Sustaining Knowledge and Governing its Infrastructure in the Digital Age: An Integrated View

Pierre Mounier (EHESS, OpenEdition, OPERAS)
and Simon Dumas Primbault (CNRS, OpenEdition / LHST, EPFL / BnF)

Foreword

Pierre Mounier and Simon Dumas Primbault

It is common to consider that the massive deployment of networked digital technologies from the end of the 1990s onwards in most developed countries, and then throughout the world, has led to an upheaval in the "knowledge order," *i.e.*, in concrete terms, in the way knowledge is produced, shared, disseminated, mobilised, and hierarchised in the various circumstances of social life. The online encyclopaedia Wikipedia, which in a few years has marginalised the monuments of reference literature such as the encyclopaedias Universalis and Britannica, is an emblematic example. The development of the open access movement for research publications, with its share of open archives, electronic journals, and other platforms, would not have been possible or even imaginable without a rapid shift in the scientific publishing sector towards making research results available online in digital format (Suber, 2012).

One of the most interesting heuristic effects of the so-called "digital revolution" is to drive the observer to pay particular attention to the conditions of possibility of knowledge production and dissemination: in many scientific disciplines, "laboratory life" in the digital age no longer resembles that of a few decades earlier (Waquet, 2015). Producing, managing, sharing, exploiting digital data involves specific practices and operations that have consequences in terms of work organisation (Antonijević, 2015). But also, accessing, reading, annotating, collecting scholarly documents is no longer done under the same conditions today, and a now abundant literature attests to this (Davallon *et al.*, 2003; Boullier *et al.*, 2003). Ultimately, digital media, as any other media, condition and shape what it is possible to think (Drucker and Svensson, 2016).

At the beginning of the century in the United States, the awareness was first expressed, and in a particularly clear manner, that the conduct of innovative research programmes could henceforth only be carried out at the price of massive investments in complex and diversified sets of computing resources. A term then came to refer to this set of interconnected hardware resources (servers, networks, processors, storage memories), software (systems, languages, applications, protocols), and intellectual resources (skills, know-how, standards, conventions) that had to be developed as much as possible to serve the most advanced research and to keep the promise of what was then thought to be a future scientific revolution. This term is *infrastructure*. In 2003, in particular, it was given a prefix that would seem a little dated today[1], under the variant of "cyberinfrastructure," in a report produced by Daniel Atkins, then Professor of Electrical Engineering and Computer Science at the University of Michigan's School of Information, on behalf of the National Science Foundation. This report has had a significant impact on research policies in the United States and other developed countries (Atkins, 2003).

Since the Atkins report, infrastructures became a central concept for the understanding of contemporary knowledge production, both amongst researchers and actors. In Europe, it became during the last twenty years an important part of the European Union Research and Innovation agenda: in 2006, the EU governments decided to align their investment strategies at a continental level. They created the European Strategy Forum for Research Infrastructures, a soft policy body that became more and more important during its two decades of existence. At the same time, the European Commission started to frame its R&I investment framework around calls specifically dedicated to infrastructures that absorb a non-marginal part of the funding. This movement is today accelerated by the development of Open Science, as many actors in the field quickly understood that the movement would not be able to fulfil its

[1] But that is still widely used in the US. In Europe, the term "e-infrastructure" is more widely used.

promise without the support of platforms, data centres, networks that make possible, concretely, to disseminate research results without barriers.

In research as well, the term "knowledge infrastructure" emerged as a central concept at the crossroads of several field studies: history of science, sociology of science, STS, library and information science. *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming* published by Paul Edwards in 2010 at MIT Press opened a new field of research under this label, and provided a first definition to be discussed by scholars: "Knowledge infrastructures comprise robust networks of people, artefacts, and institutions that generate, share, and maintain specific knowledge about the human and natural worlds". An important literature has been published on the topic since then, starting of course before Edwards' book, back to the first studies that accompanied the development of networks of computers in the late eighties and nineties (Kling, 1987; Bowker, 1994; Star and Ruhleder, 1996) and thanks to the continuous effort of collective of researchers in different places, such as the Center for Knowledge Infrastructures founded by Christine Borgman at the beginning of the century. More recently, an impressive collection of publications explored through multiple angles how the digital "knowledge machines" (Meyer and Schroedder, 2015) radically transform how knowledge is not only consumed and manipulated, but also produced in different disciplines. In a landmark series of articles gathered across four subsequent issues published in 2016 in the STS journal, Karasti *et al.* could present no less than 14 case studies to explore the topic.

As one can see, researchers and practitioners are both engaged in an effort to better understand those complex objects that are the knowledge infrastructures. Interestingly, if both produce discourse and publications, they rarely collaborate and interact in this effort. This situation is probably not specific to knowledge infrastructures. However, it can be seen as a serious issue in the case of knowledge infrastructures precisely because of how much they influence and determine the conditions of knowledge production, assessment, and dissemination. Open Science is a typical case: while the movement expands rapidly in the scientific community, it places the infrastructure that supports it (e.g. platforms, data storage, publication infrastructures) in a central place to implement it. On one hand, as we said earlier, the practitioners produce an abundant discourse about Open Science and the need to sustain its infrastructure, on the other hand, very few researchers are actually studying open science infrastructure as such. There is therefore an obvious need to gather them together and create the conditions of fruitful exchanges on this topic.

It was the main objective of the workshop organised in June 2022 at EPFL in Lausanne, to convey both researchers and practitioners to discuss how to "sustain knowledge and its infrastructure: digital knowledge infrastructures at the crossroads of governance practices". The workshop was an opportunity to elicit a mixed conversation between researchers and practitioners intertwining concrete cases and theoretical and historical perspectives across the board, reflecting the type of conversation we, the two authors of this paper, a researcher and a practitioner, had during the year in the context of a seminar organised at the Laboratory for the History of Science and Technology (LHST) of EPFL (Swiss Federal Institute of Technology, Lausanne). Common topics were explored, such as the questions of sustainability, maintenance, governance, and legitimacy that helped us better understand the current challenges that knowledge infrastructures have to face, in particular in the open science context. The following texts should be read as an attempt to continue this initial conversation and expand it to provide to readers a better understanding of how contemporary knowledge is crafted and how its production is governed by a peculiar combination of technical constraints and idealistic values: knowledge infrastructures.

Introduction
Abstracting the infrastructure: a genealogy of its usage across sectors and research fields

Simon Dumas Primbault and Pierre Mounier

Although the term infrastructure has become part of everyday language, its application to the world of research is not at all obvious and its use may seem surprising. It is, however, situated at the crossroads of several competing intellectual traditions and multiple uses, the origins of which go back to a period well before the Atkins report. Attempting to untangle the intertwined threads of the term usage may allow us to better understand the current processes of knowledge production.

At first sight, there was no reason for the term to be used in this context. The word "infrastructure" was originally a French word, used in the engineering world in the early 19th century to refer to the lower layers of material that stabilise the road surface. Anthropologist Ashley Carse has traced the chronology of the uses of this term, the variety of which has been ever increasing in the decades following its first use (Carse, 2016). It is therefore only gradually that its meaning expanded, in several stages. First in the field of transport, which was disrupted by the industrial revolution: the term was then a conceptual tool for distinguishing elements spatially (what is underneath, what is on top), temporally (what has to be built before, what is provided after), but also in terms of responsibility (public investments, private operation in the railway framework for example). At this point, Carse insists, it is important to understand that infrastructure, unlike "network" or "system," which were also used at the same time, introduced a univocal hierarchy, since it designated what was a condition of possibility for other elements. This fundamental element remained so throughout the multiple lives that this term has had in many fields since then. Thus, for example, when it was used in the aftermath of the Second World War within NATO to designate, in a landmark political move (NATO, 2001), the set of physical installations (warehouses, airports, communication systems, headquarters, radar stations), the pooling of which was necessary for the conduct of military operations in the context of the Cold War.

This historical moment is interesting because it prefigures, in a way, the logic that began to be implemented within European research infrastructures during the following decade: as NATO does not produce an integrated military force but is a coalition of national armies that remain equally independent in theory, it is on the pooling of equipment that cooperation between allied nations first focuses, especially at a time in post-war Europe when these had to be rebuilt. Thus, the virtue of infrastructure is not only that it presents a hierarchical organisation of material priorities, but it also has political virtues in that it offers possibilities for collaboration on the technical level (interoperability, reciprocal access) that give it additional importance. In a number of circumstances, of which this is a first example, infrastructure is the technical means by which organisations, communities or countries can develop cooperation that makes political sense.

In other words, it is as if the functions of the infrastructure spill over those explicitly assigned to it. Technical infrastructure has, so to speak, a political performativity. Thus, Carse notes its most extensive use in economics in the 1960s, when the theory of modernisation was flourishing: massive investment in "infrastructure" was expected to enable underdeveloped countries to take off economically and to integrate into a liberal economic system that was becoming global. Here again, the term was not neutral and had an obvious political dimension. It was used not only to designate technical and material devices, but also and specifically to refer to the achievement of a political objective of social transformation through development and economic integration. Carse concludes his historical and linguistic study by highlighting the blurring of the term's ubiquitous use in a growing number of fields, even in a speech by Ronald Reagan in the early 1980s. But it is in the midst of this ball of yarns that we will be able to grasp one of them, which will be of particular interest to us.

In 1982, Rob Kling, a researcher in information systems and computer science at the University of Irvine in California, and Walt Scacchi, a researcher in software engineering at UCLA, published an article entitled "The Web of Computing: Computer Technology as Social Organization" in which they theorised the opposition between two ways of studying computer systems: on the one hand, approaches that separate technical elements from their context of use and social organisation (what they call "discrete-entity" models), and on the other, those that integrate these social elements into the analysis (so-called "web"[2] models). In support of their demonstrations, they mobilise, for the first time with regard to computer systems, the notion of infrastructure, which they directly and consciously import from the urban planning and economic sectors:

> We find the term infrastructure useful to describe certain critical resources, whether close at hand or more remote. Urban planners and economists treat the "infrastructure of a city" as a basic physical plant which helps support other valued activities. Typically, the physical infrastructure of a city includes its utilities and transportation system. Ilchman and Uphoff (1969, p. 35) have usefully expanded the term to include a wider variety of administrative, social, and political investments to make a service more efficient and more responsive. We apply their expanded conception to the case of computing developments. (Kling and Scacchi, 1982, pp. 76-77)

Rob Kling is recognised as one of the pioneers in the United States of computer studies from a sociological perspective in the 1970s (Wellman and Hiltz, 2004). As a direct observer of the transformations of computer systems with the development of personal computing, he was particularly interested in the conflicts between distributed and centralised computer systems.

In 1990, Rob Kling and Tom Jewett published an article that proposed a case study of the deployment of a computer system, but this time in the context of a social science research team. Entitled "The Dynamics of Computerization In a Social Science Research Team: A Case Study of Infrastructure, Strategies, and Skills", this text, which is presented as an internal technical report on a research project carried out by the authors, highlights the "hidden costs" of computerisation of research practices, particularly from the point of view of work organisation. What allows them to highlight these hidden costs is the notion of "computing infrastructure," which they define as follows:

> Infrastructure is a useful concept in analyses of computing support - it denotes all the resources and practices required to help people adequately carry out their work (Kling, 1987; Kling and Scacchi, 1982). Infrastructure for computing refers to a variety of organizational arrangements for supporting computing, including recharge systems and purchasing procedures, as well as the human resources [...]. As the computing environment becomes more complex, so must the infrastructure to support it. (p. 247)

[2] No relation here with the "World Wide Web" that did not exist yet.

At this point, it is to be noted that the term “infrastructure” does not refer to a particular object or construction, but is presented as an analytical concept. When used in the singular and not in the plural, rather than designating an object in itself, the term refers to a category including objects of different natures. Infrastructure is everything that makes it possible to work. It is a set of resources, means, conditions of possibility that interact, interconnect, work together. In other words, because of its use by information science researchers to describe the new kinds of objects they study, infrastructure is becoming an increasingly abstract concept whose relationship to material objects is increasingly remote.

