A bridge too far?

Critical remarks on the concept of 'infrastructure' in CSCW and IS

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> 'But I think we might be going a bridge too far.'
> Lieutenant General Frederick Browning[1]

In the course of the last century or two, large-scale technical structures such as water and sewer systems, railways, electrical telegraph systems, administrative archives, electrical power distribution, telephony, satellite navigation, and now of course the Internet and the services facilitated by it: email, the World Wide Web (WWW), search engines, online repositories, etc. and, not least, organizational and inter-organizational coordination technologies such as enterprise resource planning (ERP) systems, supply-chain management systems, medical record systems, have been constructed and have become critical features of our civilization (e.g., Delgado, 1979; Perrow, 1984; Bijker et al., 1987; Mayntz and Hughes, 1988; Yates, 1989; La Porte, 1991; Bud-Frierman, 1994; Rochlin, 1997; Abbate, 1999; Gillies and Cailliau, 2000; Yates, 2005; Levinson, 2006; Car et al., 2008a, 2008b; Pollock and Williams, 2009; Stead and Lin, 2009). The study of computing infrastructures, in particular, has grown significantly due to the rapid proliferation and ubiquity of large-scale IT-based installations. At the same time, recognition has also grown of the usefulness of such studies as a means for understanding computing infrastructures as material complements of practical action. Subsequently the concept of 'infrastructure' has gained increasing importance in Computer-Supported Cooperative Work (CSCW) as well as in neighboring areas such as Information Systems (IS) research and Science and Technology Studies (STS). However, as scholarly study of infrastructures (especially of those that depend on computing technologies) has

[1] 'On the narrow corridor that would carry the armored drive, there were five major bridges to take. They had to be seized intact by airborne assault. It was the fifth, the crucial bridge over the Lower Rhine at a place called Arnhem, sixty-four miles behind the German lines, that worried Lieutenant General Frederick Browning, Deputy Commander, First Allied Airborne Army. Pointing to the Arnhem bridge on the map he asked, "How long will it take the armor to reach us?" Field Marshal Montgomery replied briskly, "Two days." Still looking at the map, Browning said, "We can hold it for four." Then he added, "But, sir, I think we might be going a bridge too far."' (The final conference at Montgomery's Headquarters on Operation Market-Garden, 10 September 1944, as recalled by Major General Roy E. Urquhart, quoted in Ryan, 1974, pp. 9, 89).

unfolded, the very concept of 'infrastructure' has been applied in different discourses, for different purposes, in myriad different senses. The concept of 'infrastructure' has become increasingly muddled over time. Disparities in use of the concept have become an immense source of confusion (Schmidt and Bansler, 2016). The unquestioned and seemingly un-noticed use of the term 'infrastructure' in myriad ways is hobbling the development of the area.

While we do not attempt a comprehensive review of this vast literature, we do trace some influential lines of thought and how these come together and also diverge. This work presents a critical investigation of the vicissitudes of the concept of 'infrastructure' over the last 35 years. The aim of this work is to foster greater clarity to help further develop this line of computing research and the practices it both studies and supports.[2] The broadening scope of the concept of *infrastructure* has brought more researchers and a greater variety of orientations and methods to the table to the great benefit of the research area. While it is neither necessary nor desirable to have a singular approach or focus for the study of infrastructures, the rapid growth of the area has led to a substantial amount of confusion. The broadening scope of the concept has also been useful for positioning socio-technical research as important, if not crucial, for continuing advances in the successful development, maintenance, and use of technological infrastructures. Having successfully reframed the discussion around infrastructure as a socio-technical one, greater precision is now required for distinguishing the elements that interact within and without infrastructure. Imagine if you will a surgeon who does not have the vocabulary or grammar to distinguish between heart and lungs. This would not make surgery impossible, but it would make it far more difficult. More precision is needed in defining our terms, objects of study, and the interactions between myriad nested and overlapping practices, technical components, and sub-components. Ultimately, we need increasingly sophisticated conceptual tools for understanding, talking about, and working on the problem spaces in which we are intervening.

