Defining Open Scholarly Infrastructure: A Review of Relevant Literature

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Introduction

Invest in Open Infrastructure (IOI) was founded on the premise that open, community-owned infrastructure is necessary for scholarly research to thrive. We are certainly not alone in this sentiment. Numerous organizations across the scholarly research ecosystem, including, the Scholarly Publishing and Academic Resources Coalition (SPARC), the Global Sustainability Coalition for Open Science Services (SCOSS), AmeliCA, and the Association of Research Libraries (ARL), as well as many others have recognized the critical role open infrastructures play for the communities they serve — contributing to more equitable, accessible, diverse, and resilient knowledge practices.

IOI strives to build on the efforts of others working to improve funding and resourcing for the open infrastructure on which scholarly research relies. One way we hope to achieve this is by pushing the limits of our own understanding about infrastructure in scientific research and scholarly communication. A deeper understanding will have significant implications for how we collectively engage with and support the organisations providing services that make research and scholarship possible. This report represents the beginning of an iterative process for IOI in deepening its understanding on this topic that we look forward to developing and refining as our work progresses. Ultimately, we hope this literature review can inform the development of a robust theoretical framework that can provide structure and support to future projects.

Background

To ensure its stakeholders understand the essence and scope of IOI's work, IOI produced a working definitions of both "infrastructure" and "open infrastructure" in the context of the scholarly research ecosystem in January of 2021, as follows:

> *By "infrastructure" we mean the sets of services, protocols, standards and software that the academic ecosystem needs in order to perform its functions throughout the research lifecycle — from the earliest phases of research, collaboration and experimentation through data collection and storage, data organisation, data*

analysis and computation, authorship, submission, review and annotation, copyediting, publishing, archiving, citation, discovery and more.

"Open infrastructure" is the narrower sets of services, protocols, standards and software that can empower communities to collectively build the systems and infrastructures that deliver new improved collective benefits without restrictions, and for a healthy global interrelated infrastructure system.

Unfortunately, this two-part definition:

1. Is insufficiently unsystematic (both in breadth and depth) in delineating the kinds of functions and activities scholarly infrastructure needs to support,
2. Is vague in defining the values and goals of "open infrastructure", and,
3. Does not easily translate to a robust theoretical framework that can provide structure and support to IOI's varying projects.

Approach

The following literature review outlines IOI's initial attempt towards a more sophisticated framework for understanding open infrastructure for research and scholarship by first understanding the available research on the topic to help develop a more practical and actionable approach to the question of what constitutes open scholarly infrastructure. Such a framework will ideally:

1. Facilitate the development of a systematic and standardised *definition* of open infrastructure specific to IOI's organisational functions and objectives — mediating the gaps in our current definition while effectively delineating and communicating the essence and scope of our work.
2. Inform the design of our research methods for examining open infrastructure across our varying projects[1] — establishing proven constructs, concepts, and approaches on which we can draw.

For this review, we examined a body of literature that includes works across the fields of anthropology, scholarly communications, international development studies, science and technology studies, and infrastructure studies — fields of study with which we (the authors) had the most experience and therefore familiarity.

While we aimed to balance foundational understandings of open infrastructure with both recent and peripheral discussions on the topic, this preliminary review is by no

[1] The framework described in this report will directly contribute to our Costs of Open Infrastructure project, enabling us to identify the critical providers of open technologies and systems that support research and scholarship.

means an exhaustive inventory of literature that engages with the theoretical or practical conceptions of open infrastructure. Instead, this literature review is a work in progress that will gain breadth, depth, and nuance as IOI continues its work over time.

Once our literature was compiled, we reviewed, categorized, and manually annotated it. Utilizing an inductive approach, we identified the varying ways in which infrastructure was defined and the characteristics that were attributed to it. We did this with the aim of developing:

1. An initial assessment of the current state of research on the topic of open infrastructure,
2. Recommendations for the ways in which IOI's working definition of open infrastructure can be strengthened and,
3. Recommendations for future areas of development and further research for better understanding open infrastructure.

In the following literature review we review our curated body of literature in order to outline prevailing conceptualizations of open infrastructure in the context of research and scholarship. We provide categories to better understand the ways in which "infrastructure", "scholarly infrastructure", and "open scholarly infrastructure" have each been conceptualized and defined.[2] We then offer a conclusion to this exploration that identifies key areas for future research to continue meeting the aims of this work.