In 1996, two researchers in science and technology studies (STS) and computer-supported cooperative work (CSCW), Susan Leigh Star and Karen Ruhleder, published an article that is now considered seminal in the field of infrastructure studies: “Steps Toward an Ecology of Infrastructure: Design and Access for Large Information Space” (Star and Ruhleder, 1996). In this article, the two authors set out to analyse an object of study that was of great interest to researchers at the time: virtual communities (Proulx *et al.*, 2007). In a manner quite typical of the time, they began their text with a quotation from John Perry Barlow questioning (falsely) the reality of virtual communities and their capacity to form a cyberspace that would eventually replace reality. More specifically, their case study was an interconnected computer system that allowed researchers in genetic biology to network in a distributed manner. Indeed, as they themselves mentioned in the introduction to their article, the world of computing had changed a lot since Kling’s 1987 article, and the appearance of the World Wide Web had theoretically accelerated the possibility for distant researchers to work together in “*collaboratories*”. Based from the outset on the perspectives opened up by Gregory Bateson and his “ecology of mind”, as we shall explore further on, they mobilised the notion of infrastructure introduced by Kling and then Jewett and Kling because it enabled them to highlight the primordial importance of the relationships between the entities put in contact. This radical shift in perspective, prepared by Kling and his concept of the “web,” is what another researcher in the same discipline, Geoffrey Bowker, theorised in 1994 under the title of “infrastructural inversion” in an important contribution to a collective work entitled: “Information Mythology and Infrastructure.” In this perspective, it is no longer the technical objects that are at the centre of the study, but what puts them in relation; and even the relation itself, which constitutes for Bowker and the researchers mentioned above, the infrastructure itself.

If infrastructure is not a discrete object but a set of relations, it is logical to speak of it in the singular, as the authors of the articles cited do. For example, Star and Ruhleder went so far as to define infrastructure as a context, which allowed them to position themselves under the dual umbrella of the ecology of mind and the actor-network theory:

> Information infrastructure is not a substrate which carries information on it, or in it, in a kind of mind-body dichotomy. The discontinuities are not between system and person, or technology and organization, but rather between contexts. Here we echo recent work in the sociology of technology and science which refuses a “great divide” between nature and artifice, human and nonhuman, technology and society (e.g., Latour). (Star and Ruhleder, 1996, p. 118)

This approach opened the way to a whole literature that has gradually abstracted the notion of infrastructure, going so far as to designate, for example, a moment in the analysis (when is infrastructure) or a process (infrastructuring). In the end, infrastructure is a matter of perspective, as Leigh Star notes in an article on the ethnography of infrastructure (Star, 1999). It is a methodological and even philosophical tool that Bowker *et al.* (2019), for example, can mobilise through the notion of "thinking infrastructure," which refers to the conditions of possibility of thought itself.

While this genealogy of infrastructure as a concept makes us aware of the properties of generic infrastructures, and helps us consider them from another perspective, it does not tell us yet about the specificities of *knowledge* infrastructures. That is what the following section will explore.

Knowledge infrastructures: what is at stake

Knowledge infrastructures are usually referred to as those facilities that make possible and implement not only the production of knowledge, as one might expect, but also all the other operations that deal with knowledge, such as, for example, the sharing, dissemination, exploitation, and preservation of knowledge. While the best-known and oldest knowledge infrastructures are schools and universities, but also archives and libraries, and then also *scriptoria*, printing presses, and publishing houses (Jacob 2007, 2011), the development of networked digital technologies has considerably diversified the types of infrastructures that can be encountered today. There are data repositories, platforms for hosting and disseminating scholarly publications, collaborative encyclopaedias, but also, and this is more difficult to grasp because it is more technical, discovery services, indexes and catalogues, registers of unique and perennial identifiers, systems for managing metadata, annotation, semantic enrichment, writing and editing, classification and categorisation software. Two researchers at the Utrecht University Library have attempted to list the "hundred and one" digital tools scholars can use to conduct their research (Bosman and Kramer, 2016). All of these tools, platforms and infrastructures that work together more or less efficiently form the infrastructure on which contemporary knowledge is built.

In 2016, four special issues of the journal *Science and Technology Studies* dedicated to the subject were edited by Karasti, Millerand, Hine and Bowker (Karasti *et al*., 2016) , bringing together more than 14 case studies of knowledge infrastructures from different fields and of different types. In spite of this diversity, the editors of the volume have attempted to identify a certain number of themes that are common to them and make them stand out within the broader field of infrastructure studies.

Typically, the question of *tensions* takes on a particular meaning within knowledge infrastructures in that it is activated by, on the one hand, the heterogeneity of the contexts of production and use of knowledge itself, and on the other hand, the inevitable obsolescence of this knowledge which is subject to continuous change. In other words, insofar as knowledge is itself contextual, in space, time, and the social configurations that determine its nature, validity or uses, the infrastructures that handle it are subject to particular tensions that they must very often resolve. This takes the form of issues linked specifically to questions of scale, for example when locally produced knowledge is disseminated and mobilised beyond its context of production. Boyce (2016) exemplifies it perfectly, studying the case of the outbreak surveillance system in the US, that connects clinical data and data coming from the food supply chain. For Boyce, the specific challenge of working with heterogeneous databases coming from many different sources and operated by actors from diverse backgrounds, is a good example of "frictions" that are usual in "second-order" infrastructures, aimed at repurposing data by pulling them together. Far from the common perception of data-mining as a simple plug-and-play operation, she shows how it creates a feedback loop with the data producers that implies a constant adjustment work and generates tensions into the network infrastructure itself.

Another particularity concerns the notion of *invisibility* often mentioned in infrastructure studies. Some case studies show that knowledge infrastructures do not become invisibilised as much as one might expect. And this particularity is related to the question, central here, of the accountability of the infrastructure, which is subject to a questioning of the way it produces or manipulates knowledge. Wikipedia is a typical example of it, as evidenced by Wyatt *et al.* (2016), with the "talk" pages and the numerous discussion spaces where the constant work that processes knowledge, collects, curates, translates it, is publicly exposed and constantly discussed. In that sense, Wikipedia is a knowledge infrastructure that makes itself visible for accountability reasons, and may not be the only knowledge infrastructure in that position. One assumption to explore would be that knowledge infrastructures are subjected to two contradictory pressures: to remain invisible and then undiscussed, as all other infrastructures on one hand; to make themselves visible and discussed on the other hand, because they are accountable for the knowledge they make available and trustable.

Another series of articles reveals the question of *power and values* as being particularly debated within knowledge infrastructures. The political performativity of knowledge is in a number of cases particularly debated as the infrastructure concretely implements a knowledge order that can be contested and challenged. The question of research work (or more broadly of knowledge production) and the way it is configured by the infrastructures on which it relies is also particularly important in this context. Fukushima (2016) discusses this question in the light of the base-superstructure marxist theory. Studying the "value oscillations" of japanese researchers involved in the building of biochemical compounds database, he shows that actors are subjected to a double-bind situation due to the oxymoronic nature of the infrastructure itself: low in terms of prestige and recognition and at the same time acknowledged as a determining factor of knowledge production.

Finally, and not surprisingly, knowledge infrastructures are at the centre of issues related to *openness*. This issue, far from being limited only to aspects of open access to publications and open science policies, is common to a large number of cases and situations. But if openness as a value is often proclaimed by knowledge infrastructures, its concrete implementation encounters many obstacles and proves to be relatively contingent. Shankar *et al.* (2016), for example, in a literature review article that focuses on social sciences data archives (SSDA) and the history of their development, highlight the necessity to "understand the complexities about data access that go beyond simplistic dualisms of completely open and unfortunately enclosed." Opening access to data from the point of view of the infrastructure entails complex negotiations between a variety of stakeholders, including funders and the patient crafting of a variety of business models in order to "pay the bill" and avoid the free-rider pitfall.

Three perspectives on knowledge infrastructure(s)

Historically focusing on scientific research equipment and facilities at the turn of the twentieth and twenty-first centuries, infrastructure studies have mainly—albeit not exclusively—dealt with *knowledge* infrastructure or *information* systems, and more specifically *digital* information systems. Thus, after its seminal uses both by Kling and Scacchi (1982), and by Star and Ruhleder (1996), the concept of infrastructure became for the nascent field of science and technology studies (STS)[3] a powerful means to think of science in-the-making as both social and technical, local and global, human and non-human,

[3] Although, infrastructure studies also draw on and federate communities from the history of science (LTS), ethnography and anthropology, computer and information sciences, library studies, or computer-supported collaborative work (CSCW).

natural and cultural, design and use. This made visible a number of apparent "tensions," resulting from the necessity to hold together both ends of these divides. These perceived tensions, initially understood as problems to be solved in order for the stability of the infrastructure to be ensured, were gradually construed as the driving forces of a dynamic process. Consequently, "infrastructure studies" became more inclusive of a wider variety of large distributed sociotechnical systems, to the point where it has recently been argued that the very concept of infrastructure may be losing some of its explanatory power (Williams, 2022)—it is also worth noting that, along the path, the term "infrastructure" has come to be used in the plural without its distinction with the singular being strongly problematised. Let us dwell on the three main perspectives offered by the evolution of infrastructure studies since the 1990s, focusing more specifically on the literature about information and knowledge infrastructures.

A sociotechnical perspective: from mere brick-and-mortar to fully-fledged sociotechnical systems[4]

Although the work of historian of technology Thomas P. Hughes on Large Technical Systems (LTS), and more specifically his comparative study of the birth and development of electrical networks at the turn of the twentieth century (Hughes 1983), is often quoted as seminal, Hughes' conceptual apparatus—such as reserve salient, or technological momentum—is very seldom mobilised in infrastructure studies—and, conversely, infrastructure is a concept that is not part of Hughes' vocabulary. Thus, Geoffrey C. Bowker (1994) called on Hughes' work mostly to shift the focus from mere "brick-and-mortar" technical objects to fully-fledged sociotechnical systems. Through the lens of LTS, infrastructure*s* in the plural, as circumscribable objects, became instances of large, distributed sociotechnical systems, allowing for collaborative work at a distance and over time, by both permitting and shaping the management of information. Beyond this, STS scholars have studied infrastructures from a fairly different perspective since their object substantially differs from traditional LTS in at least two ways.

Parallel to the following relational perspective defining them as a set of properties, scholars studied infrastructures through the more material prism of their components, thereby adopting a sociotechnical perspective on infrastructure*s* in the plural, construed as the assemblage of stakeholders and devices in distributed sites. As we have seen, this is apparent in Kling and Scacchi (1982), who defined infrastructure as "resources such as skilled staff and good operations procedures, as well as physical systems such as reliable "clean" electrical energy and low-noise communication lines" (p. 19)—yet insisting on modelling them as "webs" (see above).

This perspective is even more salient in the work of another group of "socially-oriented computer scientists" (Williams, 2022): for Hanseth, Monteiro, and Hatling (1996), information protocols such as Open Systems Interconnection (OSI—designed by the International Organization for Standardization, it was eventually replaced by TCP/IP) or the Internet are first and foremost a layered and composite architecture of standards and protocols in context. Dissecting these sociotechnical systems, they show how the apparent irresolvable tension between standardisation and flexibility is actually a driving force of the modularization of such systems: indeed, a system of "highly complex interrelationships" (p. 411) may grow into a synthetic unity—sometimes even a black box—thanks to the nesting of modules whose interdependencies are standardised.

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[4] Here, we use the adjective "sociotechnical" keeping its ambiguity—an ambiguity that crosses the whole field of STS—that is either denoting something that is social and technical (*i.e.* the result of social relations added on top of brick-and-mortar), or, to avoid this divide, denoting one single object (or one single relation) that is through and through both technical and social (*i.e.* acknowledging that the social can be embedded in the technical).