A place to begin this discussion is to observe that the very word 'infrastructure' has a surprisingly short history and that the term, nonetheless, is used quite flexibly in everyday discourse. It seems to have originated in in the late 19th century in French railroad engineering as a way to refer to the ballast, subgrade, and subsoil supporting the tracks, as opposed to the 'superstructure' in the form of tracks, station buildings, and rolling stock.[3] However, its use soon extended to refer to material structures underpinning other structures such as buildings and roads. In English,

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[3] 'Le passage des trains, dont la masse est souvent très lourde et animée de grandes vitesses, communique en effet à la voie et à l'infrastructure des vibrations qui causent des ébranlements dangereux pour les ouvrages mal fondés', in contrast to 'la superstructure, c'est-à-dire […] la voie et des stations et de la fourniture du matériel roulant' (Bricka, 1894, pp. 3, 126). (For an overview of the etymology, cf. Lewis, 2008).

its wider use seems to have begun during the Cold War with the establishment of NATO's Infrastructure Committee tasked with the establishment of 'static buildings and permanent installations required to support military forces' such as headquarters, pipelines, airfields, signal communications, information systems, air defense systems, storage depots, port facilities, and maintenance bases (NATO, 2001). From that usage, the term was extended to refer to the system of public works of a country, state, region, or city (water and sewage, electrical power, railroads, etc.) and then in the 1970s, by analogy, to socio-technical systems or entire industries sustaining the economic life of a country, such as postal services, shipping and container transportation, trucking, aviation, banking, etc. Thus, when one today mentions a country's 'railroad infrastructure' one may be referring to the railroad system *as a service* running the entire system of resources in the form of technical structures (tracks, signal systems, stations, etc.), the ongoing operation of trains, signals, and switches, as well as the administration of its operation, such as the provision of schedules, ticketing services, maintenance, etc. Still, while used flexibly, in ordinary discourse the concept of 'infrastructure' refers to a technical facility that provides a service to the wider world: by supporting tracks, by affording the movement of trains, by supporting the transportation of goods and people, and so on. The point of its use is that it refers to a system that under some description supports another: an infrastructure in its relation to a superstructure.

1 'Infrastructural resources'

In the general computing-related discourse, the term 'infrastructure' was originally introduced and used, as a key analytic concept, in the research area *social studies of computing* by Rob Kling, Walt Scacchi, and Tom Jewett (Kling and Scacchi, 1982; Kling, 1987; Jewett and Kling, 1991). The research problem Kling et al. were addressing was not one of technology development and systems design, nor one of general public policy, but one of sociology of technology: 'What influences the adoption of new computer-based technologies? How are particular computer-based technologies ordinarily used? What are the social consequences of using computer-based technologies?' (Kling, 1987, p. 307 f.). They were exploring ways of understanding computing as social action and for that purpose they needed to see computing technology and computer systems not as something that (somehow) arrives out of the blue but rather as something that is inherently 'social', in its inception as well as in use. Thus, in a programmatic paper, Rob Kling and Walt Scacchi (1982) subjected conventional conception of computing to an incisive critique:

> 'Most scholarly and professional examinations of the social and economic repercussions of new computing developments are based on a highly simplified conception of computing and social life. This conception focuses on certain explicit economic, physical, or information processing features of a technology. For the sake of simplicity, the social context in which the technology is developed and used, and the history of participating organizations, are ignored. […] This conception informs many analyses of computing and related activities: of the payoffs of new computing developments, of the costs to be borne by developers and the broader public, of the extent

> to which different management strategies will yield more reliable and broadly workable computer-based systems.' (Kling and Scacchi, 1982, p. 2).

