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The dawn of an open exploration era: Emergent principles and practices of open science and innovation of university research teams in a digital world

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ABSTRACT

Principles and practices of open science at universities are evolving. Increasing use and application of digital technologies and platforms in research and innovation are pushing universities to take up and develop new visions and principles for how research and innovation are performed. These open science policies and practices (i.e. open data sharing, open access publishing, open repositories, open physical labs, participatory design, and transdisciplinary research platforms) are expanding the ethos of science and innovation at universities. These new principles and practices of open science at universities are also triggering novel open innovation practices by university research teams. Open science and innovation practices hold great potential for accelerating the learning and creation of new knowledge, speeding up the research and innovation process for finding solutions for grand societal challenges, and nurturing the growth of highly innovative and entrepreneurial people. The purpose of this study was to identify emergent principles, practices, and underlying mechanisms of open science and innovation developed and encountered by research teams at universities. The results of this study provide directions for how to advance openness in science at universities and illustrate how openness in innovation is being remodelled by open science practices. Based on our findings, we propose an open exploration policy and a governance model of open science and innovation at universities in the digital world, which aspire to create increased societal value.

1. Introduction

The concept of open science is spurring new visions, principles, and practices for how research and innovation are performed at universities. Open science, based on recent synthesis of research on its usage and application, aspires for "transparent and accessible knowledge that is shared and developed through collaborative networks" (Vicente–Saez and Martinez–Fuentes, 2018). Advances in digital and communication technologies and development of various types of digital platforms are nurturing new open science policies and practices in universities, such as open data sharing (Murray-Rust, 2008), open access publishing (Cribb and Sari, 2010), and participatory design. These novel open science practices have developed in tandem with novel organising forms of conducting and sharing research through open repositories, open physical labs, and transdisciplinary research platforms. Together, these novel practices and organising forms are expanding the ethos of science at universities. However, there are currently no comprehensive empirical studies on the underlying principles and practices that university research teams have developed and are using to adopt open science in response to new policies and the new digital technologies available, nor does an analysis of the factors inhibiting and enabling open science exist.

The purpose of this study was to identify emergent principles, practices, and underlying mechanisms of open science and innovation developed and encountered by research teams at universities. We studied novel practices of open science and innovation at Aalto University in Finland. We studied 15 research teams to understand what principles and practices the teams use to engage in open science, what promoting and preventing factors influence adoption of open science practices, and what practices they use to transform open science outcomes into open innovation outcomes.

The results of this study provide clarity on emergent principles and practices of open science at the universities in a digital world. Firstly, we distinguish between open sharing and inviting practices and identify

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several forms of both that have been adopted by research teams. Secondly, we clarify openness as a multidimensional variable that can be measured and formulated by levels of transparency of science outputs, accessibility to science outputs, authorization in science production, and participation in science production. Thirdly, we expose key promoting and preventing factors that influence research teams to adopt open science practices. Fourthly, we reveal two novel forms of open innovation practices developed by forerunner research teams: inbound open innovation that uses open science outputs to create product or service innovation and outbound open innovation that uses open science outputs to promote product and service innovation. As such, we provide clarity on the governance of open science and innovation at universities in a digital world and exposure to how universities are becoming active shapers and developers of novel practices of open innovation.

We end the paper with a discussion about how these new open science practices and novel open innovation practices adopted by research teams are challenging the established governance of research and innovation at universities. To undertake this endeavour, we propose a novel open exploration policy that promotes a nexus between open science and innovation at universities in a digital world.

The article is organised as follows. We present the theoretical framework on open science and innovation in Section 2. The methodology of the study is described in Section 3. The findings of the research are presented in Section 4. In Section 5, we present a discussion of the findings and their implications.

2. Theoretical framework

Open science as a phenomena is founded on two underlying mechanisms of organising science, openness (Chubin, 1985; David, 1998; David, 2004a) and connectivity (European Commission, 2016). Novel open science practices employed by research teams at universities, such as open data, open access publishing, open protocols, open physical labs, crowdsourcing practices, or transdisciplinary research platforms, are rooted in Mertonian principles of science (Merton, 1973): communalism, universalism, disinterestedness, originality, and scepticism (CUDOS norms). However, the new open science practices go beyond Merton's visions of science. Open science today centres on the aspiration for “transparent and accessible knowledge that is shared and developed through collaborative networks” (Vicente–Saez and Martinez–Fuentes, 2018). Novel open science practices and novel ways of organising science work through digital platforms, tools, and services for researchers make science increasingly accessible for citizens, knowledge freely available for everyone, scientific outputs available, and the process of knowledge creation more efficient and goal oriented (Tacke, 2010). Understanding the impact of these emerging open science practices on the “ethos of science” described by Merton, also called “norms of openness”, is a fundamental objective for ensuring the effectiveness of research systems (Chubin, 1985; David, 1998). A post-Mertonian analysis of the evolution of openness in science is therefore needed. No comprehensive studies exist, however, on the new open science practices and principles and how they could change the governance of traditional open science institutions such as universities.

Open innovation again centres on the use of purposive inflows and outflows of knowledge to accelerate internal and external innovation (adapted from Chesbrough, 2006; Chesbrough and Bogers, 2014). The open innovation phenomenon has also impacted the way universities and research teams conduct research and contribute to innovation processes (Perkmann and Walsh, 2007). Innovation is a multistage process (Baregheh et al., 2009) that incorporates multiple kinds of practices in various stages (West et al., 2014). In the last 10 years, open innovation research and policies focused on developing and promoting more inbound than outbound practices and processes for valuable knowledge creation (Enkel et al., 2009; Bogers et al., 2017). Advances in open science policies and practices such as open data (Murray-Rust, 2008), open access to research publications (Cribb and Sari, 2010), or open infrastructure for knowledge co-creation (European Commission, 2014) have disrupted established open innovation policies and, with them, the standard types of openness in innovation, that is, revealing and selling (outbound) and sourcing and acquiring (inbound) (Dahlander and Gann, 2010). Digital and communication technologies have brought about novel unexplored opportunities and challenges for the governance of innovation in universities (i.e. reliable data sharing, quality control and reproducibility of research methods and results, management of joint research platforms, funding instruments, university-industry relations, strategic alliances, spin-offs, start-ups, and consortias). In this respect, discovering how research teams use new open science outputs to shape open innovation outcomes is a priority objective for designing effective policy and governance mechanisms for universities.