Not alien to the relational perspective—albeit insisting on defining infrastructure by its components—, the sociotechnical perspective foregrounds the assemblage[5] of actors, both human or institutional (stakeholders) and non-human or artefactual (layered composite) in *loci*. This approach led to the now canonical definition of "knowledge infrastructures" ventured by Paul N. Edwards in his book *A Vast Machine*: "Knowledge infrastructures comprise robust networks of people, artifacts, and institutions that generate, share, and maintain specific knowledge about the human and natural worlds." (Edwards, 2010, p. 17). The study from which this definition is derived focuses on the set of actors, instruments, and measurement systems that have enabled the emergence of a global awareness of climate change through the production of indicators that reveal and establish recognised scientific facts on this issue. For Edwards, the infrastructure thus defined is a condition of possibility for this political awareness, which requires the production of specific, established, and continuous knowledge.

A relational perspective: from resolving to balancing to leveraging tensions

The other seminal perspective on infrastructure deriving from the ethnographic approach of Star and Ruhleder (1996) is a *relational* one. As we have seen, drawing on Bowker's (1994) methodology of "infrastructural inversion"—an analytical gaze he developed reading Hughes on LTSs—, Star and Ruhleder (1996) claim infrastructure is relative to how it is used, therefore to a set of relations between actors, practices, soft- and hardware, standards, institutions… Infrastructure consequently "emerges for people in practice" (p. 112)—yet, the horizon, or asymptotic ideal of infrastructure is to "resolve" tensions and consequently fade into the background (p. 114).

Through this relational perspective, Star and Ruhleder "ask *when*–not *what*–is an infrastructure" (p. 113) and define a series of analytic properties (quite tellingly called "dimensions") that, *when* fulfilled, attest to an infrastructure. Thus, they define the following eight dimensions, and Star (1999) added a ninth one: i) infrastructure is *embedded* in other sociotechnical systems, ii) infrastructure is *transparent* to its users, iii) the *reach or scope* of an infrastructure is wide and multiple, iv) infrastructure have communities and are therefore *learned as part of membership*, v) infrastructure has *links with conventions of practice*, vi) it *embodies standards* to be interoperable, vii) it is *built on an installed base*, *i.e.*, pre-existing infrastructure, viii) it fades in the background (transparency) and *becomes visible only upon breakdown*, ix) it is *fixed in modular increments* rather than in bulk.

More recently, this relational perspective has been continued within CSCW, notably by Karasti and Blomberg (2018) who defined five other dimensions for information infrastructure*s* in the plural:

> (1) the profoundly *relational* quality of infrastructures, (2) the intrinsic (at least partial) *invisibility* of infrastructures, (3) the *connectedness* of infrastructures, sometimes described as "scaling," (4) the *emerging and accreting* quality of infrastructures, and (5) the role of *intentionality and intervention* in delineating infrastructures. (p. 236sq)

Interestingly for us, as we will see, they also insist on the "emerging and accreting qualities" of infrastructures that may develop properties initially outside the scope of the analytical relational view. Therefore, Karasti *et al.* (2016) as well as Karasti and Blomberg (2018) call to develop new methods to address these "qualities".

[5] Note that with Hanseth *et al.* (2021), assemblage theory is implicitly presented as one way to think about the emergence of holistic properties.

Within the relational perspective, tensions—between stability and change, standardisation and flexibility, local and global, distribution and centralisation…—are ever present, and the way they are conceptualised is also symptomatic of another shift in the field. Star and Ruhleder emphasise the "dual, paradoxical nature" of infrastructure, that "arises from the tension between local, customised, intimate and flexible use on the one hand, and the need for standards and continuity on the other" (p. 111). For them, tensions generate paradoxes—notably between evolution and resistance to change—and have to be resolved for an infrastructure to happen: "An infrastructure occurs when the tension between local and global is resolved." (1996, p. 114) This results, as we will see, in a Batesonian ecology of communication that aims at making information infrastructures solely by addressing supposed issues.

Acknowledging the intrinsically heterogeneous nature of information and knowledge infrastructures, subsequent works have deemed tensions inescapable and rather endeavoured to "balance" them. In a telling schematic summarising their study of the information infrastructure of a research project in ecology, Baker and Karasti have sought to theorise information management broadly as the "articulation work" aiming at "strik[ing] a balance" or "mediating the tensions" between science, technology, and data (2004, p. 13). Another noticeable study is Ribes and Finholt's 2009 ethnography of "four cases of scientific e-infrastructure development" (p. 380), which identifies tensions as unavoidably resulting from the intrinsic heterogeneity of actors, soft- and hardware, and places. "Tensions," they show, is an actors' category, formulated as such by infrastructure makers and maintainers who aim at balancing them, not resolving them, amounting the work of infrastructuring to "assembling heterogeneities" (Ribes and Finholt, 2009, p. 391). Eventually, echoing Edwards *et al.* for whom tensions "should be leveraged for their contributions to long-term properties of infrastructural fit, equity, and sustainability" (2007, p. 28), Hanseth *et al.*'s 2021 review of the literature where tensions play a role in the evolution of infrastructures see them as driving forces:

> We concur with Farjoun (2010) and view the tensions between stability and change as the fundamental tension from which tensions between loose/tight couplings, distributed and centralized control, and standardization and flexibility can be derived. We also concur with him in terms of characterizing the relationship between stability and change as a duality and not a dualism, meaning that we do not see stability and change as opposite ends on a continuum in need of a proper balance, but as "fundamentally interdependent—contradictory but also mutually enabling" (Farjoun, 2010, p. 202). (Hanseth *et al.*, 2021, p. 132)[6]

An ecological perspective: knowledge infrastructures as complex processes

Stemming from the intrinsic fragility of infrastructures and the essential tensions that hold things together, a third perspective helps understanding the very dynamic nature of knowledge infrastructures. From rather static to more dynamic, the general view within STS has indeed shifted from infrastructure as a ready-to-hand, transparent (or invisible) framework, only showing upon breakdown, to infrastructure*s* as processes—thus better described with the use of a verb "how to infrastructure" (Star and Bowker, 2002) or a gerund infrastructur*ing* (Baker and Karasti, 2004; Pipek and Wulf, 2009 on the iterative co-design)—and specifically for digital information systems.

For example, another major trend in the development of the field is the gradual acknowledgement of the historicity of infrastructure(s). Looking backward, both as an object (installed based), as a concept

[6] Note in passing that, for them, tensions are ultimately determined by the system's architecture-governance.

(the history of LTS), and as a feature of modernity[7] (Edwards, 2002), as well as looking forward as a matter of long-term sustainability in the "Long Now" (Ribes and Finholt, 2009)—some even likening their design to a kind of futurology (Slota and Bowker, 2019)—, scholars have nurtured an ever more diachronic understanding of such sociotechnical systems, thus making a dent in the view inherited from LTS of infrastructures as predominantly inert(ial) objects. This renewed dynamic understanding of infrastructures thrives on descriptions of complex/multi-scale/non-linear/heterochronic (Bowker *et al.*, 2010) processes that only temporarily stabilise, and have moved from mechanical strategic plans of an engineering culture to the consequences of embracing ambiguity and uncertainty, path-dependency, tensions, frictions, controversies.[8]

These properties hint at a third perspective in infrastructure studies, that is explicitly mentioned in almost all the literature, although never explicitly defined or put to work—with the exception, as we will see, of Star (1995) and Mongili and Pellegrino (2014)—: an ecological perspective. From the inception of their use by Susan Leigh Star in the late 1980s and in the 1990s, the sources of ecological concept have been threefold. In sociology, Star (1995) borrowed from Everett C. Hughes—an adherent of symbolic interactionism from the Chicago school of sociology—the idea of a "human ecology" in the evolutionary sense of a struggle for survival and adaptation to an unbounded environment, both social and natural, and made use of it to describe *Ecologies of Knowledge*—that is a sociology of science attentive to inter-relations and dependencies. In anthropology, Star and Ruhleder (1996) borrowed from Gregory Bateson an interest in relationships through communication processes (see below). Finally, beyond Bateson and the Chicago school of sociology, Star and subsequent ethnographers might also have been influenced by the very object of their study: the science of ecology itself—notably through the study of the LTER infrastructure, and it is not a coincidence either that Star and Griesemer (1986) dealt with the arrival of ecological science at the Museum of Vertebrate Zoology in Berkeley.[9] Sometimes using ecological words with no caveat (so much so that the reader can wonder whether ecology denotes the object or the approach), or sometimes explicitly acknowledged in its polysemy (Baker and Karasti, 2004), such concepts have been borrowed to explain how information and knowledge infrastructure*s* may display properties that escape the scope of the previous perspectives. Let us now trace, through the literature produced by infrastructure studies, the use of ecological concepts.

As early as 1986, Star and Griesemer mobilised Everett C. Hughes' sociology about "institutional ecology" in order to acknowledge and account for the multiplicity and heterogeneity of actors' viewpoints and interests at the Berkeley Museum of Vertebrate Zoology—yet they talked about "economies of information" still. In her 1995 *Ecologies of Knowledge*, Star meant to define a more synthetic approach: "ecological to mean treating a situation in its entirety looking for relationships, and eschewing either reductionist analyses or those that draw false boundaries between organism and environment" (p. 14). Her aim was to not be analytical along the dotted lines of the Great modern divide and thereby framed her ecological approach as a way to "refuse social/natural or social/technical dichotomies and invent systematic and dialectical units of analysis" (p. 2).[10] Although they do not denote the same object, the heuristic power of an ecological prism in shifting perspective is fairly close to that of infrastructure.

[7] Even comparing our current situation in the digital era with the 15th-16th-century "scientific revolution", and its links to the development of the movable type printing press (Edwards *et al.*, 2013, p. 19).
[8] Other keywords are open-ended, experimental, unpredictable, opportunistic, recursive…
[9] Another example is Granjou and Walker (2016) who studied ecotrons, *i.e.* scientific infrastructures that aim at creating and sustaining living ecosystems. Interestingly, this could be seen, as we will see, as a generic case of an infrastructure that aims at producing its own milieu and integrating a general ecosystem.
[10] Just as Latour's 1984 *irréductions*, she claims p. 10.

Thus, in 1996, Star and Ruhleder ventured their famous ecology of infrastructure. Although they specifically defined it in Batesonian terms, refusing a "biological approach" (p. 117), their article—concluding on the open question "when is an ecology of infrastructure?" (p.132)—describes the process of infrastructuring as the emergence of something organic:[11]

> These observations suggest streams of research that continue to explore how infrastructures evolve over time, and how "formal," planned structure melds with or gives way to "informal," locally emergent structure.
> The competing requirements of openness and malleability, coupled with structure and navigability, create a fascinating design challenge – even a new science. The emergence of an infrastructure – the "when" of complete transparency – is thus an "organic" one, evolving in response to the community evolution and adoption of infrastructures as natural, involving new forms and conventions that we cannot yet imagine. (p. 132)

Thereafter, ecological and biological concepts and metaphors have flourished in the thriving field of infrastructure studies. To cite only one,[12] Edwards *et al.* in their 2007 report linked the "base-level tensions" of infrastructures (time, between short- and long-term; scale, between local and global; and agency, between planned and emergent) (p. i) with the need to develop a more "organic lexicon" (p. 7).[13]

Consequently, in 2014, Mongili and Pellegrino endeavoured to elucidate and gather the properties of ecological thinking when applied to "information infrastructure(s)". For them, ecology is an "epistemological landscape" (p. xxxv) and, drawing on Star (1995), they defined this "ecological space" along "four categorical axes: "continuity *versus* discontinuity; pluralism *versus* elitism; work practice *versus* reified theory; relativity *versus* absolutism" (Star 1995, 14)." (p. 14) In the same movement, they returned to Star and Griesemer's boundary objects (1989) and linked them with the ecological dynamic of infrastructures: boundary objects are what circulate within them and hold them together in spite of the heterogeneity of actors, practices, places, and devices.