Against this conception, dubbed the 'discrete-elements model of computing', they sketched an alternative 'web model' approach. Where the 'discrete-elements model of computing' conceives of a computing resource as 'a particular piece of equipment, application, or technique', the 'web model' conceives of a computing resource as 'an ensemble of equipment, applications, and techniques'. Both approaches conceive of these computing resources — a 'particular piece' or 'an ensemble' — as the unit of analysis, its 'focal computing resource'.

As the decisive move in this attack, the concept of 'infrastructure' was invoked, and due to the central role it was assigned, the term was given a formal definition:

> '*Infrastructure* refers to those resources which help support the provision of a given service or product. The infrastructure for providing computer-based services includes 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.' (Kling and Scacchi, 1982, p. 7 (n. 2) and pp. 18 f.).[4]

According to Kling and Scacchi, for both approaches — the 'discrete-elements models' and the 'web models' — the 'infrastructure for supporting the focal computing resource and the organizational procedures by which it [the resource] is organized and sustained are critical elements'. Similarly, each approach presumes that the 'computer-based service is provided through a set of structured computing resources and organized infrastructure'. So far, they are on parallel tracks. However, the former approach presumes that deploying, managing, and establishing procedures for these 'infrastructural resources' ('structured computing resources' as well as 'organized infrastructure[s]') is 'separable from deployment of the focal computer-based technology'. Hence, on this view, 'Infrastructure, either technical or administrative, is a neutral resource'. In contrast, on the 'web model' view, the 'computer-based systems' are conceived of as 'a form of social organization'. Hence, 'Like any organization or institution, it [the organized infrastructure] is not necessarily neutral' (Kling and Scacchi, 1982, pp. 7 f.; Kling, 1987, pp. 311 f.).

Hence the motivation for introducing the notion of 'infrastructure': 'We find the term infrastructure useful to denote these supporting resources for computing development. They are often taken for granted, and priority is placed on the leverage to be gained by new computing developments' (Kling and Scacchi, 1982, p. 20). Kling and his colleagues introduced the concept of 'infrastructure' so as to be able to treat the organizational and practical aspects of computing on the same level as computing equipment and thus to bring to attention the invisible work and the hidden costs required of establishing the organizational framework for computing as

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[4] This definition was upheld and even sharpened later: '*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 and Scacchi, 1982; Kling, 1987). 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 […]' (Jewett and Kling, 1991, p. 247 f.).

well as the often undisclosed conflicts of interest at play in such large-scale organizational interventions.

However, the way the term 'infrastructure' is used here is a source of potential confusion. The authors explicitly distinguished between 'the focal' computing facility on the one hand and on the other the supplementary technical resources, organizational arrangements, and human skills required for it to operate. This distinction is clear enough, in that it reflects the purpose of bringing to the fore the organizational and practical embeddedness of computing. So far, the authors are in accord with the ordinary use of the term 'infrastructure'. For as already mentioned, when one talks about a country's railroad infrastructure, one will be referring to the service provided by the technical structures or installations and equipment of the railroad system in operation. And one may also, in describing the railroad services, refer to the technical installations (tracks, etc.) as the infrastructure of a country's railroad service, that is, the infrastructure of an infrastructure. So far, so good. But would one refer to, say, the administration of operations etc. of a railroad system as the *infrastructure* of the system of tracks, etc.? Hardly. That would be utterly perplexing. Much of the trouble with the notion of 'infrastructure' in CSCW and IS probably stems from this terminological choice.