Openness in science and openness in innovation are not separate constructs (McMillan et al., 2014). Open science and innovation practices at universities are constantly fuelling each other. Open science and innovation practices of universities are an emerging research field with multiple levels of analysis needed to further develop them in various scholarly communities. These practices allow the public at large to participate in contributing to research and innovation, evaluating research, increasing scientific integrity, and understanding the value of research and innovation (Tacke, 2010; Perkmann et al., 2013; Perkmann and West, 2014). Understanding how these practices impact the governance of research and innovation at universities is therefore required. The traditional institutions of open science (David, 2004a) and the novel institutions of open innovation (Chesbrough, 2015) need to be tailored, updated, and merged to reach their full research and innovation potential effectively in a digital world. Universities are firm foundations of open science and innovation practices (Bedford et al., 2018; Ayris et al., 2018) that foster innovation processes at the global, regional, national, and local level.

3. Methodology and data

We conducted a qualitative empirical research study (Gephart, 2004), taking a ground theory methodological approach (Glaser and Strauss, 1967; Corbin and Strauss, 1990; Corbin and Strauss 2008) with the aim of achieving a thorough understanding of novel and emergent open science and innovation principles and practices that research teams have developed and the underlying mechanisms that enable them to flourish or constrain them.

3.1. Research teams studied

We studied research teams at Aalto University in Finland. Aalto University serves as an exemplary site to study developing open science and innovation practices in a digital world. Aalto University was established in 2010 as a merger between three universities in the capital region: a technical university, a business school, and an art and design university. One of the key rationales behind the merger was the promotion of new multidisciplinary research and innovation practices between science, business, and industrial design researchers, practices that embrace openness in science and innovation. The vision was, through interdisciplinary and action-oriented approaches, to develop university practices in solving societal challenges (Aalto University Strategy, 2015). Furthermore, Aalto University is part of a visionary society. Finland aspires to be among the world's leading knowledge-intensive, expertise-based societies by 2025 (UNIFI, 2017) and renowned for its top education system (Economist Intelligence Unit for Pearson, 2014), being a strong innovation leader (European Innovation Scoreboard, 2018; Cornell University, 2018), and being committed to further advancement of open science in its national research system (Tuomin, 2016).

We studied 15 research teams to understand the principles and

Table. 1
Research team leaders, policymakers and university managers interviewed

Name	Position
University managers	
Anne Sunnika	Head of Open Science and ACRIS at Aalto University
Tomi Kauppinen	Head of Aalto Online Learning
Kalevi Ekman	Professor and Director of Aalto Design Factory
Policymakers	
Sami Niinimäki	Senior Adviser, Finnish Open Science and Research Initiative, Finnish Ministry of Education and Culture
Jyrki Hakappää	Senior Science Adviser, Strategic Research Unit, Academy of Finland
Sellina Päällysaho	Representative of Finnish universities of applied sciences in the Finnish Open Science Research Initiative
Research team leaders	Name of research team and School
Riikka Puurunen	Catalysis, School of Chemical Engineering
Teemu Leinonen	Learning Environments, School of Arts, Design and Architecture
Filip Tuomisto	Antimatter and Nuclear Engineering, School of Science
Pirjo Kääriäinen	CHEMARTS, School of Chemical Engineering & School of Arts, Design and Architecture
Ilkka Lakaniemi	Center for Knowledge and Innovation Research, School of Business
Virpi Tuunainen	Information Systems Science, School of Business
Ahti Salo	Systems Analysis Laboratory, School of Science
Riitta Smeds	SimLab, School of Science
Martti Mäntylä	Enterprise Systems, School of Science
Minna Halme	Aalto Sustainability Hub, School of Business
Paul Lillrank	Healthcare Engineering and Management, School of Science
Joni Tammi	Metsähovi Astronomical Radio Observatory, School of Electrical Engineering
Raimo Sepponen	Health Technology, School of Electrical Engineering
Orlando Rojas	Bio-Based Colloids and Materials, School of Chemical Engineering
Marika Hellman	BIOFILIA: Base for Biological Arts, School of Arts, Design and Architecture

practices they use to engage in open science, what promoting and preventing factors and mechanisms influence these research teams to adopt open science practices, and what practices the teams use to transform open science outputs into open innovation outcomes. Our sample was selected together with the managers of open science and innovation practices at the university. Additionally, some research team leaders suggested interviewing other research groups that we then also included. Our selection criteria included research groups from the disciplines of science, business, and art and design; groups that had engaged in multidisciplinary research; and groups that had to some degree been forerunners or active in either or both open science and open innovation activities (see Table 1). Systematic and comprehensive sampling enables better generalization, predictive capacity, and accuracy (Corbin and Strauss, 1990).

3.2. Data collection

We conducted 21 semi-structured interviews, including interviews of all the 15 research team leaders. In addition, we interviewed three managers of open science and innovation at the university and three Finnish education, research, and innovation policymakers to reinforce research reliability and better understand the context at Aalto University. In addition, these informants helped us to further understand the university's policies and practices in open science and innovation, as well as the Finnish setting of open science and innovation policies and regulations. The interviews took, on average, an hour. Moreover, we had several informal conversations with team members of the research groups when we visited the groups.