Parallel to the emergence of similar vocabulary in the design and use of knowledge infrastructures—emerging and enacting, resilience, life cycles, bibliodiversity, predatory behaviours…[14]—, this literature argues for the fact that genuinely ecological concepts—in the sense that we may borrow and adapt them to our object—can be a very relevant lens on these infrastructures. Although building on the postulate of complex interdependencies, this ecological perspective is not the

[11] It is also worth noting that they mobilise the etymology of ecology—the study of the house—, as they claim that infrastructure may become "an unambiguous home—for somebody" (p. 114).

[12] Baker, Bowker, and Karasti (2002) use the terms "data ecologies" and "ecosystem" to emphasise the heterogeneity of infrastructures. Edwards (2002) dubs infrastructure the "connective tissues and the circulatory systems of modernity" (p. 185). Star and Bowker (2002) wrote that "Infrastructures subtend complex ecologies: their design process should always be tentative, flexible and open." (p. 242). For Hepso *et al.* (2009), their "analysis pursues the metaphor of an "ecology" borrowed from biology, as it evokes strong connotations of diversity, heterogeneity, variation, niches, and redundancy" (p. 431). Edwards *et al.* (2013) characterise knowledge infrastructures as "ecologies" in order, somehow, to avoid having to define more precisely what they are (pp. 3–5). Finally, Slota and Bowker (2019) make use of the botanical metaphor of "subtension" to characterise infrastructure as what organically supports information.

[13] This said, they do not expand on said new lexicon and, subsequently, take tensions as synonymous for unbalance, while something unbalanced resolves itself past the equilibrium point. Rather, we understand tension as what holds together an infrastructure and its milieu, within the broader ecosystem.

[14] Aspria *et al.* (2016) have specifically studied the performative role of metaphors in the development of an infrastructure.

relational one since it aims at understanding emerging phenomena, holistic properties, qualities that escape the scope of the previous two perspectives. It is an attempt to adopt a more synthetic[15] perspective on the organic properties that infrastructures may display, in order to disentangle their complexity through another lens and understand a series of emergent behaviours that lie in the blind spots of too mechanical approaches.

Infrastructure as a boundary object for practitioners…and researchers

After this long review, it could be argued that "infrastructure" is merely a word, bearing no specific meaning, and that it could easily be replaced by either "network" or "system" depending on the context. Although Carse (2016) insists on the hierarchical properties of infrastructures understood as conditions of possibility (see above), we have seen that, depending on the perspective, an infrastructure may look like a network, a system, a facility, or a device. Still, infrastructure scholars use the term because they acknowledge that there is no privileged perspective—one single perspective always has blind spots—and that their object of study is inadequately described by other means. In other words, they see a family resemblance between infrastructures that justifies calling them by the same name.

Therefore, we should not take the differing views on infrastructures, deriving from the poles of these three perspectives, as necessarily competing or contradictory—nor should we reify the three poles. Rather, they account for three, mutually non exclusive, understandings of infrastructures: there is no favoured perspective, nor are they incompatible with each other; all three dimensions are represented in diverse proportions in the many studies of this bounteous field (see fig. 1).

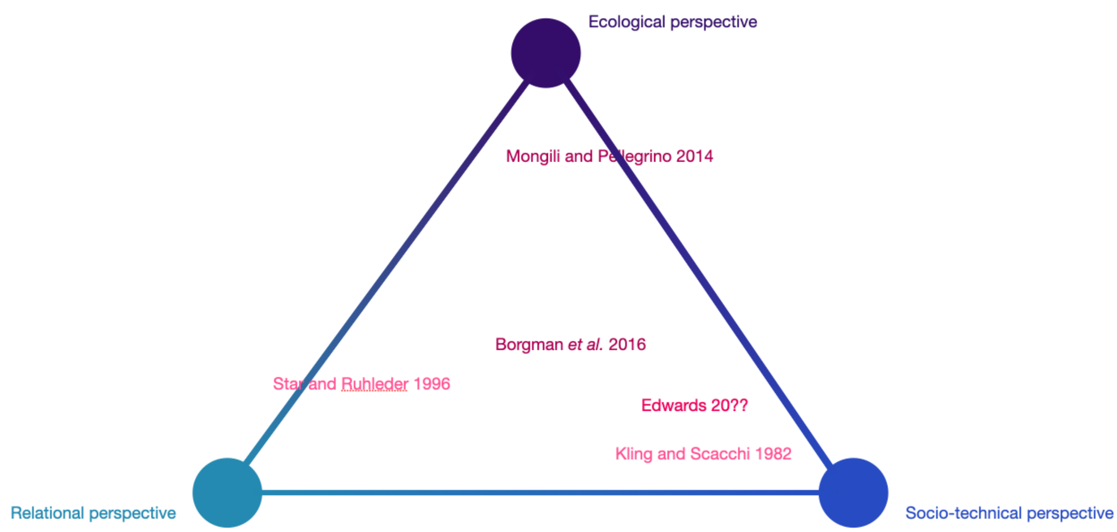

Figure 1. [Schematic in-the-making, to be completed and refined.]

[15] Rather, taking for granted that thinking conceptually is intrinsically an analytic operation, an attempt at thinking along other, complementary, lines of divides.

Furthermore, infrastructure carries another heuristic ambivalence as it is both an actors' category and an analytical concept—see above the example of NATO, or, in the history of open science, how infrastructures are both objects and words, both socio-technical complexes and policies. For that matter, it is quite telling that the term was developed both in the field and in the social sciences, by "computer-inclined" scholars or through ethnographic studies. This ambivalence between infrastructure-as-a-concept (*i.e.* stemming from policies and research in and around STS) and infrastructure-as-a-phenomenon (*i.e.* as it is mobilised by actors) is a two-way street and it is the shuttling back-and-forth between infrastructural practice and social sciences that endows the term with its performative powers. Indeed, the term "infrastructure" itself acts as a boundary object that holds together an infrastructure since it allows a wide heterogeneity of stakeholders to coordinate their collective action, acknowledging that they are talking about the same thing in spite of having different—either complementary or diverging—definitions of it.

Understanding knowledge infrastructures by their governance

Pierre Mounier

Infrastructures are very diverse. They relate to energy, water, transport, communication, goods and waste, information, and knowledge. They are everywhere and deeply embedded in the different sectors of activity they serve. However, despite this variety, there is one characteristic common to all these infrastructures, which has been well underlined by most of the researchers and observers mentioned above: infrastructures are in the paradoxical situation of appearing most of the time as massive, solid, installed devices, and yet of being very fragile. Whether by their physical appearance in the case of material infrastructures, or by their extension in the case of virtual infrastructures, but always by their ambition to last over time and to support massive activities, by the budgets they require, by the number of actors they involve, infrastructures tend to give us the sense of our own fragility, by being deployed in a space and time that most often far exceeds the finiteness of individual existence.

However, a slightly attentive observer quickly realises the essential fragility of these behemoths. They are like the Farnese Atlas, the literal infrastructure of the vault of heaven, a powerful figure with impressive musculature, but bending his neck under the burden, one knee on the ground and giving the impression of being on the verge of collapse. This ambiguous figure of Atlas, whom Hesiod describes supporting the sky with "ἑστηὼς κεφαλῇ τε καὶ ἀκαμάτῃσι χέρεσσιν", that is with his erect head and tireless hands, can tell us a lot about the resistance of infrastructure, which relies both on the solidity of static elements, and on a ceaseless activity of maintenance that holds back the fall. In other words, like Atlas, the infrastructure is not a simple pillar, it is a living organism that *makes itself* as a pillar, and must constantly mobilise new resources to continue its work, the permanence of which is by no means guaranteed, even if the persistence of the sky above our heads gives us a deceptive appearance of its permanence.

The research carried out by sociologists Jérôme Denis and David Pontille on maintenance teams within various infrastructures highlights the need to "take care of things" (Denis and Pontille, 2022). The fragility of infrastructures is that they are constantly deteriorating due to their use, wear and tear or other multiple factors. In other words, it does not always take a voluntary act to destroy the infrastructure. It is also "enough" to stop taking care of it: power outages can be caused by bombing, as well as by a power plant fleet left neglected for several decades. This particular feature of infrastructures that do not stand on their own, unlike appearances, but are subject to constant work to enable them to continue to hold things together is both congruent with the scholarly analyses detailed above that highlight a relational property intrinsic to the notion of infrastructure, and allows us to understand its essential fragility.

But if all infrastructures share the fact that they are fragile, due to their relational property, it is also certain that the fragilities they display have specificities according to the type of objects they deal with. It can be assumed that the points of fragility of a road, rail, water, gas or electricity distribution network, or of a hertzian, wire or satellite telecommunications system are not exactly the same. There are specific characteristics that distinguish the needs of these infrastructures. Then, what about knowledge infrastructures? The specific properties that knowledge infrastructures display when they are observed empirically derive from the very nature of knowledge itself, that embeds certain types of values (they carry with them a certain representation of reality), support certain relations of power (having access to knowledge or being able to define what is knowledge and what is not brings power and domination) and carry with it certain properties linked to its definition as a non-rival common good (such as being an eminent social object whose value augments with it being shared). It is therefore not surprising to find that the infrastructures supporting knowledge production, dissemination, and preservation have to deal in a peculiar way with these issues. It is not to simply say that values and power are embedded in the technical framework of knowledge infrastructure, because this is the case of every infrastructure of course. What is to be explored is rather the specific values and politics implied by the way they handle knowledge, as surfaced in different discussions and debates around knowledge production. An interesting part of this exploration is the paradoxical contradiction with the relative invisibility and steadiness of what is expected from an infrastructure in general, *i.e.* to embed and reify systems of values to make them effective and removed from debate. The recent "Open Science" movement is a typical example of this paradox.

Open Science and its infrastructure: a debate

The "open access" movement that developed from the end of the 90's mixes quite indistinctly a socio-technical rationality, with economic constraints and a very vocal debate on values and politics (Mounier, 2010): the development of open access to scientific publications and subsequently of open science that extends the same principles to data and processes (OECD, 2015) can be analysed indeed under three complementary perspectives:

- As a direct consequence of a technical innovation - the Internet - and its uptake by certain scientific communities (starting with high energy physicists) to perform better and more easily their traditional scholarly communication practices, leading to the creation of disciplinary "open archives" and "open repositories"
- As an adaptation of the scientific publishing sector to the new economic conditions set by the digitisation of publications that transforms radically the balance between structural and marginal costs in production, leading to new businesses models, based on a fee to publish (APC) rather than on a fee to read (subscriptions)
- As a political movement led by values such as the right for everyone to access knowledge as a common good that should be shared globally without restriction.

An interesting aspect to consider, is the surfacing of infrastructure as a key topic in the open access and open science narrative from 2010. In 2015, two simultaneous publications bring the infrastructure in the debate and shed light on their critical role from different perspectives: the Knowledge Exchange report, "Putting down Roots: Securing the Future of Open-Access Policies" (Johnson et Fosci., 2016) on one hand demonstrates that the different open access policies that were in development at that time in different northern European countries were relying on a variety of "open access services" such as the Directory of Open Access Journals and Sherpa-Romeo that none of the policy makers ever considered to sustain financially. The report then brought on the table the difficult question of sustainability of the "underpinning services" that enable the implementation of the policies and the underlying "OA infrastructure" that interconnects these services. The Knowledge Exchange report is one of the publications that changed the nature of the conversation around Open Access in Europe and led to the creation of a collective funding program : SCOSS, whose aim is to "help secure the vital infrastructure on which Open Science depends". A few months earlier, a group of scholars had published a discussion paper that highlighted the crucial role of infrastructure in open scholarship, but from quite a different perspective : the "principles for open scholarly infrastructures" (Bilder et al., 2015) aimed at starting a discussion in the scholarly community from this assertion: "Everything we have gained by opening content and data will be under threat if we allow the enclosure of scholarly infrastructures. We propose a set of principles by which Open Infrastructures to support the research community could be run and sustained". The paper echoed a growing concern in the community about the consolidation of scholarly communication services in the hand of a few international companies who were enlarging rapidly their scope from the narrow sector of scientific publishing (managing the publication of journals) towards much broader and more profitable developments around the interconnection, mining and reuse of all sorts of data related to the scientific activity, including publications. The "vertical integration in academic publishing" (Chen et al., 2019) led a part of the scholarly community to consider from a different perspective the hitherto invisible set of services they were using more and more intensively and how they were working together. The topic of the governance of the infrastructure that underpins scholarly practices and knowledge production surfaced quite dramatically in the open science discussion, opening the way for a whole set of new research questioning this infrastructure under moral and political values, such as inclusiveness, intersectionality, equity (Okune *et al.*, 2019). Finally, the way the infrastructure appears in the debate around open science illustrates well the specific tensions that run through knowledge infrastructures bringing sets of values and policies to be silently implemented and vocally debated at the same time.