In so far as the 'focal' entity of the given study is clearly identified, the ambiguity can be handled (with care), just as we, in daily language, can refer to the railroad system, the sewer system, the power systems, and so on as 'infrastructures' in both senses: as technical installations and as organized technical services. However, the ambiguity becomes unwieldy as soon as the 'focal' entity, and by implication the 'infrastructure' defined as its organized context, becomes heterogeneous and distributed. The focus then becomes blurred. Kling and Scacchi, for example, already open this can of worms when they go on to say that a crucial characteristic of the 'web models' approach is the assumption that 'Each computer-based service is provided through a set of structured computing resources and organized infrastructure[s]' (Kling and Scacchi, 1982, p. 8). This raises a question: How does one identify what is 'focal' and what is not? In the case of, say, the railroad system there are, so to speak, only two levels: the organized transportation service and the technical structure it depends on (if we may be allowed to disregard the fact that maintenance services also use the rail tracks and so on). But in the case of a 'computer-based service' 'provided through a set of structured computing resources and organized infrastructure[s]', it is difficult and potentially impossible to determine what is what. What would here be the criterion for determining the 'focal' entity?

Kling et al. did not address that question, for at the time the question had hardly been raised as a real-life question yet. Distributed computing was still in its infancy: The essential email protocol SMTP was not specified until August 1982, that is in same year as Kling et al.'s study (Postel, 1982; Hardy, 1996), and TCP/IP was only made the underlying protocol of ARPANET in January 1983 and did not become practical reality until the end of the 1980s (Quarterman, 1990; Abbate, 1999; Gillies and Cailliau, 2000). That is, in 1982 and even in 1987, it made perfect sense not to consider 'the focal computing resource' a problematic notion.

2 'Information infrastructures' 1.0

The widespread use of the term 'infrastructure' in computing can be dated quite precisely to around 1990 where it appeared in the form of the term 'information infrastructure'. Until then, in the decades up to 1990, the term 'infrastructure' was hardly used in the computing literature; instead the term 'network' (or 'computing network') reigned supreme, for the simple reason that it precisely describes an essential topological feature of the facilities: their being distributed and yet interconnected. But by the late 1980s the Internet protocol TCP/IP had become the standard communication protocols in ordinary computer operating systems. Given this vast and potentially global computing and communication platform, the interest of technologists and government officials turned to the question of how to exploit this new resource: What *services* could or should be built on top of it? Provided, organized, maintained by whom? In the ensuing discussion, such services were dubbed 'infrastructures' and, with increasing frequency, 'information infrastructures' (e.g., Cerf, 1987; FCCSET, 1987a, 1987b; Kahin, 1990b, 1992; McGarty, 1992; Kahin, 1997).[5]

The notion of 'infrastructure' introduced by Kling and Scacchi a decade earlier, in 1982, had no apparent influence on this movement. Indeed, by 1992, the paper by Kling and Scacchi (1982) does not seem to have received any citations (other than in Kling's own later papers: Kling, 1987; Jewett and Kling, 1991). In fact, the issue addressed around 1990 by the technologists, administrators, and government officials was not the sociological issue of how the social organization of computing might be subjected to a critical analysis that did not, from the very beginning, presume computing to be a 'neutral' entity. The issue was now rather that of exploring and planning how to exploit the Internet.

Around 1990, two broad and interrelated initiatives gained momentum.

On the one hand, the US National Science Foundation (NSF) began to explore ways in which the Internet could provide the technical platform for scientific research. In a very influential white paper, William Wulf, then assistant director of NSF's Directorate for Computer and Information Science and Engineering, outlined the idea of a 'national collaboratory', defined as

> 'a "center without walls", in which the nation's researchers can perform their research without regard to geographical location — interacting with colleagues, accessing instrumentation, sharing data and computational resources, [and] accessing information in digital libraries' (Wulf, 1989, p. 1).