We developed an interview protocol to guide the interviews (see Appendix 1). The interview questions were open ended and aimed at understanding open science and open innovation from the points of view of the knowledgeable research team leaders, the managers, and the policymakers we interviewed. We also specifically asked for open science and open innovation practices they were engaged in or had developed without exactly defining the concept of open science and innovation itself, maintaining insight and understanding developed from the interviews and understanding of the interviewees' perspectives. We tested the interview protocol with faculty and doctoral students at the respective departments of the authors, and we refined the protocol based on the piloting and feedback from our test group. We then conducted face-to-face interviews from November 2017 to January 2018. All interviews were recorded and transcribed.

In addition to the primary data of semi-structured interviews, we collected secondary data from various sources at every phase of the research, using a variety of methods to guide sampling and ensure research validity by means of triangulation (Tracy, 2010). We carried out direct observation of research teams when we visited their sites, and we made videos and took photos of the research teams. We developed research-directed diaries to document insights from meetings and seminars attended at Aalto University during the study period. We also collected Web-based material on the research groups, university guidelines, background documents, and background archival documents on open science and open innovation policies in Finland and Europe.

3.3. Data coding and analysis

We then performed data analysis based on the grounded theory approach by Corbin and Strauss (Corbin and Strauss, 1990, Corbin and Strauss, 2008) with our primary data of semi-structured interviews. The main focus of the approach was to develop a rigorous and robust understanding of the emerging phenomenon studied. Before the iterative analysis, we carefully familiarised ourselves with the secondary data to enrich and deepen our analysis of the primary data and the phenomena of open science and innovation practices and their contexts (Suddaby, 2006). We then started, by first reading the transcripts of the interviews, to become acquainted with the data. In the second phase of our analysis, we performed open coding by assigning codes to data fragments until we reached data saturation. Through the use of questioning and the constant comparative method, we obtained an initial list of codes of open science and innovation practices that the research groups had taken up, as well as preventing and promoting factors of open science practices. In the third phase, we conducted axial coding to identify a list of coherent, consistent, and distinctive categories. We refined the previous coding scheme by constantly comparing data fragments to determine similarities and differences and establish relationships between them. We then provided a detailed description of categories of open science and innovation practices and promoting and preventing factors. Finally, we completed the data analysis by doing selective coding until we reached theoretical saturation. We then transformed our data into core concepts and determined core categories and reassembled them to propose a grounded, rigorous, useful, and comprehensive conceptual model for the governance of open science and innovation at universities. To support the progression of the analysis, we used memo writing as a tool for recording analytical insights across all data segmentation processes and the storyline technique as a mechanism for integrating and drawing concepts and presenting an overview of the studied phenomenon (Birks and Mills, 2015).

4. Findings

Our findings can be synthesised into a conceptual model for the governance of open science and innovation at universities in a digital world (Figure 1). The model distinguishes four key principles of open

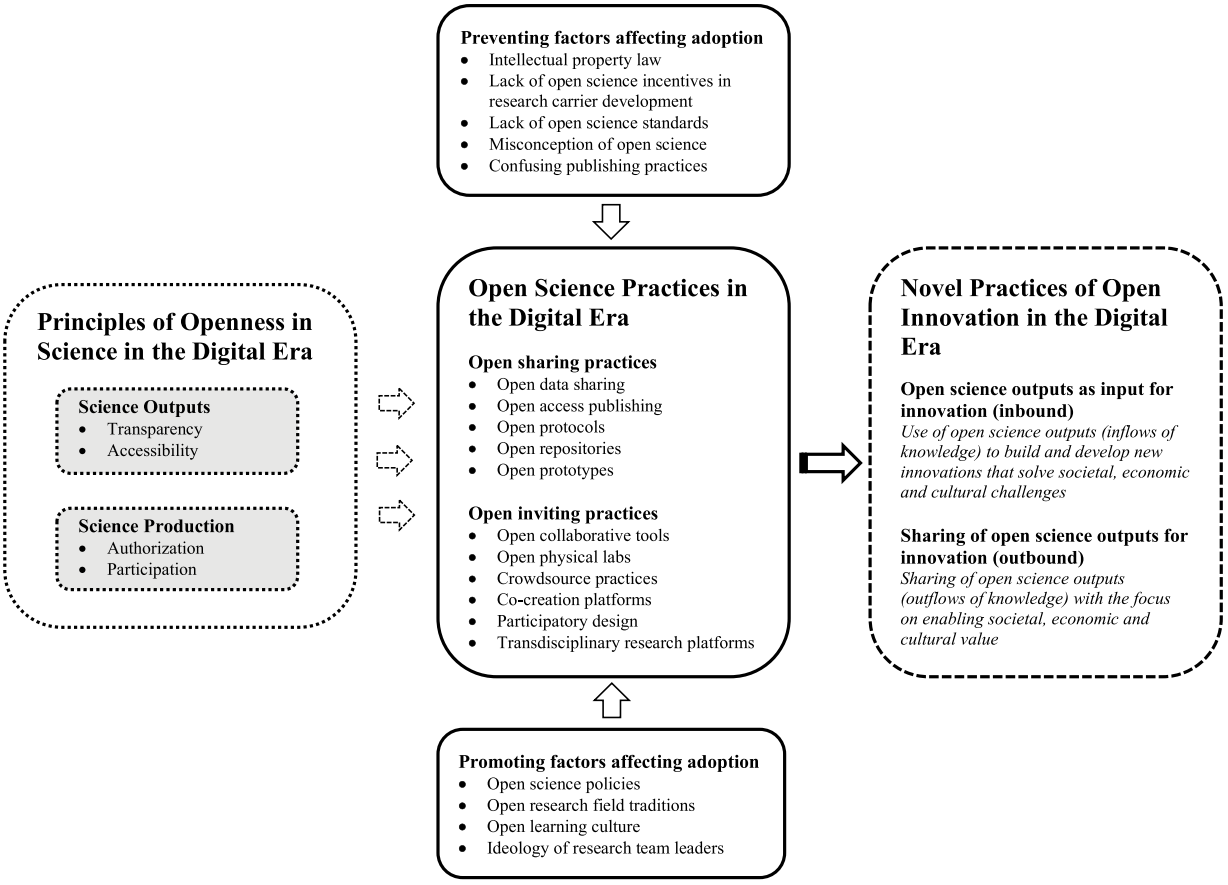

Figure. 1. A conceptual model for the governance of open science and innovation at universities in a digital world