A research programme entitled "Governing Digital Knowledge Infrastructures" was conducted on this topic from September 2021 to June 2022 at the Laboratory for the History of Science and Technology (LHST) of the Swiss Federal Institute of Technology in Lausanne (EPFL). Organised around a monthly seminar, this programme allowed us to explore these issues from several angles: questions of legitimacy posed by pirate infrastructures (Nicholas et al., 2019), the instrumentalisation of research infrastructures in the context of the European political construction (Cramer et Hallonsten, 2020), questions of values in terms of equity, inclusion and diversity that arise in scholarly publishing infrastructures (Chan, 2021), the very relevance of the notion of infrastructure in the humanities (Svenson, 2020), the question of enclosures on the information commons (Rosnay, 2021), algorithmic governance by the infrastructure (Musiani et al., 2016), and, finally, the repositioning of the question of governance in the long history of the University conceived as an infrastructure of knowledge (Montgomery et al.,) 2021. The year ended with a workshop during which other cases were discussed, bringing together infrastructure actors with infrastructure scholars in the attempt to define a common vocabulary and tackle shared issues.[16] One aspect that was striking when studying those different cases, was how the technical or instrumental organisation of the infrastructures was constantly debated in terms of ethical and political values from different perspectives: questions of inclusivity and equity, of course, but also questions of validity across various scales and legitimacy of decisions are discussed at all levels, including the most technical ones. In this perspective, the concept that would capture the best this constant process of interactions and tensions between different players that takes place at the same time at instrumental and value levels is probably the concept of *governance*.

[16] The abstracts of the monthly seminar and the ensuing closing workshop, as well as some videos and the interventions and a collaborative Miro board are available on Zenodo.
Monthly seminar, doi: 10.5281/zenodo.10036337.
Closing workshop, doi: 10.5281/zenodo.10036368.

Governance as a key concept to understand knowledge infrastructures

The emergence of the concept of governance in the academic literature in the 1980s and especially the 1990s is often interpreted as a symptom of the replacement of the notion of government in the context of the implementation of neo-liberal policies aimed at weakening the state and the concentration of power it represents. It has been shown that in reality the notion has emerged simultaneously within several fields of study (Torfing and Hansel, 2016, p. 13) to account for the diversity of actors and modes of collective action in multiple and varied contexts. If the notion of governance indeed supports studies that are less focused on the state defined as the sole or preeminent source of power, it is also to better account for the role of private and societal actors in the co-production of norms, regulations, and policies at different levels (p. 2). This does not mean that the state is systematically excluded (p. 552); rather, it is now considered as one actor among others in "interactive processes through which society and the economy are steered towards collectively negotiated objectives" (p. 4). The shift in focus that the notion of governance allows calls into question the clear dividing line between politics, which would be the exclusive domain of government, and management, which would merely manage resources to the best of a state of the art established on the basis of technical criteria alone. To take an interest in governance is to explore how the political and the technical are intertwined in the daily life of particular decisions by the force of their repetition, by the debates they provoke between heterogeneous actors, and by the norms they produce. Governance is definitely not a hard concept, in particular when it is used by the actors themselves. But precisely because of it softness and lack of precision as a concept, it reflects an open perspective in politics that implies that power is not located in a single place but ubiquitous, and that it results from the interactive negotiations between non predetermined actors, taking place through technical process and confrontation of discourses at the same time. Which describes perfectly, in our opinion, the type of issues that lay at the heart of knowledge infrastructures.

There are two topics related or close to knowledge infrastructures where the concept of governance already plays a major role: the theory of the commons and the history of the Internet. In the first case, the work of Elinor Ostrom (1990) on the governance of natural commons (such as forest resources, fisheries, and water) has recently been extended to the question of the governance of knowledge as a commons (Ostrom and Hess, 2007). In the second case, the development of the Internet has been quickly considered by political scientists and historians as a fascinating case of governance deployment where private and public actors, telecommunication companies, central states, media groups, but also researchers, engineers, entrepreneurs, and amateurs have engaged in interactive processes of co-production of norms, collectively contributing to what they call themselves: Internet governance (Musiani and Schafer, 2021). Obviously, the two topics are not unrelated. As Ostrom and Hess remind us, the term commons has taken on a directly political meaning in recent decades, when it was mobilised in the context of discussions about freedom of expression and information in digital communication networks. As they themselves point out in their opening remarks:

> First, open access to information is a horse of a much different color than open access to land or water [...] The knowledge commons is not synonymous with open access, although the content and the community network of the open-access movement, as Suber and Ghosh discuss in their chapters, are types of commons. Forgive us for repeating that a commons is a shared resource that is vulnerable to social dilemmas. Outcomes of the interactions of people and resources can be

> positive or negative or somewhere in between. Frequently, within the intellectual arena, the concept of the commons is a battle cry for free speech, universal open access. (p. 13)

But if informational commons are appropriated within value-oriented discourses, it is precisely because they are themselves carriers of values of which the actors who seize them are particularly aware. In other words, what distinguishes an informational commons from a natural commons is not only its non-rival nature. It is also the particular role it plays in a certain value system.

If the concept of governance thus makes it possible to uncover the technical at the heart of politics (everything that concerns the "interactive processes" in political decision-making), it also makes it possible to take an interest in the political at the heart of the technical. It allows us to take an interest in procedures and values, actors and discourses, tensions and inter-relationships of the infrastructures that take care of knowledge: the decision-making mechanisms within the platforms, the discourses that accompany their use and justify their choices, the design of interfaces and services, the devices that organise their activity and ensure their continuity over time. Above all, it allows us to attempt to model the way in which these infrastructures deal with the tensions that their relational nature necessarily generates.

Governing knowledge infrastructures: a proposed model

This leads us to propose a model that would make it possible to account for the ways in which various governance practices bring together and create tension between heterogeneous elements that constitute knowledge itself.

First, as emphasised by the "brick-and-mortar" approach, an infrastructure is made up of *sociotechnical components*—skills, conventions, software, and materials—that are either layered (Atkins, 2003), entangled, or woven together. Building on an installed base, a digital knowledge infrastructure either grounds itself in previous LTSs—the electric network, the World Wide Web—, structures itself around inherited conventions—classifications, protocols, standards—, or assemble existing technical solutions to serve its own needs—e.g. technical architectures, software libraries, thesauri. But an infrastructure may also define its own conventions depending on the nature of the supported knowledge, or invent *ad hoc* instruments and devices, thereby necessitating the development of related skills.

Second, the stakeholders themselves: digital knowledge infrastructures bring together and interact with relatively *heterogeneous networks of actors*. While the most traditional representations of research infrastructures focus on the figure of the researcher as a user, these representations only mask the essential role played by other actors: the administrative and technical staff who ensure the functioning of the infrastructure as a tool, but also other political and administrative actors such as policy-makers and funding agencies, and, very often, because these infrastructures are subject to the imperatives of openness, a diverse and often ill-defined "public." All these actors often have different or even divergent value systems (technical, rational-bureaucratic, scientific) and habits. They may come into conflict or come to terms with each other, find compromises or fall into open conflicts which may lead to the loss of the infrastructure in one way or another if what each of them is claiming is not met: loss of technical competence, cessation of funding, disappearance of uses.

Finally, the patient work of elaborating compromises is organised within *trading zones* (Galison, 1997) where the different actors will meet and collaborate in the best of cases: these trading zones are not only governance bodies as one might expect. They are also work spaces, interfaces, but also visuals, vocabularies, forms, supporting texts, and procedures that implement or concretely account for collaborative work between actors within the infrastructures. Trading zones are common spaces that the infrastructure creates or takes over to ensure the coordination of actors.

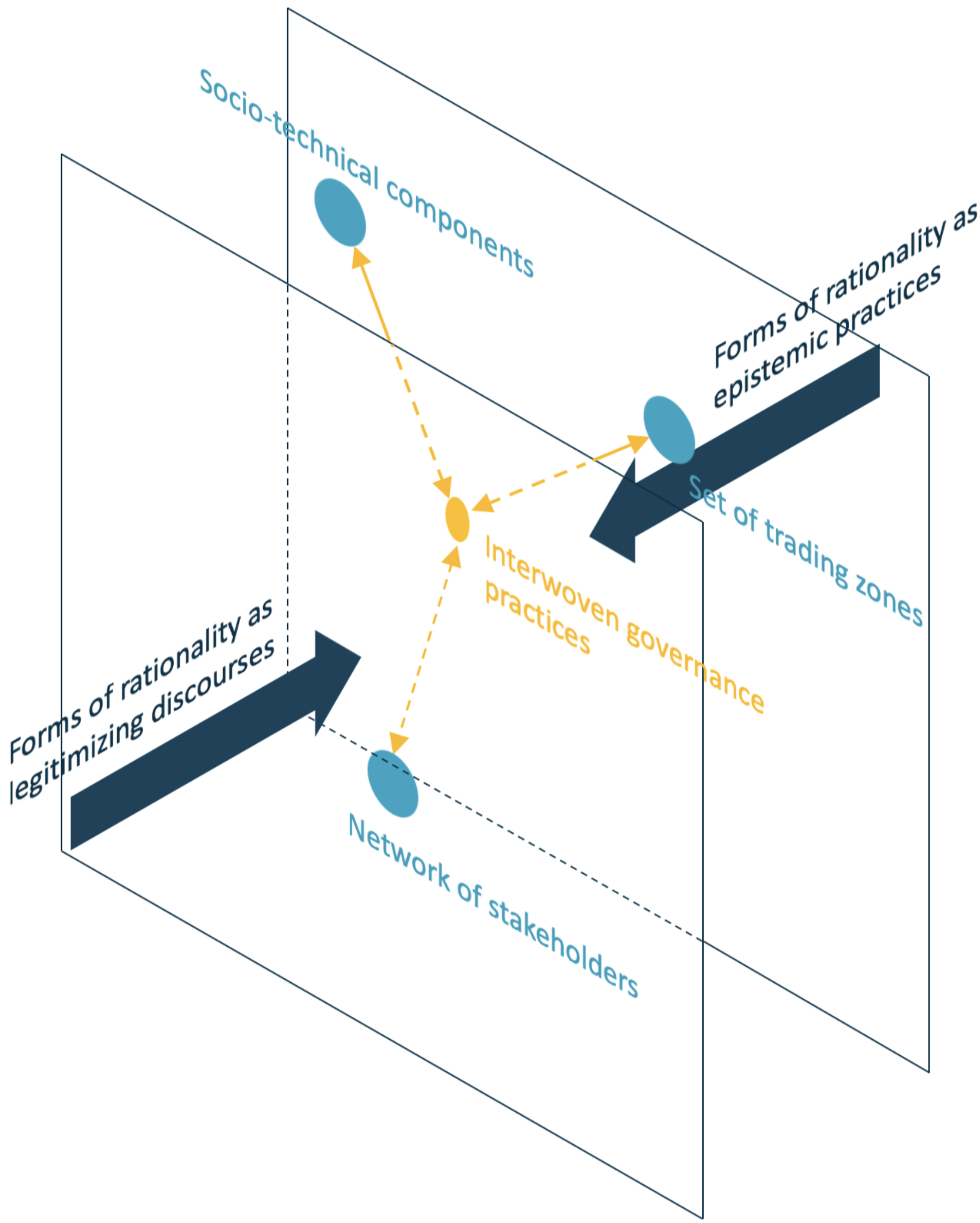

Figure 2. A model for the articulation of the sociotechnical and the relational perspectives through the prism of governance

The interplay between socio-technical components, diverse stakeholders, and the trading zone within infrastructure occurs within the confines of two external dynamics that significantly impact the power balance within this environment. On one hand, as previously mentioned, the multifaceted and ever-evolving epistemic practices that shape knowledge and its application hold sway over decision-making within the infrastructure. It's important to note that these infrastructures typically serve not just one homogenous epistemic community, but are shared across several communities, as exemplified by libraries and dissemination platforms. Consequently, decisions must be made to accommodate the specific requirements of these diverse groups.