In the context of this chapter it is important to note that the 'national collaboratory' was envisioned as more than 'a mere interconnection of computers; it was

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[5] The term 'information infra-structure' was originally coined by the US Domestic Council Committee on the Right of Privacy in 1976 in a report on National Information Policy (US DCCRP, 1976; cf,. also Bearman, 1986; Kahin, 1997, p. 164). But the (scholarly) use of the term 'information infrastructure' increased explosively around 1990, from about 900 articles in 1980-89 to 16,300 in 1990-99, that is, by a factor of 18. In the next decade, 2000-09, the total reached 29,300. (Calculated on the basis of scholar.google.com).

envisioned as offering a complete infrastructure of software, hardware, and networked resources' (Cerf et al., 1993, p. vii). The notion of a 'national collaboratory' was further explored in March 1989 at a two-day workshop organized by Joshua Lederberg and Keith Uncapher and supported by NSF (reported in Lederberg and Uncapher, 1989). In the words of a later report, 'The workshop enthusiastically endorsed the concept and in general terms identified the technologies and services that would have to exist or be developed to provide the necessary infrastructure' (Cerf et al., 1993, p. vii).

Four years later, the Committee on a National Collaboratory under NSF's Computer Science and Telecommunications Board (CSTB) undertook a 'year-long effort to study the needs of scientists for computing and information technology to facilitate collaboration, and to relate those needs to the development and use of collaboratories' (ibid., p. vii). In the course of this work, the idea of one 'national collaboratory' was abandoned:

> 'As the study progressed, the idea of developing a single national collaboratory was replaced by the idea of developing multiple scientific collaboratories. These collaboratories would share network and computing resources, software, and infrastructure but would have unique features dictated by the needs of particular scientific disciplines. Recognition of those varying needs drove the shift in focus from a single national collaboratory to many scientific collaboratories.' (Cerf et al., 1993, p. viii).

Thus, instead of a monolithic collaboratory, the committee recommended that the NSF establish a 'collaboratory testbed program' with multiple 'collaboratories':

> 'Because scientific disciplines vary in numerous ways, it should not be assumed that one mode of collaboration or one set of collaboration tools can fit all needs. Therefore, the committee recommends that the proposed research program establish several collaboratory testbeds, which should be tailored to the needs of particular groups of scientists in their respective fields.' (Cerf et al., 1993, p. 3).

Ten years later and based on a decade of practical experience of a host of studies, this program morphed into the 'cyberinfrastructures' research program. (We will address this later in this chapter).

On the other hand, also around 1990, US and other national policy makers began exploring ways to obtain benefits for society at large from adding services on top of the Internet. Such visions were presented in a *Bluebook* entitled *Grand Challenges: High-Performance Computing and Communications*, published by the White House Office of Science and Technology Policy (OSTP) in 1991:

> 'In addition to serving the needs of the scientific and research communities, the NREN [National Research and Education Network] will provide valuable experience necessary for the successful development of a broader, privately-operated national information infrastructure. Such an infrastructure would allow consumers, businesses, and schools and government at all levels to share quality information and entertainment when and where they want it at a reasonable cost.' (OSTP, 1991, p. 17).

Based on these ideas, and primarily at the initiative of Senator Al Gore, the US Congress on 9 December passed the *High Performance Computing Act of 1991*, which foresaw the development of 'an information infrastructure of data bases, services, access mechanisms, and research facilities available for use through the Network [i.e., the Internet]' (US Congress, 1991, § 3.1.C).

This initiative received further momentum during the Clinton administration (1992-2001). As one of its first measures in this context, it created, in 1993, the Information Infrastructure Task Force (IITF) consisting of high-level representatives of the federal agencies that played a role in advancing the development and application of information technologies. Tasked to articulate and implement the Administration's vision for the 'National Information Infrastructure' (NII), it quickly published an *Agenda for Action* outlining the Administration's vision of NII (IITF, 1993). Here, the notion of 'information infrastructure' was discussed in some detail:

> 'The phrase "information infrastructure" has an expansive meaning. The NII includes more than just the physical facilities used to transmit, store, process, and display voice, data, and images. [...] [B]eyond the physical components of the infrastructure, the value of the National Information Infrastructure to users and the nation will depend in large part on the quality of its other elements:
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> - The information itself, which may be in the form of video programming, scientific or business databases, images, sound recordings, library archives, and other media. Vast quantities of that information exist today in government agencies and even more valuable information is produced every day in our laboratories, studios, publishing houses, and elsewhere.
> - Applications and software that allow users to access, manipulate, organize, and digest the proliferating mass of information that the NII's facilities will put at their fingertips.
> - The network standards and transmission codes that facilitate interconnection and interoperation between networks, and ensure the privacy of persons and the security of the information carried, as well as the security and reliability of the network.
> - The people largely in the private sector who create the information, develop applications and services, construct the facilities, and train others to tap its potential. Many of these people will be vendors, operators, and service providers working for private industry.' (IITF, 1993, pp. 7 f.).

