Introducing a Framework for Open and Reproducible Research Training (FORRT)

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Abstract

Dramatic changes to the transparency, rigor, reproducibility and replicability of research practices have occurred in the last decade. Despite considerable progress towards the adoption of open science practices by researchers in many disciplines, developing pedagogy to train students in open and reproducible scholarship has received much less attention. Engaging students with the multiple dimensions of open scholarship is crucial to embedding sustainable change: it enables the future generation of researchers to practice open scholarship themselves, fosters lasting engagement with research, and allows them to better understand findings in light of epistemic uncertainty. Teaching students about open scholarship also helps it become a public good, thereby reducing knowledge inequities in academia and beyond. We address the lack of an infrastructure for open scholarship education by introducing the Framework for Open and Reproducible Research Training (FORRT). FORRT is a community-driven infrastructure for educators that advances research transparency, reproducibility, rigor, and ethics through pedagogical reform. FORRT encompasses multiple initiatives and tools to provide educators with guidance and resources to easily embed open and reproducible practices into research training. In addition to fostering a wider ecosystem for resource-sharing and discussion, FORRT has developed a wide range of initiatives, including a seven-part roadmap to the open scholarship literature, a curated database of open scholarship materials and pedagogies for customizable adoption by teachers, and a self-assessment tool to help educators evaluate the integration of open scholarship tenets in their own teaching and mentoring. FORRT actively works towards principled teaching and mentoring, an underappreciated dimension of the scientific endeavour.

Keywords: Open Scholarship, Science Education, Teaching, Transparency, Open Science, Pedagogical Community, Team Science.

Introducing a Framework for Open and Reproducible Research Training (FORRT)

Scholars have understood the benefits of open, transparent, reproducible and cumulative research practices for hundreds of years. In the 1600s, the newly founded Royal Society—the world's oldest scientific institution—chose as its motto *nullius in verba* ("take nobody's word for it"). The skepticism enshrined in its motto anticipated that science progresses most when conditions for reasoned dissent are enhanced. Such optimal conditions occur when researchers—or any interested party—have unrestricted access to study protocols, data and analyses, as well as transparent information about the normative values, assumptions, and non-epistemic goals underlying a scholarly pursuit. This openness allows researchers to fully understand, confirm, verify and otherwise build upon the results of others. It also helps them to advance academic research by considering the boundary conditions under which findings hold and to test competing hypotheses about their underlying processes. Furthermore, open sharing of resources, data, and the products of research enhances both accessibility and inclusivity for the scholarly community and the wider public. Thus, openness is not only a means to an end—i.e., optimizing conditions for dissent—but a social justice imperative. These foundational features of science and the humanities (Macfarlane & Cheng, 2008; McNutt, 2014; Miguel et al., 2014), captured by the umbrella term "Open Science" or "Open Scholarship,"[1] increase the rigor of and trust in scientific claims. This has direct implications for the credibility and public value of science (Crüwell et al., 2019; Masuzzo & Martens, 2017; Spellman et al., 2017), even to the point where it can save lives,for example, by promoting awareness among citizens or building trust and support in public policies during a pandemic (see Besançon et al., 2021).

Research transparency has attracted renewed attention in the last decade sparked by the publication of implausible findings (Bem, 2011), admissions of questionable research practices (John et

[1] We prefer the term "Open Scholarship" over the more established term "Open Science". Open Scholarship includes Open Science but also includes the humanities and other non-scientific disciplines as well as all scholarly activities beyond research, such as teaching. We deliberately use the term Open Scholarship throughout this article in accordance with the inclusive approach embodied by FORRT.

al., 2012), and prominent failures to replicate scientific results (Open Science Collaboration, 2015). Added to this is a growing awareness of the misalignment of incentives in the current system of academic publishing (Higginson & Munafo, 2016), which focus largely on research quantity and novelty rather than quality (Frith, 2020), as well as on the considerable prevalence and adverse consequences of questionable research practices (John et al., 2012). Although this *credibility crisis* began in psychology, other fields have discovered similar and worryingly low rates of reproducibility (e.g., Baker, 2016; Eubank, 2016; Maassen et al., 2020) and replicability (e.g., Camerer et al., 2016, 2018; Damian et al., 2019).

In recent years, discussions about a 'crisis' have turned into a movement (Munafò et al., 2017; Vazire, 2018) with many transparency-themed initiatives being formed.[2] Introductions, manifestos, and guidelines for conducting open and reproducible research have been published in many fields and disciplines, including the humanities (e.g., Köchelmann, 2019; Marwick et al., 2017), the formal and computational sciences (e.g., Hutson, 2018; Stodden et al., 2016), the natural sciences (e.g., Bush et al., 2020; Junk & Lyons, 2020; Levin & Leonelli, 2017; Markowetz, 2015; Nüst & Pebesma, 2020; O'Dea et al., 2021), the professions and applied sciences (e.g., Cook et al., 2018, 2019; van der Zee & Reich, 2018), and the social sciences (e.g., Breznau, 2021; Christensen et al., 2019; Dienlin et al., 2021; Elman et al., 2018; Kathawalla et al., 2021; Klein et al., 2018; Miguel et al., 2014). Despite large strides in some open scholarship practices, few initiatives have targeted changes in teaching or educational norms. As a result, many of the potential benefits of teaching and training in open scholarship remain undiscovered.

Currently, where institutions have attempted to include open scholarship into their educational offerings, they have often done so through the lens of "research integrity"—and thus addressed this primarily within their *research community* rather than for their *students*. Yet, additional emphasis on teaching and mentoring of reproducible and open research practices will help ensure that students are not

[2] Such initiatives have included globally distributed networks of laboratories (e.g., the Psychological Science Accelerator, see Moshontz et al. 2018), grassroots organizations (e.g., ProjectTier, the Mannheim Open Social Science Conference-Crowdsourced Replication Initiative, the Political Science Replication Initiative, and the Collaborative Replications and Education Project) as well as professional societies (e.g., the Society for the Improvement of Psychological Science; the Society for Open, Reliable, and Transparent Ecology and Evolutionary Biology, and the Berkeley Initiative for Transparency in the Social Sciences).

simply exposed to best practices but are experienced and trained to engage in and evaluate these practices when they complete their studies.