Key Elements from the Literature

Infrastructure Definitions

In the digital age, the term "infrastructure" has been used to refer to the "constellations of software technologies and systems usually associated with the Internet" (Karsati et al., 2010, p. 382). With the proliferation of work around this topic, terms such as "information infrastructure", "cyberinfrastructure", "e-infrastructure", and "knowledge infrastructure" have been coined to reflect the distinct frameworks and empirical breadth applied within inquiries into this broad phenomenon.

[2] These categories emerged organically as we coded our compiled body of literature. We ultimately decided that they offered the most precise classification system while simultaneously facilitating an easy-to-follow narrative for our report.

Our intention in this report is to capture all these varying conceptualizations and we use the all-inclusive term "infrastructure" as a catch-all that encompasses this diversity. However, this preliminary investigation engages to a greater extent with the literature on "information infrastructure" as we wanted to prioritise theoretical approaches that considered both the social and technical dimensions of infrastructure.

In the literature we reviewed, definitions of "infrastructure" (summarised in Table 1, below) often frame the concept as a network (see especially Larkin, 2013). Infrastructure is described as consisting of disparate entities — both technical (hardware and software) and social (practices, norms, and structures) — that as an ensemble, facilitate the linking and/or movement of ideas, signals, objects, and people (Larkin, 2013).

Definition	**Author(s)**	**Research Discipline**
Cyberinfrastructure refers to a "layer of enabling hardware, algorithms, software, communications, institutions, and personnel. This layer [provides] an effective and efficient platform for the empowerment of specific communities of researchers to innovate and eventually revolutionize what they do, how they do it, and who participates."	Atkins et al., 2003 (p. 5)	Cyberinfrastructure
e-Infrastructure refers to "in the first instance to designate the physical or material components of [a large] technological system, the advanced electronic networks that make use of the Internet and the Web, as well as, secondarily, the organizational networks that are supported by this system."	Schroeder, 2007 (p. 2)	e-Infrastructure
"Superadded to the term 'information,' infrastructure refers loosely to digital facilities and services usually associated with the internet: computational services, help desks, and data repositories to name a few."	Bowker et al., 2010 (p. 98)	Infrastructure Studies; Information Infrastructure
Knowledge infrastructure refers to the ''robust	Edwards, 2010	Infrastructure

networks of people, artefacts, and institutions that generate, share, and maintain specific knowledge about the human and natural worlds."	(p. 17)	Studies; Knowledge Infrastructure
"Infrastructures are built networks that facilitate the flow of goods, people, or ideas and allow for their exchange over space. As physical forms they shape the nature of a network, the speed and direction of its movement, its temporalities, and its vulnerability to breakdown. They comprise the architecture for circulation, literally providing the undergirding of modern societies, and they generate the ambient environment of everyday life."	Larkin, 2013 (p. 328)	Anthropology

Table 1: Definitions of Infrastructure Across Varying Research Disciplines

In these frameworks, infrastructure is described as a "supporter" or "enabler", "sinking into the background" and becoming visible to its users only when it breaks down (Star & Ruhleder, 1996, p. 112). Because of this tendency to fade into the background, infrastructure can appear unremarkable and unexciting in nature, except when it fails in some way to provide the service for which it was built (Karasti & Blomberg, 2018: Star & Ruhleder, 1996).

While there can be an invisible quality to infrastructure, this invisibility is neither perpetual or constant (Karasti & Blomberg, 2018). Larkin (2013), for example, suggests that the visibility of infrastructures exists on a spectrum, ranging from "unseen to grand spectacles and everything in between" (p. 336). He makes reference to the contingency of physical infrastructural projects that are pursued by states for what they signal to spectators — as symbols of their governance or ideologies — as opposed to their functionality.

Lea and Pholeros (2010), describe this phenomenon in their discussion of the housing projects in indigenous Australia that produce "houses-that-are-not-housing" (p. 192). While these projects construct houses in physical structure, their plumbing and electrical shortcomings — a result of "poor design, indifferent (or no) inspection, and [...] shoddy construction" (p. 207) — nullify their functionality. In short, these houses fail to provide the utility that most users expect from their housing: "safety, security, and health benefit" (p. 191).