science in the digital era that direct the work of research teams at universities: transparency and accessibility to science outputs, and authorization and participation in science production. These principles underlie the observed open sharing and open inviting practices that our research team informants had developed or were engaged in. Our study further exposes promoting and preventing factors for the open science practices to develop. Finally, our study exposes how new open science practices are triggering novel open innovation practices in universities: inbound and outbound product and service innovations. We next go through each of the elements in the model in more detail.

4.1. Open science practices in research teams

Open science practices are impacting the way research teams collect and evaluate data and design and perform scientific studies. Through our study, we identified two distinct types of open science practices in research teams: open sharing practices and open inviting practices (see Table 2).

We conceptualized the first set of practices we identified as open sharing practices. The research teams we studied exposed a variety of open sharing practices. We found that teams had practices to share data, protocols, and prototypes. An illustrative example of such practices was given by Joni Tammi, head of the Metsähovi Astronomical Radio Observatory, who explained that "the data transfer and the methods [the research group shares] are used now by more than half of the radio observatories in Europe, and soon in every observatory in Europe, as well as around the world". Many of the teams we studied had furthermore established practices to share their results and their scientific knowledge through open repositories. ArXiv, World Economic Forum, Bank of Finland, and AVAA repositories are accessible to global, regional, national, or local communities. Open sharing practices have also had an impact on the research teams' internal working. Our informants explained how the open sharing practices – open data, open access publishing, open protocols, open repositories, and open prototypes through open license practices – had accelerated the research cycle of their teams by enabling testing and recombining the scientific outputs of other scientific communities. Virpi Tuunainen, research team leader of the Information Systems Science Group, gave her summation of the value of open sharing: "Open publishing is certainly something that, not only as an idea or philosophy, is something that supports cumulative knowledge creation". All of the open sharing practices we identified that the research teams were engaged in were oriented towards spreading novel scientific knowledge in society. What is distinctive about these is that they each use non-human knowledge infrastructure that is formed using information and communication

Table. 2
Open science practices in research teams

Type of Open Science Practice	Open Science Practices
Open sharing practices	Open data sharing
Features non-human infrastructure for distributing knowledge	Open access publishing
	Sharing of open protocols
	Open repositories
	Sharing of open prototypes through open licenses
Open inviting practices	Open collaborative tools (e.g. APIS and social networks)
Features human infrastructure for creating knowledge	Open physical labs
	Crowdsource practices (e.g. citizen science)
	Co-creation platforms
	Participatory design
	Transdisciplinary research platforms

technologies.

A second set of open science practices we identified were open inviting practices. In contrast to the open sharing practices, these practices are oriented towards attracting individuals, other researchers and groups, and society to participate widely in research and to create new scientific knowledge. These inviting practices take forms such as small clubs, different sizes of consortia, and broader communities. Researchers are also increasingly engaging in practices that provide crowds with authority in research. We also found that these inviting practices of research groups vary with respect to who is invited in the development activities of new scientific knowledge, from local actors to national, regional, or global stakeholders. For example, Teemu Leinonen, research team leader of the Learning Environments Group, explained how the team he leads is looking for possibilities to improve online collaboration and online discussions by capturing the emotions of people through imaging biomarkers and computer vision. The team is learning people's emotional states through online forums or chats. This development to improve open learning environments involves global participation. What we saw from the multiple examples of inviting practices of research teams at Aalto University was that open collaborative tools, open physical labs, crowdsourcing practices, co-creation platforms, participatory design, and transdisciplinary research platforms enable the weaving of human knowledge networks, creating fertile ground for new ideas and discoveries. To summarize, open inviting practices, in contrast to non-human sharing practices, foster human interaction in science and can as such be considered the human infrastructure for creating new scientific knowledge.

4.2. The four principles of openness in science

The identification of multiple open science practices and two general types further led us to notice how the practices varied with respect to openness in multiple distinct ways in the 15 research teams we studied. Through our study, we found that openness in science is a multidimensional variable that varies with respect to four dimensions or principles: (1) transparency of science outputs, (2) accessibility to science outputs, (3) authorization in science production, and (4) participation in science production (see Table 3). Each of the principles of openness in science responds to a distinct question in relation to open science. Finally, it is important to note that any open science practice encompasses the four principles and varies with respect to the levels of openness. We next go through each of the principles of openness in more detail.

What is shared in open science? We distinguish four stages in science with respect to the outputs that can be shared: ideas, data, methods, and results. Transparency of science outputs then varies with respect to whether one or several types of output are shared. For example, Ahti Salo, research team leader of the Systems Analysis Laboratory, explained how the outcomes of his team's research, including algorithms, are “uploaded into [globally open] repositories, and I would say that that's one form of open science. If one develops an algorithm, and the claim is that the algorithm should be better, one should demonstrate it with tested examples from those repositories”. We found that research groups varied with respect to transparency of science outputs in their practices, with either one or several types of science output being shared, because such transparency of science outputs varies with respect to how extensively science outputs are shared in the process of science.