The Center for Open Science (COS; 2013), whose mission is to "increase openness, integrity, and reproducibility of research", proposed three guiding principles to steer science towards "scientific utopia". These are: (1) free scientific communication via open access publications, preprints and continuous peer-reviews to improve the accessibility and fast dissemination and evaluation of new information (Nosek, & Bar-Anan, 2012); (2) restructuring incentives to promote better scientific practices and truth over publishability of findings (Nosek et al., 2012); and (3) crowdsourcing science to promote large-scale collaboration to accelerate scientific progress (Tierney et al., 2020, 2021; Uhlmann et al., 2019). Taken together, these steps reflect a widespread awareness of, and call for, improved practices thought to usher in the "credibility revolution" (Vazire, 2018), in which scholars collectively aim to achieve higher standards of evidence, transparency, and openness in the process of science making (e.g. Nosek et al., 2018; Nosek & Lakens, 2014; Zwaan et al., 2018; Wagenmakers et al., 2012). We suggest a fourth guiding principle to steer scholarship towards "scientific utopia": the principle of engaging students—the future practitioners and consumers of science—with open scholarship through teaching and mentoring.

In this paper, we introduce FORRT—the Framework for Open and Reproducible Research Training—to address this gap in open scholarship. Established in 2018, FORRT's main goal is to build, together with educators, a pathway to the stepwise adoption of principled, open teaching and mentoring practices. It also aims to generate and sustain a conversation about the ethics and social impact of a higher-education pedagogy that emphasizes themes of scholarly openness, epistemic uncertainty, and research credibility. Finally, FORRT responds to calls for a wider interpretation of open scholarship as *inclusive* scholarship (e.g., Albornoz & Chan, 2018; Bahlai et al., 2019; Rinke & Wuttke, 2021), proposing a reflection regarding the perceived relative importance of different academic activities and advocating for greater institutional recognition of teaching and mentoring resources. Encouraging the progressive opening of teaching and mentoring resources facilitates access, discovery, and learning. This

seeks to benefit teachers, and their students, who otherwise commonly experience barriers when incorporating open scholarship in teaching and learning.

Herein, we first justify why integrating open scholarship principles into higher education is important for science and society more broadly. We then introduce the various components of FORRT as a community-driven pedagogical framework designed to recognize, support and normalize the dedicated teaching and mentoring of open and reproducible research.

The Importance of Integrating Open and Reproducible Practices in Education

In higher education, the role of edifying students' education and future—as well as kindling their passion for knowledge—typically falls on academic faculty or staff, whose job description predominantly consists of teaching and research (along with administrative tasks and service). The view that scholars are better equipped to impart knowledge to students that they have gained through their research is a key part of the academic ethos. The rationale behind 'educator-researchers' and research-informed teaching is that those on the cutting edge of their discipline have the expertise to provide students with a sense of authenticity and excitement through active involvement and contributions to the field's advancements. Moreover, educators-researchers "are more effective at instilling an actively critical approach to understanding complex research findings rather [than] a passive acceptance of facts" (Marsh & Hattie, 2002, p. 604).

For academics to be inspiring educators they must not only know a given set of scientific facts but also be familiar with the procedures by which scholarly knowledge is generated. Marks (2009) raises a fundamental question about science education:

> *"If science is a process of knowledge production, then is science education best expressed as teaching students the process or as teaching them the knowledge itself? If we focus on teaching students the accumulated knowledge, the facts of science, then we are not actually teaching them science. Rather, we are teaching them science's products, and indeed we are misleading them by substituting the teaching of scientific facts, as if it were the teaching of science itself" (p. 22).*

It is not sufficient to teach about scientific facts or what scientists "know"—science education requires teaching about *how* scientists learn what they know. This is because a collection of scientific evidence (or the unreflective and decontextualized communication thereof) does not yield scientific literacy (Sharon & Baram-Tsabari, 2020). Thus, we argue that scholars and students would benefit from integrating open scholarship into their teaching and mentoring practices.

The importance of integrating teaching about the process of science into the teaching of subject-specific content has been articulated with regard to teaching research integrity. The National Research Council (2002, p .85) of the United States argued "The educational program should be built around the development of abilities that give rise to responsible conduct, [. . .] education in the responsible conduct of research should be provided within the context of the overall education program, [. . . and] the instruction should be provided as much as possible by faculty who are actively engaged in research related to that of the trainees." We support these recommendations, and further argue that training in open and reproducible research practices would yield similar benefits.

The Benefits of Open and Reproducible Research Training

Scholarship, at its core, is a system of methods of inquiry and knowledge production. While these vary widely from one field to another—contingent on studied phenomena (i.e., formal, natural, social and applied sciences) and on the use of various methods (i.e., qualitative and/or quantitative)—a common thread that unites the different fields of the scientific enterprise are transparent, accessible and cumulative research practices (with the inclusion of reproducible and replicable science for empirical fields).

Many of the changes encouraged to foster adoption of open scholarship in the last decade have been grassroots campaigns sparked and sustained by individual early adopters, rather than top-down initiatives at the institutional level. As a result, the adoption of open scholarship practices remains unevenly distributed across rank, field, institution, and country, with these asymmetries reinforced by privilege (Nosek, 2019). This means that, although some researchers have embraced open scholarship practices in their own labs, there appears to be much less systematic incorporation of open scholarship

practices in the education pipeline. As a consequence, it is still common that students finish their studies without learning about open scholarship during their studies (Chopik et al., 2018). Indeed, although most social science programs mandate specific training in statistics and ethics, it is difficult to find evidence of programs requiring any required training in open scholarship. We suggest that there are at least three reasons why training students in open scholarship practices is beneficial.