That is, the NII was conceived of as a set of *services* providing content ('the information itself') by means of the facilities of the Internet and concomitant software and protocols.

Note that the 'information infrastructure' might as well have been conceived of and termed 'information superstructure', in as much as what was talked about were service facilities to be erected upon the infrastructure in the form of the Internet. From the point of view of computer network engineering, this would have made perfect sense. But the add-on facilities expected to be developed were probably called 'information infrastructure' because they were seen as service-providing utilities on par with water and power supplies and in order to distinguish them from those of the computing network (the Internet proper). Anyway, a distinction was introduced between the underlying structure of the Internet and the facilities that, running on this distributed platform, would provide ‘information content’, the ‘information infrastructure’.[6]

However, there is an inherent ambiguity with the term ‘information infrastructure’. What exactly is it meant to denote: form or content? Let us take the case of an ordinary city library. This can most certainly be referred to as part of the city’s ‘information infrastructure’ in that it, by giving free access to books, newspapers, magazines, etc., provides an ‘information’ service to the citizens of that city. In this case, what is the ‘information infrastructure’? Is it the collection, etc., or is it the classification scheme for managing the collection? Does the infrastructure change whenever new books are acquired or old books discarded? In the context of public policy discourse, in which the term ‘information infrastructure’ emerged, the distinction between form and content is of little or no concern. In that kind of context, a country’s railroad infrastructure is considered *as a whole*: tracks, rolling stock, station buildings, personnel, ticket sales, administrative procedures, all of it: the entire rail transportation industry. Similarly with a library: From the point of view of the ‘information infrastructure’ discourse, a library is seen as a unitary service facility: books, shelves, buildings, archives, staff, acquisition budgets, and lending procedures, all of it. In other words, from the point of view of public policy discourse, the ‘information infrastructure’ is *both* form and content. — But from the point of view of designing and managing it, a notion of ‘information infrastructure’ that conflates form and content makes little or no sense. Different design issues are at play: there is an issue of the design of a reasonably comprehensive and yet manageable classification scheme, and there is the different ‘design’ issue of selecting which books etc. to acquire. Of course, while distinctly different, these design issues cannot be completely separated. Acquisition policies are, for instance, constrained by the storage capacity of the library: meters of shelf-space or terabytes of server capacity. Similarly, the classification scheme (catalogue, index, shelf labels, etc.) has to match the variety of documents acquired. Still, while the issues cannot be *completely* separated, they are anyway distinctly different. — This ambiguity is inherent in the public policy discourse on ‘infrastructures’.

3 ‘Infrastructural inversion’

In the early 1990s, networked computing became practical reality. By the end of the 1980s, TCP/IP had become standard in practically all operating systems. Hence the issue of building services on top of the Internet was no longer merely a vision in public policy debates but was beginning to take shape, as exemplified by the experimental work initiated by the NSF in 1990 on the ‘national collaboratory’ and of course the World Wide Web (launched at CERN in December 1990).[7]

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[6] Brian Kahin (Harvard) and McGarty (MIT) both made attempts to distinguish explicitly between ‘network’, ‘architecture’, and ‘infrastructure’ (Kahin, 1990a; McGarty, 1991, 1992).

