologies for younger people and those with specialized skill sets to be involved. In turn, wider participation provides unique opportunities for volunteers to develop knowledge and know-how and seek employment in a sector that would otherwise be largely inaccessible.

It becomes evident that such a model of increased participation in the development of high technology is possible. Yet for it to be sustained and adopted more widely, significant institutional support would be required as well as wide structural change. This illustrates how the current discussion on how to reap the benefits of publicly funded research is not enough to provide radical options which may build on the insight provided by cases like ESTCube. It can point the way toward genuine democratic participation in the development and appropriation of such technology in society.

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