First, open scholarship enhances research *quality and integrity.* Training students to engage in open practices will help increase adoption rates and ensure they are widely adopted in the future. Much has been written about the benefits of implementing open scholarship practices (Chambers, 2017; Hales et al., 2019; Vazire, 2018; Willinsky, 2006) and we will not reiterate them here. However, critically for our purposes, for trainees to use open scholarship practices in their own work, it would be helpful to experience and/or receive instruction not only in the importance of these practices, but also in how these practices are conducted. Given how the incentive structure of academia influences research, (i.e., researchers' degrees of freedom, questionable research practices) often to the detriment of research quality (i.e., inflated rate of false positive results, asymmetric distribution of *p*-values in publications, reproducibility crisis), early career researchers untrained in open scholarship practices may be unaware, unsupported and subsequently less likely to implement them independently. If these topics are not imbued at the onset of their professional careers, it is unlikely that the next generation of researchers will understand, value, and maintain the better institutional constraints and open research procedures implemented at the dawning of the reproducibility crisis.

Second, training in open scholarship enables students who do not become researchers to be more *effective consumers of research*. Given that the majority of higher education students will not pursue an academic career, higher education presents a valuable opportunity to formally teach prospective consumers of research how scientific research is conducted in an open and transparent manner and how to evaluate research critically. In doing so, scholars not only increase the chances of leaving a lasting impression on students' beliefs about science, but also on how they envision, evaluate, and trust science,

which strongly influences how they will interact with it in their future. For example, individuals from countries with high societal trust in science tend to report greater confidence in vaccines (Sturgis et al., 2021, but also see Azevedo & Jost, 2021).

A third—and commonly overlooked—benefit is that open scholarship supports *social justice*. The current model of scientific production and educational practices contributes to and reproduces global inequalities. Science is built on the same foundations as society itself, which means that it has inevitably inherited many of society's systematic barriers hindering the success of traditionally marginalized groups—whether based on gender, race, ethnicity, origin or social class ("Is science only for the rich?", 2016). Thus, perpetuating the lack of open sharing of data, resources, and the products of research only serves to maintain the status quo (see Ledgerwood et al., *in press*).

Current academic structures around science communication, prestige-based funding, and teaching and mentoring practices often serve as a bottleneck, considerably hindering the chances of minorities in academia while perpetuating power imbalances and exploitation of privilege (Siler et al., 2018). Accordingly, the Matthew effect in science (Merton, 1968) describes how academic structures contribute unfairly to the advancement of already well-established scientists, given that, contrary to popular belief, the key factors predicting recognition of one's scientific work are seniority, location, and institutional reputation rather than research quality. Recognition then trickles down to funding, visibility and citations of one's scientific work (Merton, 1988), which ultimately contributes to increasing inequality with regards to which scientific ideas and perspectives get more diffused and therefore become more impactful to future scientific investigations (Morgan et al., 2018). For example, individuals awarded a grant accumulate more than twice the funding during their subsequent eight years compared to non-successful applicants, even with near-identical review scores (Bol et al., 2018). Similarly, junior researchers who co-author with prominent scientists have an ongoing competitive advantage, including continued collaboration with top-cited scientists and a higher likelihood of becoming one themselves (Li et al., 2019). Thus, inequality in academia is a pervasive issue, influencing not only who has access to higher

education and who gets to be a prominent scholar (see Roberts et al., 2020) but also which populations get studied (Henrich et al., 2010).

Creating the conditions for knowledge to become a public good—accessible to all members of society, is one way to help mitigate inequalities surrounding the access, learning, and production of scientific content (Steltenpohl et al., 2019). This is in line with the idea that science is a community endeavor, wherein open inquiry and public participation is at the heart of the scientific enterprise. The integration of teaching subject content along with open and reproducible scholarship sits at the very foundation of this idea as it gives students and aspiring scholars the necessary tools to engage with science-making. Such practices could maximize student's and early career scholars' likelihood of present and future engagement with resources, facilitating the acquisition of knowledge. Furthermore, open teaching initiatives allow for a wider variety of societal actors—including researchers, citizen scientists, policy makers, businesses, and third sector organizations—to collaborate and contribute their expertise towards a common goal in science production. These initiatives promote greater diversity and democratization of science, and improved scientific literacy, consumption, and participation among the lay public. Ultimately, this means greater alignment between the scientific process and its outcomes with principled values, and the needs and expectations of the society.

Principled Teaching and Mentoring

In the previous sections, we have discussed the benefits to the academic community, to students, and to society of integrating open scholarship practices into higher education. In what follows, we advance our ideals about *principled teaching* and *mentoring*—that is, teaching and mentoring that integrates both subject matter and open and reproducible scholarship tenets. We argue that teaching and mentoring have the potential to powerfully motivate positive change; indeed, others have argued that one potential solution to the replicability crisis is to make replication an explicit part of higher education pedagogy (Everett & Earp, 2015; Frank & Saxe, 2012; Grahe et al., 2012; Hawkins et al., 2018; King et al., 2016; LeBel, 2015; Standing, 2016) and in a 2016 survey, researchers identified better mentoring and

supervision as one of the most likely strategies to improve science (Baker, 2016).

Principled teaching and mentoring are based on the idea that the facts of science should be taught relative to the process by which those facts were acquired. This includes the understanding that assessing the quality of scientific findings hinges on research design, measurements and instruments, sampling methods and representativeness. This idea is enshrined at the core of the open scholarship movement, the credibility revolution (Vazire, 2018), open access (Nosek, & Bar-Anan, 2012; Tennant et al., 2016), and measurement practice reforms (Flake & Fried, 2020; Parsons et al., 2019). Principled instruction can happen both in classroom settings (e.g., through courses about open scholarship, or content courses that integrate tenets of open scholarship) as well as through scientific mentorship, as occurs when students are trained in open scholarship practices as part of their own work.

To understand and evaluate scientific work, students must first be familiar with the notion that scientific claims should be taken in light of epistemic uncertainty—i.e., the intrinsic incertitude about the validity of claims. Typically, academics are familiarized with, and utilize, heuristics in line with epistemic uncertainty, especially when it comes to judging the output of each other's work. Indeed, epistemic uncertainty is one key aspect motivating the peer-review system. We argue that science education would also benefit from systematically integrating field content with epistemic uncertainty. As an example, an analysis of twenty-four leading introductory psychology textbooks found widespread dissemination of scientific urban legends and insufficient criticality with acknowledgement of the complex and controversial nature of many findings (Ferguson et al., 2016). This has the unfortunate consequence of teaching students a false sense of certainty about 'the facts' of science, which can be thought of as misleading, if not unethical (Marks, 2009).