Science and Technology Studies (STS) embraces the "foregrounding the truly backstage elements" (Star, 2002, p. 16) of the mundane. In this work, researchers seek to center the background practices and unnoticed work of various knowledge workers, including designers, developers, users, managers, and other mediators, that facilitate a functioning infrastructure (Star, 2002). For more on this work, please see Table 2, below.

Definition	Author(s)	Discipline
Infrastructure emerges in relation to organised practices. It "occurs when local practices are afforded by a larger-scale technology, which can then be used in a natural, ready-to-hand fashion."	Star & Ruhleder, 1996 (p. 114)	Ethnography; Knowledge Management; Information Systems
"Following Star and Ruhleder (1996), an infrastructure emerges when it reaches beyond a single event on a temporal scale or a single site practice on a spatial scale [...occurring] when here-and-now practices are afforded by temporally extended technology that can be used in an everyday, reliable fashion. Infrastructure becomes transparent when it exists as an accessible, ready-to-hand installed base that enables envisioning future usages."	Karasti et al., 2010 (p. 400)	Information Architecture; Science and Technology Studies

Table 2: Conceptualization of Infrastructure as Related to Organisational Practice

The field of STS, therefore, understands infrastructure not just in terms of interdependent components of a network but also in terms of "configurations" of practices and activities (Karsati et al., 2010; Star & Ruhleder, 1996). Popularised by Star & Ruhleder (1996), such a framework shifts understanding of infrastructure from being static and definitive ("what infrastructure is") to dynamic and relationally configured ("we can't be definitive about what infrastructure is, but rather in the ways infrastructure emerges") (Bowker et al, 2010; Karsati et al., 2010; Star & Ruhleder, 1996).

This marks a significant shift towards the study of infrastructure's specific dimensions and characteristics, resulting in the concept most often being "defined by jotting down a laundry list of characteristics" (Bowker et al., 2010, p. 99) (summarised in Table 3, below).

Characteristics of Infrastructure	Author(s)
The configuration of the following nine (9) dimensions form 'an infrastructure': (1) Embeddedness (2) Transparency (3) Reach or scope (4) Learned as part of membership (5) Links with conventions of practice (6) Embodiment of standards (7) Built on an installed base (8) Becomes visible upon breakdown (9) Is fixed in modular increments, not all at once or globally	Star & Ruhleder, 1996
Based on a synthesis of characteristics emerging in prominent literature, infrastructures can be characterised by the following five (5) dimensions: (1) their profoundly relational quality (2) their intrinsic (at least partial) invisibility (3) their connectedness, sometimes described as "scaling" (4) their emerging and accreting quality of infrastructures (5) the role of intentionality and intervention in delineating infrastructures	Karasati & Bloomberg, 2018
Infrastructures have a "modular, multi-layered, rough-cut character [...]. [They] are not systems, in the sense of fully coherent, deliberately engineered, end-to-end processes. Rather, infrastructures [...] consist of numerous systems, each with unique origins and goals, which are made to interoperate by means of standards, socket layers, social practices, norms, and individual behaviors that smooth out the connections among them. This adaptive process is continuous, as individual elements change and new ones are introduced — and it is not necessarily always successful."	Edwards et al., 2013 (p. 5)
"Information infrastructures are characterised by openness to number and types of users (no fixed notion of "user"), interconnections of numerous modules/systems (i.e. multiplicity of purposes, agendas, strategies), dynamically evolving portfolios of (an ecosystem of) systems and shaped by an installed base of existing systems and practices (thus restricting the scope of design, as traditionally conceived). Information infrastructures are also typically stretched across space and time: they are shaped and used across many different locales and endure over long periods (decades rather than years)."	Monteiro et al, 2013 (p. 576)

Table 3: Characteristics of Infrastructure Identified by Various Authors

Scholarly Infrastructure Definitions

In this report, we use the term "scholarly infrastructure" to refer to infrastructures that are specifically associated with research and scholarly knowledge production. Across the literature reviewed, this phenomenon has also been referred to as "scholarly communication infrastructure", "scholarly publishing infrastructure", "e-research infrastructure", and "knowledge infrastructure" — each reflecting a distinct framework and empirical breadth.[3]

The definitions of scholarly infrastructure that we reviewed (summarised in Table 4, below) utilise the popular metaphors of infrastructure as a "supporter" or "enabler", describing the phenomenon as the thing upon which the scholarly knowledge production and dissemination — or its particular components — operate. These definitions also often frame scholarly infrastructure as a network, describing it as a system that pulls diverse actors, organisations, and perspectives across domains, disciplines, and geographies together to engage in common practices.