With whom is open science shared? Accessibility to science outputs varies in terms of who is given access to outputs. We found that accessibility varies as a result of economic and political interests, scientific scope, regulations, and cultural barriers. In our analysis, if accessibility varied among the research teams we studied, then we distinguished between local, national, regional, and global accessibility to science outputs. We found that many research teams aspired for global accessibility to scientific outputs. For example, Tammi, head of

Table 3
Four Principles of Openness in Science

Question	Principles of Openness in Science	Levels of Openness			
		Level 1	Level 2	Level 3	Level 4
WHAT is shared in open science?	**Transparency** of science outputs (ideas, data, methods, and results)	One type of science output is shared	Two types of science output are shared	Three types of science output are shared	All science outputs are shared
With **WHOM** is open science shared?	**Accessibility** to science outputs	Local accessibility(i.e. Helsinki)	National accessibility (i.e. Finland)	Regional accessibility (i.e. EU)	Global accessibility
HOW is open science created?	**Authorization** in science production (trust-based principles)	Club-based authority ($\leq$ 10 participants)	Consortium-based authority ($\leq$ 100 participants)	Community-based authority ($>$ 100 participants)	Crowd-based authority ($>$ 500 participants)
WHERE is open science created?	**Participation** in science production	Local participation (i.e. Helsinki)	National participation (i.e. Finland)	Regional participation (i.e. EU)	Global participation

the Metsähovi Astronomical Radio Observatory, explained, “We try to make our data completely available or as available as possible”.

How is open science created? Authorization in science production is considered a movement from the paradigm of openness (open innovation) in terms of confidentiality principles to the openness (open science) expressed by trust-based principles (authority). Researchers trust different research stakeholders to create scientific knowledge by using novel mechanisms of “intellectual trust” (e.g. crowd authority). We identified four categories of authorization among the research teams we studied: club-, consortium-, community- and crowd-based authority. For example, Riikka Puurunen, research team leader of the Catalysis Group, explained how they “have submitted one joint publication with 62 co-authors”. This exemplifies open science practices that allow intellectual trust to be established (consortium-based authority) and joint production among and between public and private actors.

Where is open science created? Participation in science production addresses where rather than how science is created. We found that research teams have opened their research labs, created collaborative research platforms, and opened up the research process to crowds (citizen science platforms). This allows for participation in the creation of scientific knowledge by stakeholders distributed across geographic areas. We found that participation in open science production varies from local to national, regional, and global participation. Several of the research teams reported an emphasis on increasingly global participation. Marika Hellman, head laboratory manager of BIOFILIA, explained how her lab's mode of operation “is all about collaboration across the world with other bio art laboratories, societies, artists, biohackers”. In addition, she noted that “BIOFILIA is a workshop space where anyone within the Aalto community could come and do projects with living material in their research or in their learning”. She further explained how the science participation practices that the lab engages in mean that “you're just open. You share what you have, you share your ideas, you listen to other people and can find collaboration between the arts and sciences fields”.

4.3. Promoting and preventing factors for the adoption of open science practices in research teams

Our study exposes both promoting and preventing factors for open science practices to be developed in university research teams (see Table 4). We found that open science policies, open science research field traditions, the open learning culture of the research team, and research team leaders’ ideology promoted the adoption of open science practices. Furthermore, we found that intellectual property laws governing research teams (university regulation and/or national/EU laws), lack of incentives for research career development, lack of standards (regarding data governance, infrastructure, practices, publishing protocols, skills, and technical support), misconceptions of what open science entails, and confusing publishing practices have prevented the adoption of open science practices. We next review our findings with respect to each of the promoting and preventing factors in more detail.

Promoting factors for the adoption of open science practices by research teams

We found that open science policies in Finland and at Aalto University enabled the research teams studied to develop open science practices that encompass a high level of transparency regarding science outputs, a high level of accessibility to science outputs, the acceptance of novel organizing forms of trust-based authority in research projects, and a high level of participation in science production. In the last five years, European and Finnish policymakers in education, research, and innovation have developed multiple policy programs to build and nurture open ecosystems through open science and innovation policies that are already implemented in annual budget negotiations with universities. Sami Niinimäki, senior adviser on the Finnish Ministry of Education and Culture's Open Science and Research Initiative, told us that the Ministry of Education “has a funding model for higher education institutions […] for the base of these negotiations. We use the assessment of the culture of openness”. The open ecosystem policies are intended to promote a co-creation atmosphere for knowledge production between research organisations, academic institutions, companies, and citizens. They are also intended to encourage researchers to reveal and make accessible their science outputs and created knowledge by encouraging researchers to engage in open access publishing and to share their data. For example, the Academy of Finland (the main research funding agency in Finland) now asks researchers to submit data management plans as part of their research proposals. Furthermore, the European level has more policies with a focus on actively promoting interoperability among open repositories in Europe. Together, these open science policies promote the development of open science practices in university research teams.

We also detected that open research field traditions are key for the adoption of open science practices with high levels of transparency, accessibility, trust-based authority, and participation. We found that research fields that have fast testing or recombination cultures (e.g. design or BioArt) and those oriented to collaboratively explore the borders of conventions with the purpose of finding solutions that address social challenges (e.g. astronomy and sustainable materials) embrace novel open science practices more noticeably. Furthermore, many of our informants told us that fostering open science culture in a research group or a department takes time to develop. Anne Sunnika, Manager for Open Science at Aalto University, expressed to us vividly that “openness depends on people”. She continued, “It depends on in which department you are in [...], what the openness level is there. It depends on people, and it takes time. Change of culture, it takes a lot of time”.