One conspicuous case of unfounded uncertainty is the pervasive belief that statistical analyses give a 'seal of objectivity' to research conclusions, despite the fact that this preconception may be ill-

advised (Freese & Peterson, 2018)[3]. Berger and Barry (1988) argue that acknowledging data interpretation's inherent subjectivity allows us to recognize the role that statistical analysis plays in integrating new evidence with existing knowledge. Thus, integrating tenets of open scholarship into teaching also helps to provide students with first-hand practical experience with probing the production of knowledge and evaluating it more critically.

As one of a few examples, the Collaborative Replications and Education Project (CREP; Grahe et al. 2018) offers students training opportunities to conduct large-scale collaborative replication projects, as well as training and support for teachers wishing to guide their students through such research. Principled education can leverage the aforementioned ideals to teach all students—not only those pursuing a career in academia—about the procedures of science and its intricacies alongside offering hands-on experience addressing concepts of reproducibility, replication, pre-registration, and analytical flexibility. In addition, students also benefit from working on tasks addressing the broad range of skills that they will need as professionals, such as understanding and communicating data insights (collect data or perform experiments), precise and complete record keeping, accurate reporting of results, and a commitment to dissemination.

Principled education finds normative support in several social sciences' codes of conduct—we use psychology as an example but do not intend to limit focus on any particular field. For example, the Ethical Principles of Psychologists and Code of Conduct of the American Psychological Association (APA; 2002) stipulates that "when engaged in teaching or training, psychologists present psychological information accurately" (Section 7.03b) and that researchers "undertake ongoing efforts to develop and maintain their competence" (Section 2.03); and "take reasonable steps to ensure that course syllabi are accurate regarding the subject matter to be covered, bases for evaluating progress, and the nature of

[3] Importantly, the notion of principled teaching is not restricted to quantitative sciences. The same tenets are applicable to the production of knowledge in general. Observational and qualitative research, for example, are contingent upon methods utilized, analytical choices, and theoretical framework. This is also true of literary and language studies (see Erasmus of Rotterdam, 1525; Queneau, 1947).

course experiences" (Section 7.03a). Considering the reproducibility crisis, we believe a reasonable interpretation of these guidelines involves communicating the possible caveats and uncertainty associated with any scientific work, and to focus on continuous self-improvement and education as a means to teach effectively. Indeed, the ideas instilled in the APA's Code of Conduct portray the scientific enterprise as a continuous learning process, whose application in science education contributes to a more realistic portrayal of the subject matter and promoting the curiosity and interest of students about the academic profession.

Facilitating Principled Teaching and Mentoring

We see at least two main barriers to researchers incorporating principles of open scholarship into teaching and mentoring of students. The first barrier is the current publication culture, which effectively places a premium on quantity over quality and novelty over confirming published findings (Allen & Mehler, 2019; Flier, 2017; Hill & Stein, 2021; Moher et al., 2018; Naudet et al., 2018) and encourages aggressive competition over collaborative teamwork, praising the individual over the many and varied efforts of a large team. This culture—antithetical to scientific ideals of cumulative and team science—naturally informs how students are taught and mentored, thereby entrenching the reluctance of current and future scholars to implement open scholarship practices out of concern that it will hinder their—and their students'—productivity, employability and career progression. Secondly, the current academic incentive structure discourages scholars to devote time and energy into incorporating open scholarship practices into training. As scholars' professional success is usually measured by publications and grant funding track records—and a typical academic workload is to teach, to conduct research and write grant applications—teaching can become deprioritized thanks to the competing demands of career progression and mobility in the job market place, both of which rely largely on research and grant-writing productivity. Thirdly, even if academics have a teaching-focused role—where there may be less pressure to publish or capture grants for job security—there is considerable administrative burden to incorporating open scholarship into pre-existing modules or pedagogical culture of their institute. The issue is

compounded by the fact that even if this burden were to be overcome, there is no top-down recognition or reward for doing so, even despite growing evidence that open scholarship enriches the learning experience of students and will inevitably provide a competitive advantage in their future careers in research or research-related job roles.

The current incentive structures of academia can be interpreted as working against both implementing open scholarship practices and changing methods of training to teach students how to use them. Therefore, the integration of new research practices into teaching and mentoring may appear to be a substantial task for most researchers and educators, considering the important time constraints they face. The burden of implementing these efforts can be reduced with new and existing initiatives such as open educational resources (OERs), massive open online courses (MOOCs), pedagogical communities (e.g., FORRT), and databases of open access materials (e.g., under Creative Commons license). There is also a plethora of general and subject-specific infrastructures to achieve open education through new pedagogies such as Open Core Courseware, GitHub, and freely available statistical suites such as R-based programming. A substantial contributor to the success of these initiatives is their relative community. These community-based initiatives can be further supported at the institutional level with universities incentivizing the incorporation of open scholarship practices into the curricula.

FORRT: from Vision to Reality

FORRT is a community-driven, grassroots organization designed by, and envisioned for, educators wishing to integrate their discipline content with open and reproducible scholarship tenets. We envisage a scientific utopia in which openness, accessibility, inclusivity, and reproducibility are considered normative practices. In order to realise this true scientific utopia, we need a fourth pillar—principled teaching and mentoring—to ensure these practices are taught to prospective researchers and consumers of science. FORRT's mission is to empower educators and their students to not only develop strong competencies in open scholarship but also actively incorporate it into their teaching and learning. Together with educators and students, we are building pathways to the stepwise adoption of principled,

open teaching and mentoring practices, whilst also generating a conversation about the ethics and social impact of higher-education pedagogy. FORRT's community-sourced initiatives are gathered in our e-learning 'educational nexus' online platform (https://forrt.org/nexus), twelve of which are described below, following a four-pronged approach.

Prong 1: FORRT's Didactic Framework

FORRT's didactic framework is intended to provide educators with a comprehensive but straightforward framework to teach and mentor open and reproducible science as well as qualify and quantify the degree of open and reproducible research practices in their teaching and mentoring. This is achieved through FORRT's clusters and self-assessment tool, respectively.