[7] Before the end of the 1990s, the term ’the Internet’ had also, by and large, replaced earlier terms such as ’the information superhighway’ (Kahin, 1997, pp. 184 f.). Likewise, in public policy discourse and in ordinary

A pioneering study of one of the first efforts to build a ‘collaboratory’ was undertaken by Leigh Star and Karen Ruhleder from 1991 to 1994 and was reported in a CSCW conference paper (1994) that was shortly after reworked into a journal article (1996). This study has been hugely influential, which can be seen from the fact that the two articles together have received more than 1,700 citations.[8] It has also, by virtue of the eminent role is has played in the subsequent infrastructure literature, contributed significantly to the confusion that is now obvious. We will therefore deal with it in some depth.

The study investigated the building of a communication and publishing system, the Worm Community System (WCS), which was meant to support the cooperative effort of the global community of biologists engaged in sequencing the gene structure and studying other characteristics of the nematode (roundworm) *Caenorhabditis elegans*: ‘The vision was of a kind of supra-laboratory stretched over the entire scientific community. The needs for both standards and customizable components were equally strong. The system development process also became an effort to bring together communities of practice with very different approaches to computing infrastructure’ (Star and Ruhleder, 1996, p. 112).

However, the WCS project ended in ‘ultimate failure’ (Star and Ruhleder, 1996, p. 112), not because the *C. elegans* community had no need for collaboration technology to support its widely distributed cooperative effort, but basically because the WCS lost out to competing computing services and technologies: ‘the WCS fits well the cognitive map of the scientist with respect to information: links between disparate pieces, graphical representations, layers of detail, etc. Yet relatively few worm biologists have “signed on” to WCS, even as the community itself is growing rapidly’ (ibid., p. 131). And the cause of the failure, according to Star and Ruhleder, was that the WCS in its design was a ‘closed system’. It could run only a very constrained selection of work stations and operating systems: ‘The World-Wide Web, on the other hand, can be accessed from a broad variety of terminals and connections, and Internet computer support is readily available at most academic institutions and through relatively inexpensive commercial services.’ (*ibid*.).[9]

As an ‘analytic framework’ to understand that experience and its failure,[10] Star and Ruhleder invoked the notion of ‘infrastructure’ as ostensibly used by Kling and his colleagues (they cite Kling and Scacchi, 1982; Jewett and Kling, 1991). But where Kling et al. had inverted the usual relationship between infrastructure and

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language in general, the term ‘information infrastructure’ has been replaced by the term ‘Internet’ as a general reference to the Internet (as defined by the Internet protocol suite (TCP/IP, etc.) and the underlying physical structure of cables and routers) *as well as* everything that has been put on top of it: electronic mail the World-Wide Web, the WWW indexing services (Google, Yahoo), the databases to which one can get access via these services such as Wikipedia, and the various ‘social media’.

[8] The 1996 article has received 1,480 citations (according to scholar.google.com, accessed December 2016).

[9] The second author of this chapter was involved in a similar —and similarly failed — attempt to build a dedicated communication and publishing system for European mathematicians (Schmidt and McAlpine, 1988).

[10] It is of course beyond the scope of this chapter to discuss the analysis of the case, but it should anyway be mentioned that Star and Ruhleder actually do not employ this ‘analytic framework’ in their analysis of the case; they instead apply a communication model developed by the cyberneticist anthropologist Gregory Bateson.

superstructure by shifting focus from the computing system to its practical organizational embeddedness and dubbed it 'infrastructure' while still maintaining the computing system as the 'focal' entity, Star and Ruhleder went much further. Their concern was stated quite explicitly:

> 'Most of us, in speaking loosely of infrastructure, mean those tools which are fairly transparent for most people we know about, wide in both temporal and spatial scope, embedded in familiar structures — like power grids, water, the Internet, airlines. That loose talk is perfectly adequate for most everyday usage, but is dangerous when applied to the design of powerful infrastructural tools on a wide scale, such as is now happening with "national information infrastructures". Most importantly, such talk may obscure the ambiguous nature of tools and technologies for different groups, leading to de facto standardization of a single, powerful group's agenda.' (Star and Ruhleder, 1996, pp. 113 f.).