Definition	**Author(s)**
"e-Research infrastructures are networked systems in which technologies and social institutions are intertwined, [combining] extensive networks of physical artefacts with the organizational capacity to implement and sustain them. [...They are] both: a large technological system insofar as they consist of a number of interdependent social and technical systemic parts (and large because the system covers the globe); and an infrastructure insofar as it supports research."	Schroeder, 2007 (p. 8)
The "fundamental substrate upon which scholarly research operates [...] seamlessly and successfully supporting knowledge work".	Lagoze et al., 2015 (p. 1054)
The "tools and services that underpin the scholarly research life cycle".	Chen et al., 2019 (p. 1)

[3] Terms such as big science, data-driven science, networked science, open science, Digital Humanities, science 2.0, e-Science, e-Social Science, and e-Research have also been used by researchers examining knowledge production processes in the digital age (Karasti et al., 2016). These works fall out of the scope of this report.

“Technological infrastructure that runs scholarly communication and publishing.”	Maxwell et al., 2019 (p. 6)
“Infrastructure vital to the advancement of the sciences”.	Watkinson & Pitts, 2021 (para. 1)
Scholarly communication technologies “includes tools, platforms, and standards that can be locally adopted to support one or more of functions of the lifecycle of scholarly communication, which is conceptualized as including the following activities: creation, evaluation, publication, dissemination, preservation, and reuse.”	SComCaT, n.d. (para. 3)

Table 4: Definitions of “Scholarly Infrastructure”

Furthermore, we found numerous studies that describe scholarly infrastructure by centering the practices of individuals and/or organisations within the scholarly knowledge production process (Chen et al., 2019; Kramer & Bosman, 2017; Lewis, 2020). These works mirror understandings of infrastructure common within the field of STS: as emerging in relation to organised practices and connected to particular activities.

For example, Chen et al.’s (2019) investigation into the vertical integration of scholarly infrastructure first outlined the stages of the academic knowledge production process (see Figure 1, below) and then charted varying scholarly tools and services across these stages.