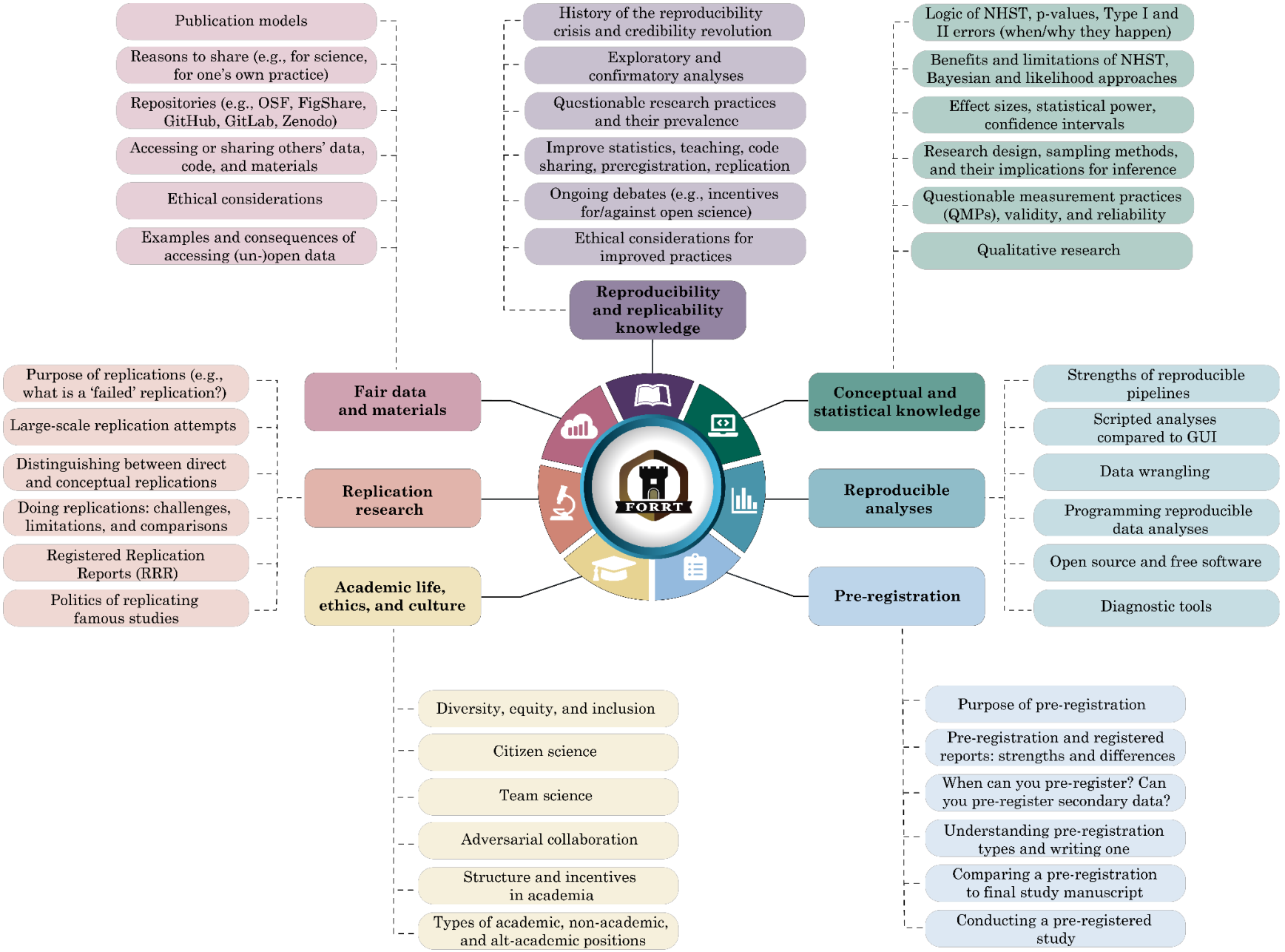
FORRT's Clusters (https://forrt.org/clusters).

Teaching open and reproducible scholarship effectively requires that educators are familiar with the relevant literature and aware of ongoing debates in the field. Drawing on the know-how of more than 150 experts in several internal and external hackathons on open scholarship, FORRT has identified clusters of knowledge that are central in the open and reproducible literature[4]. Presenting this information in a systematized and organized way is intended to familiarize researchers with prevailing themes in the literature. The current framework is composed of seven clusters: (1) reproducibility and replicability knowledge, (2) conceptual and statistical knowledge, (3) reproducible analyses, (4) preregistration, (5) FAIR data and materials, (6) replication research and (7) academic life and culture (see Figure 1).

Each cluster is further broken down into sub-categories to provide educators with useful information on the extent of open scholarship, and topics connected to one another. The complete list of clusters and subclusters as well as their corresponding suggested literature can be seen at https://forrt.org/clusters.

[4] These clusters represent the current state of the field, but are part of a framework which is intended to be dynamic and to be adjustable to portray—in time—the advancements of the field.

Figure 1.
FORRT's clusters and subclusters.



FORRT's Self-Assessment Tool (https://forrt.org/self-assessment).

To help educators evaluate their own teaching and mentoring, FORRT has devised an educational survey. This is intended to be used as a learning tool, with which educators can attain a nuanced perspective on the degree of open and reproducible research incorporated in their teaching and mentoring. FORRT's self-assessment tool (a) can gauge low and high levels of adoption of principled education—and is thereby able to incorporate newcomers and experts; (b) is applicable to both teaching and mentoring; (c) delineates a clear path forward, per knowledge area; and (d) differentiates between information and application. There are no prerequisites to use the self-assessment tool and respondents are given the opportunity to evaluate their teaching, mentoring or both. In an effort to make the self-assessment tool as comprehensive as possible regarding current practices in open scholarship, FORRT's clusters and subclusters were used as its basis. Thus, for each course that respondents seek to self-assess, they are walked through each FORRT cluster and invited to reflect on *the extent to which students are exposed* to content relevant to that cluster in their course (i.e., none, topic is discussed informally, topic is built into the course and assessed through assignments) and on *the level to which students are required to engage* with the content (i.e., not yet enacted, knowledge, practice, application). This assessment protocol aims to facilitate the translation of educational ideals into a tangible and coherent framework while being broad enough in scope to apply to a wide array of courses, mentoring styles, and their respective pedagogies. In addition, for each cluster evaluated, respondents are given the chance to indicate whether they would like to receive suggestions related to that cluster, tailored to the level of enactment already reported to be in the course. In addition to this self-assessment being useful for educators, the data generated by the tool may be useful for the community. By collecting anonymized information from educators, it is possible to assess and track how much open and reproducible content is being integrated into courses across institutions and countries. This may help to highlight the challenges being faced by educators of different backgrounds and diverse disciplines, inform evidence-based policies aiming at