We observed that a deeply embedded open learning culture in research teams fuels open science practices with high levels of authorization and participation in science production and creates highly innovative and entrepreneurial individuals. People, not systems, are making the change. Spearheading this change are researchers who participate in open learning courses aiming to facilitate collaboration across disciplines (e.g. Bit Bang lectures), work in open physical labs (e.g. BIOFILIA activities) or transdisciplinary research platforms (e.g. CHEMARTS at Aalto University), or apply open learning approaches and methods (i.e. experiential or experience-based learning) enabled by digital means (i.e. MOOCS) in their lectures. An example from Pirjo Kääriäinen, research team co-leader from CHEMARTS, provides insight and an open-minded perspective on how and where to find information: “What I see these young people do, what they keep on doing on the

Table. 4
Promoting and Preventing Factors for the Adoption of Open Science Practices by Research Teams

Promoting factors	Preventing factors
• Open science policies • Open research field traditions • Open learning culture of the research team • Ideology of research team leaders	• Intellectual property law in science projects with companies and other research organisations • The lack of open science incentives in research career development • The lack of open science standards: data governance, infrastructure, practices, publishing protocols, skills, and technical support • The misconception of open science • Confusing publishing practices

educational side, they keep on searching for different kinds of information in very strange places. For example, they search online for certain recipes when they want to grow bacterial cellulose".

Finally, we discovered that the ideology of the research team leader (s) played a critical enabling role in the development of open science practices. We noted that team leaders who shared a strong belief that science is a tool for progress and that science needs to be open for the public good had been most active among our informants in promoting open science practices with high levels of transparency, accessibility, trust-based authority, and participation. For these researchers, science was not an "ivory tower". These research team leaders considered science as naturally open and belonging to society. These ideas are reflected in the comments provided by Teemu Leinonen, research team leader of Learning Environments: "It's almost like an ideological decision […] It's a vision which is known from history on science and research, and it's very much kind of the idea of enlightenment".

Factors preventing the adoption of open science practices by research teams

We found that the current open innovation policy, which boosts collaboration with companies and research organisations such as private research labs, restricts intellectual property rights in science projects through strict consortia agreements. These practices, we noted, constrain the adoption of open science practices with high levels of transparency and accessibility of science outputs in research teams. Filip Tuomisto, research team leader of antimatter and nuclear engineering, highlighted that "if you work directly with companies, they are the ones who prevent adopting open science principles". University regulations and national and EU laws on copyrights and patents also restrict the transparency and accessibility of science outputs including open data, open access publishing, open protocols, and open prototypes. Sami Niinimäki of the Finnish Ministry of Education and Culture, the senior official in charge of the Finnish Open Science and Research Initiative, shared his concern with us about these restrictions: "The copyright legislation, for example, is not giving enough room to operate in a fully open way as quickly as possible. It's leaning too much towards the contract model still".

We also uncovered a lack of open science incentives in research career development keeping research teams from adopting science practices with high levels of transparency, accessibility, trust-based authority, and participation. Our informants explained that researchers do not value openness in science practices when there are no direct incentives to increase transparency, accessibility, trust-based authority, or participation before publication. The current tenure track system adopted by many universities around the world – and by many Finnish universities since the 2009 university reform – puts a strong emphasis on publications in top-tier journals, the number of publications, and the number of citations, but places little emphasis on the openness of science outputs. The current carrier incentive system clearly constrains the adoption of open science practices. As Minna Halme, research team leader of the Aalto Sustainability Hub, expressed to us, "You basically proceed on your career through your publications […] This is not a problem for me any longer because I'm a tenured professor, but it's obviously a problem for any junior academics who want to go more the open-science way".

Open science is an emerging phenomenon. Several of our informants told us that because of that, open science has only recently been on the policy agenda in higher education. Unfortunately, a lack of established open science standards at the national, European, and global levels continues to persist. There is a lack of established, widely accepted standards and publishing protocols (e.g. no single standard as to how long the embargo period should last); data governance (e.g. access to data and practical processes and how to make decisions on that); and e-infrastructure interoperability and tools (e.g. the lack of "good-enough" services). Our informants suggested that this could be due to the lack of open science role model practices, few training courses for researchers about open science and open science practices, and few resources and lack of technical support capabilities at universities. Jyrki Hakäpää, senior science adviser in the Strategic Research Unit of the Academy of Finland, explained to us that "people don't know how to do [open science]", and continued, suggesting that "universities should have services and support for scholars showing and giving them examples on how to do it".

We also discovered that researchers do not have a clear understanding about what open science is or the sociocultural change it will bring about in the coming years. This is partly due to open science's lack of visibility within the university, as Anne Sunnika, Manager for Open Science at Aalto University, explained to us: "I would say that Aalto [University] as an organisation engages in open science, and we say that it is important, but the evidence of how important it is, it's maybe not very visible from the researchers' point of view". However, in addition to the lack of visibility, misconceptions and narrow views on open science are rooted in universities. An illustrative example of a more constrained view on the openness of science was provided by one of the research team leaders, who explained that "the general public should not engage in reading scientific articles […] They don't get anything from reading scientific articles". The misconceptions about what open science is and why open science culture should be an aspiration do not allow researchers to visualize its potential applications and impact on society as a whole.

Lastly, we identified confusing publishing practices that hinder the adoption of open science practices with high levels of transparency and accessibility of science outputs by research teams. The high cost of open access publishing and the current classification of open access journals in rankings discourage researchers from exploring open access publishing. One of the research team leaders, explained, "It's costly […] Actually, it's easily 2000–3000 euros per paper", then continued to say, "We [have] evaluated more than 1000 journals in the JUFO rankings [the Finnish journal ranking system that is the Ministry of Education and Culture's measure of funding for universities] […] and the open science journals are not awfully good in that ranking".