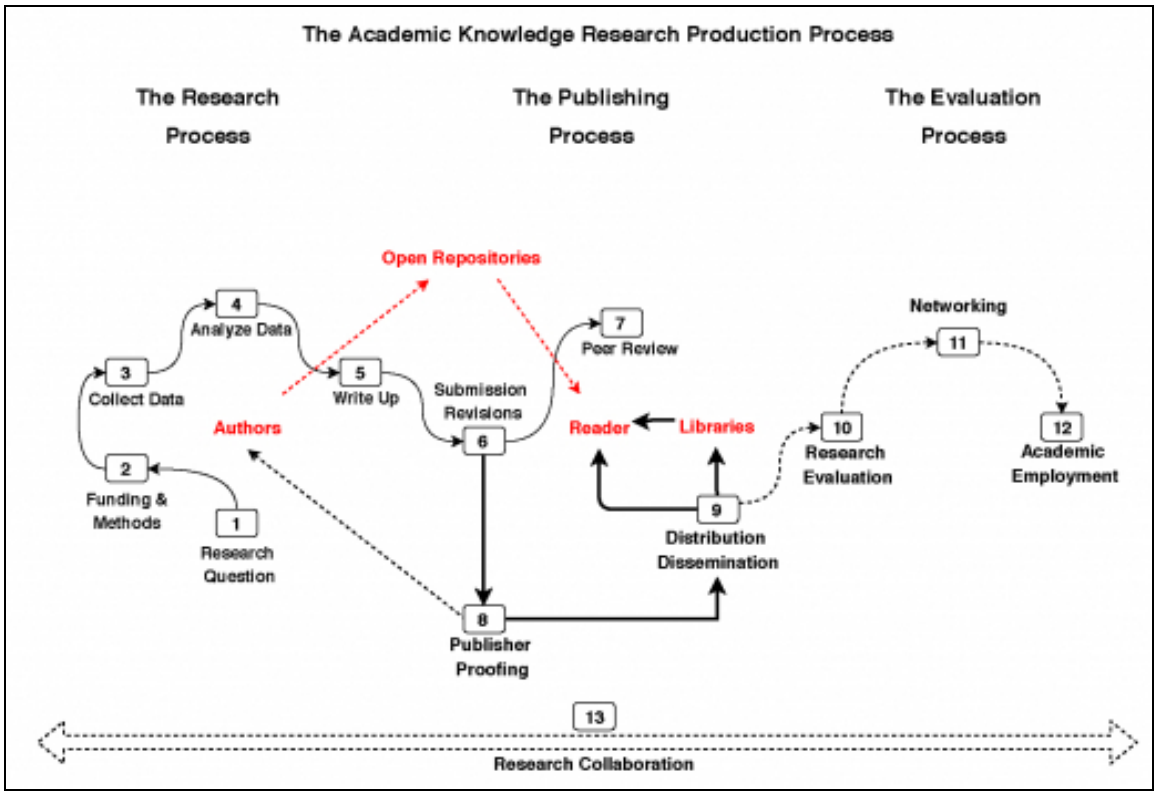

Figure 1: The Academic Research Knowledge Production Lifecycle by Chen et al. (2019)

Furthermore, both Kramer and Bosman (2017) and Lewis' (2020) works in identifying tools, services, and systems that make up the scholarly infrastructure ecosystem utilized a similar approach. These authors first identified a typical workflow for scholarly research and then classified observed tools and services based on their position within the authors' respective workflows (see Figure 2 and Figure 3 below). While we're aware there are other frameworks that exist for this approach, we limited ourselves to these initial three (3) and hope to expand our understanding of alternative frameworks in the future.

Phase Number	Activities (30)	Research Phases (7)
0	project management	preparation
1	crowdsource/ define research priorities/ ideas/ collaborations	
2	fund get contract	
3	search (lit/data/patents/code)	discovery
4	get access	
5	get alerts/get (reading) recommendations	
6	reference management	
7	read/view	
8	annotate/tag (during/after reading)	
9	experiment & collect/mine/extract data	analysis
10	share notebooks/protocols/workflows	
11	analyze	
12	visualize	writing
13	write (+ code)	
14	cite	
15	translate	
16	archive/share code	publication
17	archive/share data/video	
18	archive/share publications	
19	archive/share posters	
20	archive/share presentations	
21	present research findings	
22	peer review and comment/recommend (pre-pub)	
23	select journal to submit to	
24	publish	
25	outreach/valorization	outreach
26	researcher profiling (& social network)	
27	comment	assessment
28	peer review (post-pub)	
29	measure impact (of output, e.g. article)	
30	assessment (of researcher/research group)	

Figure 2: Research Workflow Phases Adapted from Kramer & Bosman (2017)