improving educational practices, and substantiate the advocacy of scientific organizations/agencies. Therefore, the data from the self-assessment will provide the community with an overview of current practices that may elucidate the factors behind the emergence, development, and sustainability of scientific integrity, principled teaching and open education. As with science, cumulative development in teaching is indispensable. Hence, FORRT is working with national and regional open science and education institutions, agencies, organizations, groups and individuals, both in wider society and the local community, such as the UK's Reproducibility Network (UKRN), the German Open-Science Network (NOSI) and Reproducibility Network (GRN), and the American Center of Open Science (COS)—to ensure that FORRT is useful and impactful beyond its main educational scope and that the resources developed can be used to advocate for institutional change allowing for the full realization of principled education.

Prong 2: FORRT's Pedagogical Tools

FORRT advocates for the creation and sharing of pedagogical resources that can reduce some of the burden on educators looking to incorporate open and reproducible research principles into their teaching. To this end, the second prong of FORRT's initiatives is intended to equip educators with high-quality pedagogical tools on open and reproducible scholarship practices to facilitate its integration into curricula and educators' teaching, mentoring, and research practices.

FORRT's Curated Resources (https://forrt.org/resources).

To further facilitate the process of educators searching for educational resources and pedagogic tools on open and reproducible research and to increase the findability, accessibility, interoperability and reusability (FAIR) of such resources, FORRT has created a database of curated online materials on open and reproducible scholarship in compliance with the Open Educational Resources (OER Commons; https://www.oercommons.org). This database aims to organize the resources available on open scholarship while enriching them with educational metadata, which expedite the process of educators sorting through current materials and choosing the ones that best fit their needs.

Because open scholarship is a dynamic field, the community is critical to helping keep the database up to date. As such, FORRT's database of curated resources is designed by the community, for the community. FORRT encourages contributors to label resources according to their type (e.g., full course, syllabus, assignment), educational level, language, conditions of use (e.g., public domain or other), subject area, primary user (e.g., student, teacher) and to add useful tags. Resources are also categorized according to FORRT's framework of clusters pervading the literature on open and reproducible scholarship. Anyone can contribute by submitting new resources[5].

FORRT's database of curated resources is based on the premise that small-time commitments made by the community can yield meaningful improvements in organizing current resources on open-scholarship education. Moreover, it incentivizes incremental improvements while decreasing informational and time encumberment for educators. Thus far, FORRT has curated more than 700 open scholarship resources. Interested members of the community who are looking for materials can search the database by FORRT's clusters or by using specific search terms.

FORRT's Glossary (https://forrt.org/glossary).

As the landscape of open scholarship evolves, scholars and educators are constantly updating their knowledge and vocabulary. FORRT's glossary is devised to be an access point for those wishing to learn about openness, integrity, accessibility and reproducibility in research and education, whilst also representing a useful resource for those already engaged in these discussions. FORRT's glossary is an ongoing initiative, having successfully completed its first stage, and includes over 110 contributors from the academic community who have defined more than 250 open scholarship terms (Parsons et al., under review). The glossary aims to provide concise definitions of the most important and widely-adopted terms relating to open scholarship and help clarify terminologies, including where terms are used interchangeably or where terms are used with different associated meanings in varied fields. To this end,

[5] For those interested in contributing, the best way to submit new resources is via FORRT's website, but here is the stable link: https://tinyurl.com/FORRTResources

each term in the glossary is presented together with a brief definition, using non-technical language and appropriate references. Where there are several, potentially competing, definitions for a term (e.g. some fields use reproducibility and replicability in opposing ways), alternative definitions and related references are provided. FORRT's glossary is a crowdsourced project, cutting across experts and students, where the definition of terms is provided (and agreed upon) via consensus-based methodology by the very users of such terminology. Terms relating to social justice were prioritised for inclusion such that it provides a stepping-stone for more rapid developments in these areas.

FORRT's Summaries (https://forrt.org/summaries).

To reduce the burden on educators integrating open and reproducible practices into their teaching and mentoring and to aid in the learning process of any person interested in getting familiarized or staying up to date with the open scholarship literature, the FORRT community has prepared over 200 summaries of academic articles related to varied topics on open and reproducible practices. Every summary contains the article's abstract, its main takeaways, direct quotes (when relevant), and suggestions of articles on similar topics. A distinction is made between *Open and Reproducible Scholarship* and *Diversity, Equity, & Inclusion* summaries to highlight that the topics of social injustices and diversity, equity, inclusion and accessibility are often neglected in academia, as well as in the open and reproducible scholarship literature. To ensure the quality of the summaries, each one of them is drafted by a member of FORRT's community and then revised by two other independent FORRT members. As the literature on open and reproducible scholarship grows, FORRT's summaries are continuously extended[6].

FORRT's Lesson Plans (https://forrt.org/lesson-plans).