4.4. Novel open innovation practices in research teams

Our study revealed that the adoption of open science practices and principles by research teams triggers novel innovation principles and practices. We found that these novel open innovation practices, which aim to transform scientific knowledge into product and service innovations, were developed by research teams that were forerunners of open science practices. Based on our study of 15 research groups, we found that 7 of them – the Center for Knowledge and Innovation Research, CHEMARTS, Enterprise Systems, Health Technology, Learning Environments, Metsähovi Astronomical Radio Observatory, and Systems Analysis Laboratory – were engaged in various novel open innovation practices. Based on the insights from interviewing the research leaders of these seven research groups, we identified two distinct types of practices.

Novel inbound open innovation practices: The use of open science outputs to create product or service innovation in research teams

We identified a novel type of inbound open innovation practice, one that is founded on the use of open science outputs to create product or service innovation in research teams at the universities. This practice centres on the use of non-human and human infrastructures as inflows of knowledge to accelerate innovation in the research team. This novel practice refers to the use of open science outputs to build and develop new applications and innovations that solve societal, economic, and cultural challenges. An illustrative example of the development of such practice comes from Joni Tammi, head of the Astronomical Radio Observatory. He explained how his research group "are developing a service where we can take the signal from our atomic clock and transfer it basically via Internet for everyone who wants to use it [...] and for that, we are using [...] some of the data transfer protocols and technical

development, technical solutions that we found from scientific literature". He further explained the process and the benefits: "We take the data or […] the blueprints, and we can make our own version of that. We would never probably do it if we would have to pay for the patents or pay for tens of thousands or hundreds of thousands of euros for the product". Raimo Sepponen, research team leader of Health Technology, provided another example when he explained how his research team "have used imaging [technologies] […] to evaluate MRI-images [from] […] data banks [with] […] MRI images having normal and pathological images so that we can see what's happening, [and] […] we have used data [electrocardiographs] from open sources for diagnosis of arrhythmias". He further explained the process to us: "There's a large amount of cases, and then you can test your solution on how it performs with those cases". He concluded that the access to open data have helped the research group to advance prototypes and innovations in diagnostics of arrhythmias. To summarize, we found that research teams have been using open science outputs as knowledge inflows to create internal product or service innovation.

Novel outbound open innovation practices: the use of open science outputs to promote product and service innovation by anyone

The other novel type of open innovation practice we identified is an outbound open innovation practice, one that is founded on the use of open science outputs to promote product and service innovation by anyone. This novel outbound open innovation practice, in contrast to the inbound approach, focuses on the use of non-human infrastructure as outflows of knowledge to accelerate external innovation. This practice refers to the refinement and sharing of open science outputs with foci of enabling societal, economic, and cultural value. We found that research teams are using open science outputs as outflows of knowledge to promote external product and service innovation. Teemu Leinonen, research team leader from Learning Environments, provided an illustrative example of this novel open innovation practice that his research team were engaged in: ". . . this open-web idea, so in a way, anybody could download the data very easily from our applications, like the LeMill, which is for building learning materials collaboratively by teachers. So, anybody could take the data from there very easily, because it's on open web, find out that who is working a lot on what kind of topics and use it as data for research. So, they end up to be like open-science platforms, too, those learning applications". Another illustrative example of novel outbound open innovation practice comes from Raimo Sepponen, research team leader of Health Technology Group. He explained to us that the auscultatory data they have collected have been made "openly available because there is a large amount of work to collect the data, and it's good then to put it openly available because then some people don't need to do all that collection and evaluation […] that really helps the development [scientific discoveries, prototypes and innovations]". However, engagement in novel outbound open innovation practice has also raised concerns among research team leaders. Our informants expressed similar concerns about the difficulty to identify and control who use the data, methods and other science outputs they have shared: "I know that those auscultatory recordings have been used. I don't know which firms or which groups but that has been used" and "But I can see the connection. I can see that something we did 15 years ago is now in the market or is coming up with the start-ups. But I can't track back how it did end up in there. Of course, because we've been working with the open-science, so it's been available for everybody". As such, the observed novel open innovation practices are still at an emergent stage and the principles of exploitation are consequently also still up for development and debate.

5. Discussion and implications

From the Enlightenment era, when the norms and practices of open science were articulated (David, 2004a), until today, openness in science has continued to evolve in accordance with the economic, political, sociocultural, and technological constructs of each period. Digital technologies, including software, data, and hardware, communication technologies, and the development of various types of digital platforms have come to disrupt how science can be shared and collaboratively performed around the world. Digital technology enables the sharing and performing of science instantly and interactively. These technologies are as such spurring new open science principles and practices by research teams of universities; that generates new possibilities for collaboration among researchers, but also new forms of interaction between university researchers and research institutes, companies, municipalities, citizens and international organisations (e.g. the United Nations, World Bank, and European Commission).

While the policies, debates, and actions at national, regional, and worldwide levels in regards to openness in science still seem to revolve around "sharing science outputs" through open data and open access, there has already been a considerable shift in the mind set of researchers towards bringing about more openness across the entire research cycle (Plutchak, 2018) by university research teams taking up and developing novel types of open science and innovation practices. Scientific communities already use open sharing practices including open protocols, open data sharing or open repositories, and open inviting practices – that is, open physical labs, participatory design or transdisciplinary research platforms, for "co-creating science".

The results of this empirical study of 15 research teams provide an in-depth insight on what novel open science and innovation practices have developed and are being used today by university research teams. Our study provides a solid basis for outlining directions for how to advance openness in science in universities in a digital world. More specifically, our study contributes by firstly developing a taxonomy (Doty and Glick, 1998) of the principles of openness in science in today's digital world. We specify openness as a multidimensional variable that can be measured and formulated by means of the proposed levels of transparency of science outputs, accessibility to science outputs, authorization in science production, and participation in science production. Secondly, our study exposes open sharing and inviting practices in science adopted by research teams at universities. Thirdly, we synthesise preventing and promoting factors affecting the adoption of these open science practices. Finally, our study brings forth the central role of an open learning environment in enhancing the adoption of open science principles and practices by university research teams. The induction of open learning culture of the research team as a promoting factor, and the misunderstanding of open science as a preventing factor, reveal that an open learning environment is a contextual factor in the model.