On the other hand, discourses of legitimation, which define the position and purpose societies assign to their knowledge infrastructures, play a pivotal role. These discourses exert a substantial influence on the vision and mission of the infrastructure, given that they often require substantial investments for construction and significant budgets for ongoing operation. Knowledge infrastructures frequently find themselves in close proximity to policymakers and funders, setting them apart from other components of the knowledge ecosystem, such as researchers.

These infrastructures are frequently regarded as mere instruments for implementing policies, and as a result, they are subject to external discourses that seek to rationalise and legitimise the resources they demand. These discourses, external to the infrastructure itself, often instrumentalize knowledge in pursuit of broader goals, such as overcoming in competition between nations, fostering economic growth, or addressing societal challenges. These external discourses create a form of external pressure on the infrastructure, directly conflicting with the epistemic practices of its users, which are guided by the inherent nature of knowledge.

Consequently, the infrastructure is often caught in the middle, squeezed between these two external forces, which are frequently manifested in the governance structure of these infrastructures through supervisory boards and scientific committees.

Eventually, the knowledge infrastructure brings together heterogeneous actors who constantly negotiate their practices and objectives within multiple trading zones while they use and produce at the same time the sociotechnical components of the infrastructure. From this threatening heterogeneity, the infrastructure becomes a dynamic configuration, that is, in the literal sense, a composite. Indeed, infrastructures can be studied as dynamic configurations linking actors and their representations, but also material productions, organisational norms, and social relations. What Jöelle Le Marec and Igor Babou have described as “composites” in their report on the digitisation of a research library:

> The aim is to describe heterogeneous and dynamic configurations: “composites.” “Composites” characterise situations in which individuals mobilise both the meaning of material objects and representations, carry out actions and implement systems of norms or operating rules. [...] These composites are dynamic: the elements, actions and norms that constitute them form systems that change as the tasks performed by individuals evolve. [...] A composite characterises a set of social, technical, and semiotic processes mobilised in the context of a professional task described by the actors and observed through the objects that are produced or manipulated on this occasion. Composites are distinguished from related notions such as media and devices because they are,

above all, knowledge embodied in situations and relations between objects, discourses and representations. (Le Marec and Babou, 2003, p. 158)[17]

The notion of composite thus makes it possible to take into account the weaving work that turns the infrastructure, understood as a heterogeneous configuration, into an unstable coherence of the complex whole of which it is composed. Furthermore, following Le Marec (2002), this approach allows us to define a method of investigation that combines the micro and macro levels of observation, and combines ethnographic and semiotic methods in order to "consider with equal attention the phenomena that have found their inscription, and those that are neither inscribed nor symbolised, but which manifest themselves during the inquiry, in interviews and observations" (Le Marec and Babou, 2003, pp. 157-158).[18] Only thus can we seize governance as inscribed—in schemes and by-laws—, as practised—in context by actors—, and as the subject of debate. Studying the governance of knowledge infrastructures means observing the way in which all of these constraints and dimensions are set in motion by interactive processes aimed at achieving a common objective: producing, disseminating, qualifying, curating, and preserving certain types of knowledge.

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[17] Translated from the French by the authors: "*Ce sont des configurations hétérogènes et dynamiques qu'il s'agit de décrire : des « composites ». Les « composites » caractérisent des situations au sein desquelles des individus mobilisent à la fois la signification d'objets matériels et des représentations, réalisent des actions et mettent en œuvre des systèmes de normes ou des règles opératoires. [...] Ces composites sont dynamiques : les éléments, actions et normes qui les constituent forment des systèmes se transformant au cours de l'évolution des tâches effectuées par les individus. [...] Un composite caractérise un ensemble de processus sociaux, techniques et sémiotiques mobilisés dans le cadre d'une tâche professionnelle décrite par les acteurs et observée à travers les objets qui sont produits ou manipulés à cette occasion. Les composites se distinguent de notions voisines comme celle de média et de dispositif car ils sont, avant tout, des savoirs incarnés dans des situations et des relations entre objets, discours et représentations.*"

[18] Translated from the French by the authors: "*considérer avec une égale attention les phénomènes qui ont trouvé leur inscription, et ceux qui ne sont ni inscrits ni symbolisés, mais qui se manifestent dans l'enquête, au moment des entretiens et des observations*"

For an ecology of knowledge infrastructure(s)

Simon Dumas Primbault

Drawing on the evolution of STS over the past thirty years, this programme starts from the postulate of *the essential fragility of infrastructures*. As Borgman *et al.* (2016) have shown thanks to a long-term ethnographic study of data practices at two major astronomic infrastructures—the Sloan Digital Sky Survey and the Large Synoptic Survey Telescope—, their "durability," or "persistence over time," is a daily endeavour within infrastructures—especially in times of growing scarcity (Borgman *et al.* 2020): it is a constant invisible work of cataloguing, archiving, standardising, generating metadata. Building on the repair studies encouraged by Jackson (2014), Denis and Pontille (2022) also extensively worked on the care for things, that is all the people and practices necessary to *maintain* something, *i.e.* the mundane and daily activity to ensure its material and functional continuity before and beyond acts of repair that intervene only upon breakdown.

Even more than an interest for maintenance and repair, infrastructure studies endeavour to document their object through an antiessentialist prism inherited from ethnomethodology and interactionism—and more recently from pragmatic sociology. Refusing to reify infrastructure, they approach it as a process (see above), always in-the-making, and strive to shed light on the sociotechnical mechanisms that may explain its stability. Indeed, it is more complex for infrastructure studies to explain why things endure, than to explain why they break down—not solely because everything ultimately decays, but more importantly because the very *raison d'être* of infrastructure is to hold together a heterogeneity of stakeholders. Consequently, the sustainability of knowledge infrastructures is a burning issue, both in terms of their environmental impact, and more broadly of their persistence as infrastructures. As we will see, the challenge for them could be conceived as sustaining heterogeneity and change by putting their socio-technical structure in tension to hold things together.

The ecological perspective on infrastructure detailed above is of particular interest for that matter. Already in 1999, Star linked the fragility of infrastructure with their ecology by opening her paper with the following quote:

> Resources appear, too, as shared visions of the possible and acceptable dreams of the innovative, as techniques, knowledge, know-how, and the institutions for learning these things. Infrastructure in these terms is a dense interwoven fabric that is, at the same time, dynamic, thoroughly ecological, even fragile. (Bucciarelli, 1994)

Indeed, such a perspective may help explain how diversity plays a role in the stability of an infrastructure, how it may develop holistic—or organic—properties that the sociotechnical and relational perspectives cannot seize, and how it can fit within a broader ecosystem by developing interdependencies with other infrastructures or platforms.

Therefore, reaching an "integrated view" (Bowker *et al.* 2010, p. 113) on knowledge infrastructures may only be achieved by articulating the relational, the sociotechnical, and the ecological perspectives together. This is what this section aims at by venturing a definition for a genuinely ecological approach. From singular infrastructures to the milieux they generate to the global "ecosystem" resulting from their interactions at the higher scale, this contribution tries to show how we can put to work relational, socio-technical, and ecological perspectives on infrastructures in order to explain their persistence and ensure their sustainability.

Ecologies of information

Interestingly enough, one of the early mentions of "ecology" related to digital infrastructures is to be found, again, in Kling and Scacchi's 1982 piece on "The Web of Computing."[19] Although they made loose use of the concept without problematizing it, their reference is a 1958 article by sociologist Norton E. Long who aimed at modelling "The local community as an ecology of games"—*i.e.* of banking, newspaper, manufacturing, etc.—rather than as a simple and too narrow polity, economy, or society.

Another case is Bonnie A. Nardi and Vicki L. O'Day's 1999 *Information Ecologies: Using Technology with Heart*. Respectively anthropologist and computer scientist, Nardi and O'Day based their general argument on a host of ethnographic studies they led on diverse fields during the 1990s, notably digital libraries at Hewlett-Packard and Apple, online virtual communities, or amateur gardeners. Aiming their book at a very broad audience, they also aimed their argument at technology in general as the subtitle makes clear, not solely infrastructures. They discuss the powers of metaphors in framing our understanding and use of technology—technology as a tool, as a text, as an assistant—and argue that we need renewed *complementary* metaphors to conceive of digital technologies and use them "with heart."

Building on Jacques Ellul's conceptualization of *technique* as an autonomous system that overdetermines people's actions and society as a whole, they draw from it the idea of technology as an environment that we inhabit, within which all of our experiences are embedded, and through which they are mediated. Though, refusing the "inevitability" of the technological system's momentum and its inescapable driving force, Nardi and O'Day propose to think of infrastructures in the plural, and the circulation of information within them, as "local habitations" that enable individual praxis as "leverage to affect technological change" (p. x). They call these habitations "information ecologies":

> We define an information ecology to be a system of people, practices, values, and technologies in a particular local environment. In information ecologies, the spotlight is not on technology, but on human activities that are served by technology. [...] In a library, access to information for all clients of the library is a core value. This value shapes the policies around which the library is organized, including those relating to technology. A library is a place where people and technology come together in congenial relations, guided by the values of the library. (p. 49)

It is worth noting that the new ecological set of metaphors advocated by Nardi and O'Day as complementary to that of tool or system, was originally born out of an ethnographic study of private digital libraries where they observed an emphasis on people and, above all, *values* and the need to embed them within infrastructures in order to use technology "with heart." Their proposition is eventually not a change in method or model, but rather a change in perspective: to use concepts borrowed from ecology—namely diversity, coevolution, keystone species, locality—in order to shift attention towards the meanings and impacts of technology.[20]

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[19] See Lyle et al. (2020) for a survey of ecological uses in HCI and CSCW.

[20] Biological and ecological thoughts were imported in a host of other fields and disciplines during the 1990s and 2000s: concepts as well as mathematical models were used in cultural ecology, media ecology, cognitive ecology, or political ecology. It is also worth noting that this is not a one-way street: concepts always travel through cross-circulation and appropriation, notably the concept of information that was conversely adopted by biologists and ecologists (Kuehn, 2022, p. 3).

Infrastructures and their platforms

Therefore, contrary to held opinions, early ecological perspectives do not exclusively stem from the import within the academic field of business-oriented neoliberal understandings of action. Still, there might be legitimate concern to steer away from such metaphors as they have been loaded with neoliberal overtones and consequently used in business management and politics—see notably Beatty (2014), Norris and Suomela (2017), and Stiegler (2019). But this is not a sufficient reason to discard them point-blank, not only because they do not exclusively originate from these discourses, but also, and more importantly, because they are abundantly used by the very actors who design, develop, and maintain said knowledge infrastructures. In fact, they do so consciously and, in most cases, cannot be accused of uncritically reusing neoliberal buzzwords. Situated at the confluence of a diversity of previously separated professional communities, digital knowledge infrastructures continuously struggle with vocabularies—either because one word may have several contradictory meanings, or because newly introduced words may be misunderstood by certain stakeholders.