Developing educational resources is essential to facilitate engagement with, and adherence to, research integrity, transparency, openness, accessibility, replicability and reproducibility. Despite the

[6] Future plans regarding the summaries involve (1) the curation of summaries for all references included in the present manuscript as well as in the FORRT's self-assessment tool; (2) the classification of existing summaries into useful and didactic categories; and (3) the inclusion of each summary into FORRT's database of curated resources.

growing awareness of the benefits of training in open scholarship methods within research practices, there remains a lack of systematic incorporation of open scholarship practices in taught courses across higher education. While many pedagogical resources are regularly developed for this purpose, they are not often openly and actively shared with the wider community. Although the potential reasons for this are diverse, one reason may be the dearth of available ready-to-use educational resources. To support educators bridging that gap, the FORRT community set out to produce an open educational resource drawing from experts, interested parties, and stakeholders to produce evidence-based, high-quality lesson plans and activities available to teaching faculty, thereby reducing the labour required to develop and implement open scholarship content. In total, we compiled nine lesson plans and almost sixty class activities that can be integrated into taught courses 'out of the box' (Pownall et al., 2021). Each lesson plan was enriched with—and categorized based on—theme, learning outcome, activity length, and method of delivery. These lesson plans are neither static nor rigid; FORRT welcomes contributors and feedback on our openly available existing materials, and plans to host hackathons and seminars to improve, update, and further expand these pedagogical resources.

FORRT's Reversals and Replications (https://forrt.org/reversals).

Replications of previous scientific work are at the core of the Open Scholarship movement. Successful and failed replications are quite important in informing teaching as well as new research projects. However, as replication efforts become more widespread, it can be challenging to scholars and educators to keep themselves up to date with which effects in their field replicate and which do not. FORRT's reversals and replications aim to collate replications and specifically so-called reversal effects (i.e., when effects have their original direction flipped in a replication) in social science.

This initiative is a living-resource, freely available, crowd-sourced, and community-driven collection of over 200 documented effects that have either not been replicated or even reversed through empirical research across social sciences. Scholars from varied backgrounds and areas of social science are invited to contribute with effects which have been subjected to replications in their respective fields.

To be included, scientific claims must meet at least one of the following criteria: (i) the scientific claim has failed to replicate; (ii) it was studied in a meta-analysis and effect sizes were notably smaller than the original ones; (iii) the presence of publication bias regarding the scientific claim has been detected; (iv) clear errors in the analysis related to the original effect have been pointed out; (v) the scientific claim was formally retracted or (vi) there is evidence of fraud related to the original effect.

FORRT's Open and Reproducible Science Syllabus (https://forrt.org/syllabus).

To provide educators with an example of how they can draw resources from FORRT's educational nexus to integrate open scholarship into their teaching, FORRT has developed an Open and Reproducible Science 101 syllabus. FORRT's syllabus was developed as a seminar series covering 9 weeks of teaching. In an attempt to provide a comprehensive overview of the open scholarship literature, the syllabus builds on FORRT's cluster framework. As such, the proposed topic for each week is one of FORRT's clusters and it's related literature. For each week, there are suggestions of core and additional readings. Moreover, the syllabus is comprised of a series of assignments and proposed activities for students. Importantly, this syllabus is not intended to be a "one size fits all" approach. Educators can use this syllabus in its current format but are welcome to adapt it to meet their current courses and needs.

Prong 3: Recognizing and Commending Excellent Teaching and Mentoring

FORRT encourages and facilitates the sharing of teaching resources related to embedding open and reproducible science, as well as the recognition and citation of these resources for their cumulative and community value. FORRT supports efforts in this direction, such as sharing, citing, and repurposing teaching resources to help begin the transition to the scientific teaching utopia we have described. Accordingly, FORRT's third prong aims to help modify the academic incentive structure about teaching and mentoring through recognition and commendations of excellent teaching and mentoring.

FORRT's Pedagogies

The FORRT community is collecting and cataloguing exemplary instances of principled education, that is, pedagogies in teaching or mentoring of open and reproducible principles that have been

successfully implemented by scholars and educators of different fields. FORRT's pedagogies encompass reflections on increasing the dissemination, recognition and re-purposefulness of teaching practices and materials, experiences of adapting courses to incorporate reproducibility and transparency, and perspectives on the social and ethical responsibilities towards teaching open scholarship principles.

FORRT's pedagogies have several goals. First, we hope that scholars, instructors and educational institutions striving to develop or reform degree programs and courses can use FORRT's pedagogies as an initial template towards the creation of their own pedagogies. Second, it aims to highlight the instructor and their educational method. Through recognition and commendations of excellent teaching and mentoring, we hope to encourage a movement towards a better assimilation of principled teaching and mentoring into the academic incentive structure. Finally, we hope that, in the long term, this initiative can contribute to fostering social justice through the opening and democratization of educational resources.

FORRT's Educators' Corner

To facilitate the exchange between educators, FORRT offers a platform where teachers of different fields and disciplines can share their stories, experiences, successes and hardships in implementing principled teaching and mentoring, as well as their educational practices and initiatives that may be of interest to the open scholarship community. Similar to FORRT's pedagogies, the Educator's corner aims to recognize the efforts of educators in developing classes, materials, tools and initiatives regarding principled education and social justice in academia. It is our hope that this virtual space can increase the visibility of educators' efforts towards principled education, while encouraging them to exchange ideas, learn from each other, and stay up-to-date with best practices regarding open and reproducible teaching and mentoring.

Prong 4: Fostering social justice in academia

Finally, FORRT advocates for diversity, equity, inclusion, and accessibility in academic contributions by fostering social justice through the opening and democratization of scientific-educational resources to those who otherwise would be educationally disenfranchised.

FORRT's Open Office Hours

The FORRT community periodically holds its open and reproducible scholarship "office hours" in an attempt to democratize access to open scholarship discussions to anyone in the world wishing to learn, adopt, and disseminate open and reproducible tenets. This initiative is also available to those with interest or questions about teaching and mentoring open scholarship concepts and to those already engaged in raising awareness of the pedagogical implications and associated challenges of integrating open scholarship tenets into higher education (e.g., curricular reform, epistemological uncertainty, methods of education). FORRT's free to access open office hours are hosted online by members of the FORRT community.

FORRT's Remote Mentorship Program

FORRT aims to facilitate and encourage the transition to open and reproducible research practices by students in the early stages of their academic life. To this end, FORRT devised an initiative in which interested students (a) from underprivileged and underrepresented backgrounds, (b) non-WEIRD and (c) without access to local OS-friendly institutions or personnel, are matched to willing scholars endorsing 'cross-borders' and/or online mentoring of Bachelor or Master theses on the Topic of Open, Meta, and Reproducible Scholarship. Potential mentees interested in this initiative fill in an application detailing their education level, their field of work and their research. FORRT then endeavours to find a volunteer mentor with fitting expertise, discipline, and skills. Provided that a match can be found, mentors and mentees are put in touch and are free to discuss between themselves how they would like to proceed. FORRT also aims to document this process and give proper commendation to educators willing to participate in this initiative, so that engagement in such educational activities can contribute towards researchers' visibility, prestige, tenure and promotion reviews.