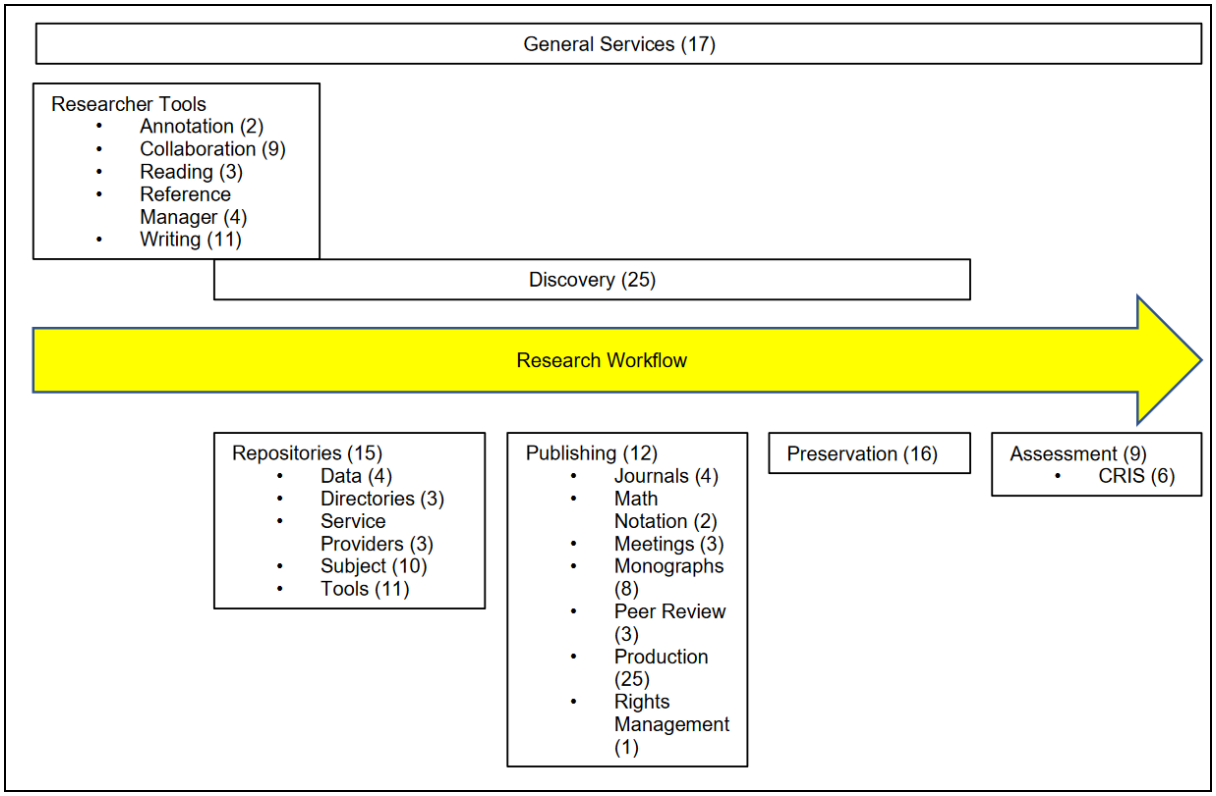

Figure 3: Research Workflow Developed as Part of the Lewis' (2020) Bibliographic Scan of Digital Scholarly Communication Infrastructure

Open Scholarly Infrastructure Definitions

In this report, we use the term "open scholarly infrastructure" to refer to scholarly infrastructure that is owned and/or operated by non-commercial actors, such as academic libraries, consortia, professional associations, communities of practice, independent non-profit organizations, and other research bodies. Across the literature reviewed, this phenomenon has also been referred to as "open infrastructure", "open science infrastructure", "open common infrastructure", "community infrastructure", and "community-owned infrastructure" — each reflecting a distinct framework and empirical breadth.

Definition	Author
Infrastructure that is "trusted and relied on by the broad community it serves."	Bilder et al., 2015 (para. 4)
"Those services that are invisible to the end user but which contribute, directly or indirectly, to the successful implementation of OA workflows".	Knowledge Exchange, 2016 (p. 26)
"Projects that provide software or services that support open scholarship."	Lewis et al., 2018 (para. 5)
"'Academy-owned' and 'academy governed' tools, platforms, and services".	Skinner, 2019 (para. 6)
"The structures and services needed for Open Science/Scholarship to operate, e.g. services, protocols, standards and software that the academic ecosystem needs in order to perform its functions during the research lifecycle."	Ficarra et al, 2020 (p. 10)
"Open science infrastructures refer to shared research infrastructures (virtual or physical, including major scientific equipment or sets of instruments, knowledge-based resources such as collections, journals and open access publication platforms, repositories, archives and scientific data, current research information systems, open bibliometrics and scientometrics systems for assessing and analysing scientific domains, open computational and data manipulation service infrastructures that enable collaborative and multidisciplinary data analysis and digital infrastructures) that are needed to support open science and serve the needs of different communities."	UNESCO, 2021 (p. 12)
"In an Open Science context, 'infrastructure' — the 'structures and facilities' — refers to the scholarly communication resources and services, including software, that we depend upon to enable the scientific and scholarly community to collect, store, organise, access, share, and assess research."	SCOSS, 2022 (para. 2)

Table 5: Definitions of "Open Scholarly Infrastructure"

Works that directly explore open scholarly infrastructure or its derivatives often draw from two different frameworks, the open source framework and a framework emphasizing the threat of knowledge enclosure. These are discussed in more detail below.

Many — often earlier — works examining this phenomenon draw from the extensive literature on "open source", focusing on the ways in which software, standards, and protocols can promote the accessibility or transparency of infrastructure development, maintenance, and services (Schroeder, 2007; West & O'mahony, 2008). More recently, there has been a shift towards a framework that draws from political economy, instead focusing on the threat of enclosures to community-owned and -operated scholarly infrastructure (see for example, Skinner, 2019; Moore, 2020). As Bilder et al. (2015) note:

> *We believe we risk repeating the mistakes of the past, where a lack of community engagement lead[s] to a lack of community control, and the locking up of community resources. In particular our view is that the underlying data that is generated by the actions of the research community should be a community resource – supporting informed decision making for the community as well as providing [a] base for private enterprise to provide value added services.*

While these frameworks draw from different theoretical traditions, both regard infrastructure and its disparate parts beyond commodity production — their valuation existing beyond the logic of the market. In this sense, open scholarly infrastructure functions not just in support of productive practices around scholarship and research, but also in support of social practices and values as well (Helfrich, 2013, as cited in Heinrich Böll Foundation et al., 2013). Some of the explicit values that open scholarly infrastructure has been envisioned to support can be found in Table 6, below.