This empirical study further reveals how openness in innovation at universities is being remodelled. The new principles of openness in science – transparency, accessibility, authorization, and participation – are shaping established openness in innovation (revealing, selling, sourcing or acquiring (Dahlander and Gann, 2010)). Our study shows how the new open science practices are triggering novel open innovation practices in forerunner research teams at universities. We identify a novel inbound open innovation practice that relies on open science outputs to create products and/or service innovations. We further identify a novel outbound open innovation practice that relies on the use of open science outputs to promote product and service innovation outside the university setting. These novel emerging practices at universities hold great potential to accelerate both internal academic and external societal processes of learning and creation of new knowledge, speeding up the research and innovation process for finding solutions for sustainable development goals and society's grand challenges, and nurturing innovative and entrepreneurial people.

Based on our findings, we assert that these new open science practices and novel open innovation practices adopted by research teams are challenging the established governance of research and innovation at universities. Such governance challenges arise in relation to reliable data sharing, quality control and reproducibility of research

methods and results, and the management of joint research platforms, university-industry relations, strategic alliances, spin-offs, start-ups, and consortias. A statement from Martti Mäntylä, professor and research team leader of the Enterprise Systems group, reflects this idea: "We now understand that it's not just about publishing results in open science, but also [about] creating the kind of institutions that will facilitate the uptake". In this new era of open science and innovation, what we term an open exploration era, universities, traditional open science institutions (David, 2004a), and novel open innovation institutions (Chesbrough, 2015) are under transformation. They must update their governance systems to respond to the new opportunities presented by digital technologies as well as demands for new principles and practices of open science and innovation in a digital world.

We suggest that this gap between the prevalent governance structures of open science and open innovation in universities and the emergent novel principles and practices of open science and innovation by university research teams can be bridged by adopting an adaptive and continuously evolving open governance model. To undertake this endeavour, we propose a novel open exploration policy that promotes a nexus between open science and innovation at universities in a digital world. An open exploration policy of universities considers the university as a holistic open science, innovation and learning ecosystem – an open exploration ecosystem – in which open science, innovation and learning practices in concert advance scientific breakthroughs and innovation in society.

An open exploration policy of universities has the potential to foster agile engagement with international organisations (e.g. United Nations, EU, OECD, and the World Bank) for developing innovative solutions for solving societal grand challenges: the ending of poverty and hunger, ensuring healthy lives and well-being for people, ensuring inclusive and equitable quality education, achieving gender equality, ensuring sustainable cities and communities, and combating climate change. Such innovative solutions include for instance communication solutions, medical solutions, humanitarian assistance, mobility solutions, energy and water solutions, and protection of civilians. An open exploration policy as such aspires for innovative solutions to grand challenges through co-creation of knowledge among researchers, research institutes, companies, states, municipalities, citizens, and international organisations.

From an academic perspective, our findings expand the Mertonian norms of open science (Merton, 1973) by specifying four principles of openness in science in a digital world. Open sharing and inviting practices not only build on Mertonian institutional imperatives of communalism, universalism, disinterestedness, and organised scepticism (CUDOS), but also advance the ethos of science in terms of scientific collaboration. Furthermore, the now-identified two novel types of open innovation practices at universities require further analysis to identify and distinguish various subtypes founded on open science practices in a digital world.

From the university leadership's perspectives, our results contribute by outlining a governance model of open science and innovation for universities in a digital world. This model provides helpful guidance on designing, setting up, and implementing open science and innovation practices at universities. In addition, our model provides guidance for practical suggestions for how to measure the progress of open science and innovation at universities. Our framework can as such help policymakers evaluate the degree of openness in science and innovation at universities. Our governance model can help in designing effective policies, roadmaps, and funding instruments to promote open science and bridge the gap between open science and open innovation at universities. For example, in the European Union, our findings and our proposed open science and innovation governance model can provide helpful guidance for advancing the European Open Science Agenda set up by the Open Policy Platform of the European Commission. On a global scale, the model can be helpful for universities that have signed the United Nations' Sustainable Development Goals Accord, and can provide guidance for promoting responsible, sustainable, and humanistic research and innovation through global knowledge co-creation as stipulated in the UN 2030 agenda.

To conclude, open science, innovation, and learning are drivers of an open, visionary, and fertile university environment that explores the borders of knowledge to create the future. Our governance model of open science and innovation and our proposed open exploration policy for research and innovation in universities aim to foster the creation of increased societal value from knowledge and an open society. This new policy is a tool for building local, national, regional, and global knowledge communities and raising the welfare level of each. We are at the dawn of an open exploration era.

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Appendix 1

Interview protocol

Question 1. Research Teams/Aalto Managers/Policymakers. Do you engage in open science?

Question 2. RT/AM/PM. What are the open science promoting factors that (you and your research team/Aalto's researchers/Finnish researchers) have adopted?

Question 3. RT/AM/PM. What are or what have been the preventing factors faced by (you and your research team/Aalto's researchers/Finnish researchers) in adopting open science practices?

Question 4. RT/AM. What are the practices that (you and your research team/Aalto's researchers) use to engage in open innovation?

PM. What are the best practices that (Finnish researchers) use to engage in open innovation?

Question 5. RT/AM/PM. Have (you and your research team/Aalto's researchers/Finnish researchers) used knowledge from open science platforms to create product or service innovations?

Question 6. RT/AM/PM. Is or have the developed scientific knowledge or practices that (you or your research team/Aalto's researchers/Finnish researchers) have contributed to in open science projects been used by other researchers or by firms to create product or service innovations?

Question 7. RT/AM/PM. Do you engage in open learning?

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