FORRT's Support for Underprivileged and Underrepresented Early-Career Scholars.

Underprivileged and underrepresented minorities who are early-career researchers often suffer racism, discrimination and significant barriers to their professional development. In an attempt to

challenge existing systemic and structural barriers towards a fairer, diverse, equitable, more inclusive, and accessible academia, FORRT aims to promote the thriving of underprivileged and underrepresented students, trainees, and early-career scholars, by serving as a link between willing mentors and mentees in their engagement with academia, its several duties, as well as open and reproducible science practices. This initiative works in the same way as FORRT's remote mentorship program with the difference that here mentorship is more broadly construed, departing from mentorship in academic theses to help with several other academic tasks (e.g., revision/feedback on application materials, grant/funding proposals, academic writing, research ideas, statistical analyses, etc).

Concluding remarks

FORRT's goal is to align the ideals of wider discourses around credibility and open science with the practices of our day-to-day work as scholars and educators. FORRT works to create widespread individual and institutional buy-in by providing infrastructure, community, and resources in a way that lowers the cost for individuals and institutions to pivot away from legacy approaches to research training towards more rigorous, cutting-edge practices that ensure a normalization of more open and reproducible academic research from the bottom up. In this way, FORRT fills a niche in the emerging ecology of open scholarship initiatives with its specific targeting. The Transparency and Openness Promotion (TOP) Guidelines (Nosek et al., 2015) as well as other prominent reform efforts in the wider open scholarship space such as the San Francisco Declaration on Research Assessment (DORA; https://sfdora.org/) and the Hong Kong Principles for assessing researchers (Moher et al., 2020) are aimed at the outputs of the academic system on different levels, from individual researchers to institutions like journals, funding bodies, and universities. FORRT aims to target these different levels of the academic system, focusing on the input: improving how research is conducted and how it is taught and diversifying those who learn from it. In this sense, FORRT's focus on teaching and education corresponds to a ground-level approach to open scholarship reform where most existing initiatives aim at structural or systemic aspects of academic work.

In addition, the TOP Guidelines, DORA, the Hong Kong Principles and other such initiatives incentivize open and reproducible research practices by providing standards for evaluating and rewarding research outcomes. While journals, funders, and academic institutions put in place policies and infrastructures to improve research practices, changes to the practices of individual researchers are needed to remain up-to-date with these advancements and meet improved standards of open, transparent, and reproducible research. FORRT provides a supportive community and collection of open resources and initiatives to facilitate such positive incremental developments.

Implications for stakeholders

When achieved, the activities of FORRT benefit several key stakeholders in the scientific enterprise. For students, principled research training exposes them to a more honest educational process, especially with respect to the ethical and epistemic commitments that are at the heart of the scientific enterprise. A principled approach to open and reproducible methods of education generates an atmosphere of constructive curiosity and problem-solving in the classroom. It creates first-hand practical experience in probing the production of knowledge for students, which serves to turn them into more competent consumers and creators of science. By bringing academic activity into greater reach for students it also fosters a more confident consideration of research-based options within and outside of academia in students' career planning.

For teachers, FORRT offers a pedagogical entry point to better research practices for both younger and older generations. The multidisciplinary FORRT community and the resources it provides support the transition into and continued development of open and reproducible teaching and mentoring practices (Azevedo et al., 2021). FORRT's approach to providing relevant pedagogical learning materials, tools and applied pedagogies lowers the opportunity costs for teachers to pivot towards an education that is centered around openness, reproducibility, and rigor. FORRT streamlines the education pipeline by (a) simplifying access to a curated and vetted list of resources for open and reproducible scholarship and (b) providing a platform for the curated provision of educational, research and teaching materials as well as

exemplary applied pedagogies.

For the scientific community, and indeed society more broadly, FORRT aims to generate positive downstream consequences in the form of more reproducible, more robust work conducted not only by today's students who will be tomorrow's researchers but also by the researcher-teachers who might use FORRT to become more attuned to the demands of open and reproducible research through its offerings. For example, FORRT aims to improve the conditions for the production of knowledge and increase science's value as a public good, which is accessible to all members of society. For citizens, this access can be direct, in the form of access to freely available research outputs and open educational resources, but in many more cases it will be indirect by allowing key agents in civil society, such as journalists and NGOs, and politics, such as elected representatives to access, to convey and otherwise use robust scientific information on their behalf. The advocacy for the use of science as a public good builds up societal capacity to prevent harmful effects that may come from the increasing opportunities for non-experts and propagandists to sow mis- and disinformation today, including on public issues of existential importance like public health, migration, and climate change. Such public knowledge also mitigates inequalities in the ability to access cutting-edge scientific outputs, including results of research studies as well as teaching and mentoring materials. By advocating for reducing inequality in the access to scientific information, FORRT aims to foster the democratization of science and the creation of greater opportunities for students and the wider public, including disadvantaged groups, where previously there were fewer or even none.

In sum, FORRT fills a void in the wider open scholarship ecology. Its community and infrastructure create opportunities for scholars to shape the minds and future of coming generations of scientists and consumers of science that were not available before. Scholars have an opportunity and responsibility to influence their students in a meaningful way: they can broaden the horizons of their imagination, teach them how to do research independently, help them discover connections between phenomena that seem unrelated at first, and develop in them the confidence to challenge outdated dogma.

In light of this, FORRT aims to support scholars in taking up this opportunity and living up to the responsibility that comes with it.

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Author's statement

For more than two years, this manuscript was open to everyone's feedback as part of FORRT's open contributorship, diversity, and inclusion mission and advocacy. Go team science! We are incredibly grateful and humbled for all the engagement it has harnessed. All contributions are formally recognized. We used tenzing for contributions taxonomy, which was adapted from CRediT (https://casrai.org/credit).

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