The right choice of words therefore appeared to them as a way to embed values into the infrastructure. Indeed, the term "community" initially appeared in the daily vocabulary of some infrastructure actors to denote with their users a relationship of cooperation rather than mere competition—and may consequently redirect them towards more appropriate partner services. Subsequently, the term "ecosystem" was reappropriated to denote a working environment that is more than an economy of services provided to clients, and understood in terms of management; rather, it is made up of people, values, knowledge... The concept of ecosystem also carries connotations of the uncertainty and indeterminism of a complex and global environment whose meshwork generates threshold effects and path-dependencies.[21] Thorough ethnographic studies actually show that infrastructures' actors make use of Geoffrey Bowker's "infrastructural inversion" to reflexively understand their own practices (Parmiggiani and Monteiro 2016; Dagiral and Peerbaye 2016). In return, this vocabulary—together with other ecological metaphors about bibliodiversity, life cycles, and predatory journals—is slowly starting to emerge in the predominantly mechanical models proposed by national, European, and international policies on infrastructures—see, for example, ESFRI's life cycle. Anyone wanting to obtain technical, institutional or financial support shall eventually need to understand their project also in these terms.

More generally, the use of the term ecosystem—of research, publishing, innovation…—to designate what was once more simply a system, a network, an infrastructure or an institution, is one of the symptoms of a gradual transition from a system of production, regulation, and appropriation of knowledge inherited from the twentieth century—science as a public good at the service of the progress of a welfare state—to a new system—sometimes described as neoliberal or as a knowledge economy. Here, the sciences are subject to market logics that promote the financialization of innovation and project-based funding, as well as competitive dynamics in the production of knowledge, underpinned by symbolic economies such as scientometrics (Pestre, 2006; Bonneuil and Joly, 2013).

In this new context, where science is seen as a source of competitiveness, the advent of digital technology and the Internet has helped to open up and break down a number of "black boxes" that used to act as mediators within the whole science infrastructure, giving rise to a set of sociotechnical interdependencies between new actors and components, or actors that were previously enclosed within

[21] Private discussions with engineers, editors, managers, librarians at OpenEdition.

integrated systems. Scientific publishing houses, for example, are the result of the vertical integration of a number of stakeholders, techniques, and forms of governance into a black box that acts as an intermediary between authors and readers. The economics of the open-access diamond model makes it possible not only to lift the lid on this black box, but also to disintegrate and reorganise the skills, experience, and professions involved in publishing—editorial chain, production of editorial units, hosting, distribution, indexing, cataloguing—in the service of the open science ecosystem.

This phenomenon is what Jean-Christophe Plantin *et al.* (2018) called the "splintering" of knowledge infrastructures and their consequent platformisation, that is their fragmentation into smaller functional units that work interdependently and as such make up for an "ecology:"

> Because they integrate many semi-independent systems, internetworks can only rarely be designed, controlled, or standardized from above; instead, fully developed infrastructures are complex ecologies whose components must continually adapt to each other's ongoing change. (Plantin *et al.*, 2016, p. 296)

According to Plantin *et al.* (2016), platforms exhibit a very specific architecture, distinct from that of infrastructures: they are an assemblage of programmable modules accreting around a stable core, and they allow external actors to "plug-in" through APIs. The dynamic emerging from this interplay of dependencies is consequently best described as an ecosystem that we will try to define below.

In this regard, *digital* knowledge infrastructures are a very specific kind of infrastructures that developed with the advent of networked computation and blossomed in the age of big data. Digital knowledge infrastructure are therefore essentially permeable to platform logics—this is already visible in Hanseth, Monteiro, and Hatling's (1996) article on TCP/IP and OSI (see above), and particularly so in today's many flavours of "middleware" offered to users (Drucker and Svensson, 2016). The risks are numerous to see platforms further splinter knowledge infrastructures and to capture value by harnessing labour (Plantin and Thomer, 2023), but one should not take for granted that platforms are intrinsically dangerous. While indeed some endeavour to make up for a single integrated ecosystem by building enclosures that keep value, users, and knowledge within "walled gardens", others emanate from public infrastructures striving to re-empower the actors of science by providing them with open means of knowledge production and circulation.

Because ecological metaphors can be extremely heuristic, because they aptly describe the phenomena brought about by a new regime of science, and because they are consciously mobilised by infrastructure's actors, there is an urgent need to give them credit. The aim of the present section is therefore to make the ecological perspective on knowledge infrastructures explicit by defining it. One pitfall to avoid is either yielding to vitalism, or naturalising technique while trying to adopt a more organic perspective on infrastructures. Consequently, we do not understand ecology as a means to naturalise knowledge infrastructures—on the contrary, the previous model will show the scaffolding of how everything is initially governed, what values one wants a given infrastructure to embody. Similarly, we do not take ecology as a means to make their study scientific—it is not a matter of a predator-prey model and digital Malthusianism, neither a competition for limited resources deriving from ill-formed versions of "social Darwinism", nor is it an injunction to adapt and evolve to fit the environment as if it were an unmovable given. Rather, we take from Ludovic Duhem

> [...] the idea that ecology is irreducible to the scientific study of ecosystems and the commitment to the protection of nature, and that it must therefore be understood in a broad sense as a relational, dynamic, scalar, and complex approach that can be applied not only to natural environments but also to artificial ones, and in particular to the digital environment, which has now become the associated milieu of our human existence, *i.e.* that which gives new conditions and meanings to our ways of thinking and acting. (Duhem, 2017)[22]

Following Duhem, we take ecology to be the discourse on what is inhabited—in our case, infrastructures in the plural, as well as the infrastructure—and how it is inhabited. A library, for example, cannot be understood as an ecology. But we can write an ecology of a library if we understand it as a specific milieu that is inhabited by its users and stakeholders, its books and its classifications (Nardi and O'Day, 1999). We ask the question of how actors live and thrive in this structure, how they govern it, how they fill the voids of this complex scaffoldings, and how, eventually, the infrastructure and its associated milieu may exhibit holistic properties. How do organic properties emerge from a composite—*i.e.* a rather mechanical socio-technical system made dynamic by a play of tensions?

Infrastructures and their milieux

Rather than addressing the global ecosystem from the start, thereby risking naturalising our object, we want to proceed from the previous composite model and build our ecological perspective from the ground up, starting from the local and material. Similarly to Nardi and O'Day, this will enable us to bypass the autonomous and rather totalitarian technical system *à la* Ellul. Following Duhem, we would like to turn to another concept that denotes a more complex and dynamic, more relational and scalar reality: Gilbert Simondon's "associated milieu."[23] In his 1958 essay *On the Mode of Existence of Technical Objects*, Simondon attempted to define a "*mécanologie*" as the discourse on technical individuals, a subdiscipline of "technology," the discourse on technique (Guffroy and Bontems, 2018). For Simondon, a technical object can become a technical individual only if it creates its own conditions of possibility by shaping its own milieu—and reciprocally:

> a milieu that the technical object creates around itself and that conditions it, just as it is conditioned by it. This simultaneously technical and natural milieu can be called an associated milieu. It is that through which the technical object conditions itself in its functioning. This milieu is not fabricated, or at least not fabricated in its totality; it is a certain regime of natural elements surrounding the technical being, linked to a certain regime of elements that constitute the technical being. The associated milieu mediates the relation between technical, fabricated elements and natural elements, at the heart of which the technical being functions. [...] It is this

[22] Translated from the French by the authors: "*L'idée que l'écologie est irréductible à l'étude scientifique des écosystèmes et à l'engagement pour la protection de la nature, et qu'elle doit par conséquent se comprendre au sens large comme une approche relationnelle, dynamique, scalaire et complexe pouvant s'appliquer non seulement aux milieux naturels mais également aux milieux artificiels, et en particulier au milieu numérique devenu aujourd'hui le milieu associé de nos existences humaines, c'est-à-dire ce qui donne des conditions et des significations nouvelles à nos manières de penser et d'agir.*"

[23] Note that, historically, Georges Canguilhem and Jakob von Uexküll respectively reclaimed the concept of milieu and invented that of *Umwelt* to fight against social determinism and reductionism of life to mechanical processes (Feuerhahn, 2017).

> associated milieu that is the condition of existence for the invented technical object. (Simondon, 2017[1958], p. 59)[24]

Provided that we take infrastructures as (socio-)technical beings, as we saw with the model, and that we broaden the scope of "natural elements surrounding the technical being" to all socio-technical elements *a priori* external to a given infrastructure—natural resources, the installed base, its future users, other infrastructures—, we may understand the organic development of an infrastructure as the gradual exudation of its own associated milieu, reciprocally becoming the condition of possibility for the infrastructure to thrive—*i.e.* it becomes itself a milieu for certain activities of production and circulation of knowledge, e.g. a platform or a middleware. The associated milieu of an infrastructure is therefore not an inert and crystallised environment, merely surrounding it, but a genuine sociotechnical ether produced by the infrastructure and that produces it in return—it does not pre-exist the infrastructure and yet is its condition of existence. A dialectic then takes place between the infrastructure as a sociotechnical scaffolding—our model—and its associated milieu in its many dimensions—material and technical, social (a community), informational… This dialectic described by Simondon may be reminiscent of processes of infrastructuring by governing the assemblage of elements into a value-laden ensemble:

> the elements that will materially constitute the technical object and which are separate from each other, without an associated milieu prior to the constitution of the technical object, must be organized in relation to each other according to the circular causality that will exist once the object will have been constituted; thus what is at stake here is a conditioning of the present by the future, by that which is not yet. Such a futural function is only rarely the work of chance; it requires putting into play a capacity to organize the elements according to certain requirements which act as an ensemble, as a directive value, and play the role of symbols representing the future ensemble that does not yet exist. (Simondon, 2017[1958], p. 60)[25]

But while for Simondon this organisation of elements is merely the functional arrangement of material—even mechanical—parts, we think of it in terms of *governance*. And it is precisely because such

[24] Translated from the French by Cecile Malaspina.
"[...] *un milieu que l'être technique crée autour de lui-même et qui le conditionne comme il est conditionné par lui. Ce milieu à la fois technique et naturel peut être nommé milieu associé. Il est ce par quoi l'être technique se conditionne lui-même dans son fonctionnement. Ce milieu n'est pas fabriqué, ou tout au moins pas fabriqué en totalité ; il est un certain régime des éléments naturels entourant l'être technique, lié à un certain régime des éléments constituant l'être technique. Le milieu associé est médiateur de la relation entre les éléments techniques fabriqués et les éléments naturels au sein desquels fonctionne l'être technique.* [...] *C'est ce milieu associé qui est la condition d'existence de l'objet technique inventé.*" (Simondon, 1958, p. 57)
[25] Translated from the French by Cecile Malaspina.
"[...] *les éléments qui matériellement constitueront l'objet technique, et qui sont séparés les uns des autres, sans milieu associé avant la constitution de l'objet technique, doivent être organisés les uns par rapport aux autres en fonction de la causalité circulaire qui existera lorsque l'objet sera constitué ; il s'agit donc ici d'un conditionnement du présent par l'avenir, par ce qui n'est pas encore. Une pareille fonction d'avenir ne peut que très rarement être l'œuvre du hasard ; elle nécessite la mise en œuvre d'une capacité d'organiser des éléments en vue de certaines exigences ayant valeur d'ensemble, valeur directrice, et jouant le rôle de symboles représentant l'ensemble futur qui n'existe pas encore*." (Simondon 1958, p. 57)

an assemblage is governed that it may exude its associated milieu and concretize into a technical being.[26] Indeed, the infrastructure may either become a *medium* for its community—a "middleware" of access to knowledge (Drucker and Svensson, 2016)—or part of the installed base for another infrastructure—e.g. a platform.