Values for Open Scholarly Infrastructure	**Author**
Infrastructure that is characterised by "unrestricted access and use, being free of charge to users, and using non-exclusionary (open) standards."	Schroeder, 2007 (p. 2)
Governance	Bilder et al., 2015

• Coverage across the research enterprise • Stakeholder-governed • Non-discriminatory membership • Transparent operations • Cannot lobby • Living will • Formal incentives to fulfil mission and wind-down Sustainability • Time-limited funds are used only for time-limited activities • Goal to generate surplus • Goal to create contingency fund to support operations for 12 months • Mission-consistent revenue generations • Revenue based on services, not data Insurance • Open source • Open data (within constraints of privacy laws) • Available data (within constraints of privacy laws) • Patent non-assertion	
Infrastructure that "deliberately allow[s] for multiple forms of participation amongst a diverse set of actors, and which purposefully acknowledge[s] and seek[s] to redress power relations within a given context."	Okune et al., 2019 (p. 2)

Table 6: Values for Open Scholarly Infrastructure

In addition, there are examinations of the political nature of infrastructures outside the scope of this initial work that are important for understanding this dynamic, particularly with respect to indigenous cultures and other historically marginalized groups. These include Adema & Hall (2013), Albornoz et al. (2020), Birkinbine (2020), and Christen (2012).

Conclusion

As demonstrated in the literature reviewed above, there is a strong and vigorous debate about these core concepts. While we don't find it easy to create a simple distillation of these disparate ideas into a single formulation, it's clear that

infrastructure is vitally important for what it enables and how it is structured is essential to its operation.

Understanding the relationships and interactions of various stakeholders within and outside the infrastructure service is key to understanding the infrastructure as a whole, and while it is appealing to apply simple labels (such as "open") based on easily observable features (is there a Github repository?), it's vitally important to look at the totality of the relationships and features in order to make a more nuanced determination about the type and structure of an infrastructure arrangement, whether it's working properly, and how it might be reimagined to better achieve our desired outcomes. Simply put, there is no one definition of infrastructure but what the reviewed literature provides us with are numerous conceptual tools with which we can potentially better understand and interrogate the concept.

Going forward, IOI will need to determine which of these tools will work best with our objectives and processes as an organization. In order to do this, it's important we expand the breadth of this literature review to better include conceptualisations of infrastructure outside of the more prominent "information infrastructure" literature we reviewed here. Potential areas for a more holistic understanding of open infrastructure include: (1) technical frameworks for infrastructure (e.g. cyberinfrastructure), (2) political economic frameworks for infrastructure (e.g. commons enabling infrastructure), (3) intersectional frameworks for infrastructure (e.g. inclusive infrastructure, feminist infrastructure), and (4) disciplinary approaches (e.g. library and information sciences). Somewhat pressing, is our need to develop theoretical and practical approaches to our open infrastructure work. We hope to expand on this literature review in depth by further reviewing existing STS approaches to studying and understanding infrastructure, critically reviewing the limits to these approaches, and by adapting them for open infrastructure contexts as we move to make distinctions in the space (such as "critical" and "at-risk", to name a few).

Additionally, this review also makes clear that the distinguishing feature between open infrastructure and its commercially-run and -operated counterparts is the fact that its value lies not just in its ability to support productive functions but how it fosters positive and desirable social practices and values. It is insufficient to simply assert certain values without demonstrating those values are embodied in the infrastructure service that is being provided. The actions must match the words to ensure a truly healthy and viable ecosystem of open infrastructure services.

While we understand this exercise is insufficient to the need for a comprehensive framework, we hope this stands as a helpful addition to the ongoing conversation both within IOI and the larger community in which we are embedded, encouraging everyone to think deeper about these key issues in order to realize better coordination and mutual support towards our shared aims of an open research infrastructure that serves all stakeholders and helps further the pursuit of knowledge in all its forms.

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