We can now define the "ecosystem," in the singular, as the global scale where singular infrastructures are dynamically put into relation through their milieux—technical, social, informational… As a sort of *a priori* non-governed meta-milieu, the ecosystem is akin to *the* infrastructure in the singular, and its many dimensions. It may also exhibit specific dynamics of competition or collaboration between infrastructures and their milieux, mutual influence on their respective internal governance, processes of specification or standardisation. As the structured environment in which infrastructures and their associated milieux are immersed and with which they have to interact, the ecosystem remains a nebulous thing for both infrastructure actors and scholars. The scalar approach here advocated—from the infrastructure as a sociotechnical system to its milieu to the ecosystem—is an attempt at collectively building an integrated view by weaving together a relational, a sociotechnical, and an ecological perspective.

A quick example may help us understand what is at stake here. Wikipedia, launched in 2001 as a side project to crowd-source the writing of Nupedia, an encyclopaedia edited only by experts, is the paradigmatic example of a sustainable digital knowledge infrastructure. Taking advantage of the Internet and the wiki technology as installed bases, Wikipedia rapidly supplanted Nupedia thanks to a rising community of collaborators. Gradually the rules for contribution and the editorial policies were made explicit, initially by the founders and, increasingly, by the users themselves through debate and discussions, thereby growing into a social milieu—the Wikipedians. Today, the Wikipedians can be seen as a decentralised self-organised community that not only contributes to the content and rules of the encyclopaedia but also governs itself by dialectically applying the procedures of Wikipedia. This "space of self-regulation" (Cardon, 2015) was made possible not only because its rules were gradually enacted by the community itself, but also because said community grew as a very homogeneous social milieu later reinforced and reified by bots and patrollers (Joubert, 2019). Anyone willing to contribute will have to abide by the rules and epistemology of the encyclopaedia and learn them, sometimes the hard way, in contact with more seasoned Wikipedians. In other words, Wikipedia exuded its own Wikipedians, who conversely became the very conditions of possibility of the encyclopaedia, not solely because it is a technical piece of software, but also because the members of this exuded milieu—mostly Western white male, STEM practitioners in their 30-40s—are the ones most likely to spontaneously develop Wikipedia's epistemology—based on Ayn Rand's liberal and objectivist philosophy—during their training or professional practice. To be precise, what is shared by this community is not the content of the articles which is often the subject of debates, but rather the procedures that frame these debates—and hence, ultimately, the belief in some objectivist postulates. Tensions, as they are framed, are productive forces for Wikipedia, to the extent where "even good bots fight" (Tsvetkova *et al.*, 2017). For the ethnographer Jemielnak, this is an indicator of a certain ideology:

[26] This may seem to go against Simondon's assumption that, for "superior ensembles," such as laboratories, the creation of an associated milieu is "undesirable" (Simondon 2007[1958], p. 66), only because Simondon thinks of these assemblages solely in functional terms, rather than also in terms of governance.

> it is clear that the Wikipedia community relies as much on cooperation as it does on conflict [...] In some ways, Wikipedia forms a "community of dissensus." [...] Such a chaotic and uncoordinated way of seeking consensus and resolving disputes reflects a laissez-faire and hands-off approach to Wikipedia, which is unlikely to change if only because it draws people to this community. (Jemielnak, 2014)

The originary ideology and consequent format it imposes on discussions and articles act as epistemic gatekeepers as well as powerful means not to erase tensions but to frame them and turn them into productive forces.[27]

This strength of Wikipedia is also one of its biggest weaknesses. The symbiotic relationship between Wikipedia and its Wikipedians is indeed a threat to the diversity of its contents and to the unavowed biases that may plague them. Being its associated social milieu, it will not suffice to open Wikipedia's community to a broader audience in order to address these issues. Rather, to make the encyclopaedia more diverse and inclusive in a global context without submitting the new knowledge to Western epistemology and frameworks, it would be necessary to acknowledge the ideological nature of its procedures—and, for example, highlight the discussion pages—, change the epistemology of the "neutral point of view"[28]—favouring, for example, multiple versions of some articles' sections—, and include less logocentric forms of knowledge—such as oral knowledge, thereby lending the encyclopaedia to more diverging interpretations as well.

Ultimately, at the scale of the ecosystem, Wikipedia together with its associated milieu weave ties, either voluntarily or incidentally, with other infrastructures. For example, STS scholars start to understand the relationship between Wikipedia and Google as either a kind of symbiosis or of parasitizing. Indeed, most of Wikipedia's traffic massively comes from search engines, and specifically from Google, and hence benefit from a boost in the search results when the expectation from a given query is the kind of factual information delivered by the encyclopaedia. But while Google does indeed boost the referencing of Wikipedia pages for *some* queries, it also regularly harvests its content—as well as other platforms'—in order to produce a general knowledge graph that shows after request as so-called "knowledge panels" and may answer simple queries such as "what is an infrastructure?" thereby diverting—even just stopping—the traffic.

Through the example of Wikipedia, a specific knowledge infrastructure appears, together with other infrastructuring forces, as the material condition of possibility for the emergence of a milieu, and reciprocally. A dialectic emerges between the infrastructure and its milieu through at least two types of interaction: the governance *of* the infrastructure by its milieu, and the reciprocal governance of the milieu *by* the infrastructure. Yet, this example only addresses one of the many facets of the associated milieux of digital knowledge infrastructures—in this case, knowledge milieux (Dumas Primbault *et al.*, 2021)—, but we should not turn a blind eye to the multiple dimensions of milieux: social, informational, but also material and energetic—hence raising issues about the protection of nature and the sustainable use of limited resources (Petit and Bertrand, 2018; Petit and Collomb, 2022). One way to enquire about infrastructural associated milieux without favouring one of these dimensions is to use other ecological

[27] This raises the provocative question of what is the common of Wikipedia: the knowledge it contains or the procedures it enacts?

[28] See, for example, https://noircirwikipedia.org/fr/accueil/

concepts as probes into the holistic and organic properties of milieux. The following subsections hint at three potential emerging properties of knowledge infrastructures.[29]

Resilience and Maintenance

Resilience can be roughly defined as the ability for a system to recover an identity, function, and state of reference after a perturbation—in our case, financial cuts, loss of data, corruption of integrity… It is different from mere adaptation in that the overall structure of the system may remain intact as long as a certain threshold is not reached, thereby leading to a new state of equilibrium.

Resilience may result from (continuous) maintenance as there is no rupture, no event (Denis and Pontille, 2022) when a system exhibits resilient properties. But it may also be a property embedded in design: decentralised systems, or distributed architectures, such as peer-to-peer networks are examples of such design addressing issues of recovery after local perturbations on specific nodes of the network. Redundancies—through mirror URLs for example—or replication—by forking—are also solutions implemented by "shadow libraries" (Karaganis, 2018) such as Libgen or Sci-hub to be able to resist global choke points enforced by ISPs or governance discrepancies within them.

Vicariance and Repair

Vicariance can be defined as the ability of one element within a system to replace another one that is missing or failing, and fulfil the same ecological function. This can also be observed at the scale of single organisms when one organ fulfils, albeit not perfectly, the role of another failing organ. This usually results in a somewhat "abnormal" functioning of the system, *i.e.* not at its state of equilibrium.

Vicariance may result from (temporary) repair as there was a rupture in the normal functioning of the system (Denis and Pontille, 2022). Again, shadow libraries may act as illegal vicars whenever one cannot access certain resources due to the presence of paywalls (Nicholas *et al.*, 2019). Other such properties at the level of individuals have been ethnographically observed by Nardi and O'Day who documented how librarians help readers reformulate, broaden, and specify their queries when the search engines (ineluctably) fail them (Nardi and O'Day, 1999).

Diversity and Inclusion

Diversity is one of the most important properties of a thriving ecological system. It can be defined as a measure, both quantitative and qualitative, of the variation of species, processes, and interactions. In the case of digital knowledge infrastructures, the diversity and inclusion of a wide range of stakeholders and users, of knowledge and informational resources, of means of involvement, is of utmost importance.

Because infrastructures embed values and result from political endeavours, they "do not serve all users equally" (Okune *et al.*, 2019, p. 2) at the risk of "epistemic injustice" (Albornoz *et al.*, 2020). It is therefore fundamental to include by design the broadest diversity of users, stakeholders, and processes in their functioning and governance. Inclusion also means turning tensions into the productive forces that keep together these people. This can be illustrated by the issues raised in co-designing platforms—such as Impresso where the historians' goals were orthogonal to the funding bodies'[30]—or in establishing community-led governance—such as for the COPIM project where there is "always an element of

[29] See Morin (1977) for a thorough discussion of "emerging" properties in complex systems.
[30] Maud Ehrmann, private communication.

agonism”[31]. In the same vein, the prehistory of Gallica with the “*Poste de lecture assistée par ordinateur* [Computer-aided reading station]” highlights a situation where a homogeneous group of scholars was replaced with an ever-more inclusive team of librarians, archivists, editors, readers (Béquet, 2015; Bermès, 2020).

Anti-extractivism and Sustainability

How to make a knowledge infrastructure environmentally sustainable by paying attention to all the resources consumed and waste produced and, subsequently, accounting for energy consumption in data practices such as, for example, machine learning (García-Martín *et al.*, 2019), or “recycl[ing] waste information” (Edwards, 2016)?

Understanding the ecosystem in the broadest sense entails seriously taking into account the fact that infrastructural milieus are also tightly related to and dependent on environmental milieus, in the sense of supposedly natural ecosystems. It is widely recognized and documented that the infrastructures supporting digital, computational, and networked activities—such as data centres—generally relate to material resources, human labour, and natural milieus in an “extractivist” manner (Brodie, 2023): rare metals, energies, information, and labour are extracted from soils and people without any consideration for the social and ecological consequences of such practices. It is therefore urgent to pay attention to how exactly the knowledge ecosystem weaves ties with its environment: how far they ramify and reconfigure said environment—e.g. how the deployment of 5G networks endangers avian ecosystems (Schwoch, 2021)—and, reciprocally, on how disturbances in environmental milieus lead to the malfunction of infrastructural milieus—e.g. the impact of sea level and temperature rising on the Internet infrastructure (Durairajan *et al.*, 2018).

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These are mere examples of a list of holistic properties that a knowledge infrastructure and its associated milieu may exhibit. One could think of many others:

- Can adequate transparency as a property be achieved by including the associated milieu in the governance scheme, opening the black boxes of algorithms, or publicly documenting the activities of the infrastructure, thereby instilling trust as a value?
- Beyond the mere storage of data and metadata and the associated “long-term preservation” or “disaster-recovery” issues, how can an infrastructure and its milieu also develop a form of memory of obsolete or lost knowledge, as well as human memory of know-how, practices, and tacit knowledge?

Note that nurturing these ecological properties is akin to embedding values into the infrastructure; and these properties are highly interdependent. Consequently, they need to be addressed simultaneously. For example, openness of code may help resilience, vicariance, and transparency while open access will foster the inclusion of a diversity of users and must be followed by measures for bibliodiversity. We believe that the sustainability of a given infrastructure can be ensured when its associated milieu is the more organic, when its holistic properties are strong and tightly interwoven.

[31] Janneke Adema, private communication.

The ecology of infrastructures is the discourse on how infrastructures exude ecological properties, and how human and non-human actors inhabit their associated milieux and the ecosystem. But it is also a call to design and develop digital knowledge infrastructures in an ecological fashion. Indeed, today's growing knowledge infrastructures and the literature about them are proof that it is high time to shift focus from heavily material, physics-informed infrastructure inherited from wartime Big Science (Cramer and Hallonsten, 2020) and driven by supposed non-values (such as rationality, efficiency, emergency, short-term) to something else, notably for the humanities and social sciences (Svensson, 2020). How to embed values into the infrastructure(s)? How to create infrastructures that are not normative, yet frame people? How to care about a community driven by a culture of collaboration? How to make infrastructure(s) ecologically sustainable? How to design and dovetail forms of governance to tackle these issues?

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