The point seems to be that since 'information infrastructures', as envisioned in the discussions about 'collaboratories' and the NII of the early 1990s, would not merely provide elementary data communication conduits such as basic computing networks but also 'information' *content*, research would need to address the classification schemes and standards that, inexorably, are incorporated in networked computing facilities as soon as such facilities, as 'information infrastructures', provide content. Hence, 'infrastructures' could no longer be conceived of narrowly as large-scale technical installations. It was, rather, necessary to shift focus to take into account issues as potentially problematic, politically and socially, as classification schemes and standards. A narrow focus would be 'dangerous' because it would 'obscure' conflicts of interest and thus marginalize or suppress the concerns of less 'powerful' stakeholders. To shift focus, Star and Ruhleder argued for a reconceptualization of the very concept of 'infrastructure'. What they proposed was, citing what Geof Bowker shortly before had dubbed an 'infrastructural inversion' (Bowker, 1994, p. 235), 'a figure-ground gestalt shift'.

They begin their argumentation by raising a deliberately astonishing question: 'When is an Infrastructure?', citing Yrjö Engeström for the question 'When is a tool?' (1990, p. 175). Having argued that 'A tool is not just a thing with pre-given attributes frozen in time — but a thing becomes a tool in practice, for someone, when [!] connected to some particular activity', they went on to state that 'By analogy, infrastructure is something that emerges for people in practice, connected to activities and structures' (Star and Ruhleder, 1996, p. 112):

> 'When, then, is an infrastructure? Common metaphors present infrastructure as a substrate: something upon which something else "runs" or "operates," such as a system of railroad tracks upon which rail cars run. This image presents an infrastructure as something that is built and maintained, and which then sinks into an invisible background. It is something that is just there, ready-to-hand, completely transparent.
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> But such a metaphor is neither useful nor accurate in understanding the relationship between work, practice and technology. It is the image of "sinking into the background" that concerns us. Furthermore, we know that such a definition will not capture the ambiguities of usage referred to [when it is observed that] without a Braille terminal, the Internet does not work to support a blind person's communication. And for the plumber, the waterworks system in a household connected to the city water system is target object, not background support. Rather, following

> Jewett and Kling (1991), we hold that infrastructure is a fundamentally relational concept.[11] It [?] becomes infrastructure in relation to organized practices. Within a given cultural context, the cook considers the water system a piece of working infrastructure integral to making dinner; for the city planner, it becomes a variable in a complex equation. Thus we ask, *when* — not *what* — is an infrastructure.
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> Analytically, infrastructure appears only as a relational property, not as a thing stripped of use. Bowker (1994) calls this "infrastructural inversion," a methodological term, referring to a powerful figure-ground gestalt shift in studies of the development of large scale technological infrastructure' […].
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> *An infrastructure occurs when the tension between local and global is resolved*. That is, an infrastructure occurs when local practices are afforded by a larger-scale technology, which can then be used in a natural, ready-to-hand fashion.' (Star and Ruhleder, 1996, pp. 112, 114).

Thus 'inverted', 'infrastructure emerges with the following dimensions':

> [1] *Embeddedness*. Infrastructure is "sunk" into, inside of, other structures, social arrangements and technologies;
>
> [2] *Transparency*. Infrastructure is transparent to use, in the sense that it does not have to be reinvented each time or assembled for each task, but invisibly supports those tasks;
>
> [3] *Reach or scope*. This may be either spatial or temporal — infrastructure has reach beyond a single event or one-site practice;
>
> [4] *Learned as part of membership*. The taken-for-grantedness of artifacts and organizational arrangements is a *sine qua non* of membership in a community of practice […];
>
> [5] *Links with conventions of practice*. Infrastructure both shapes and is shaped by the conventions of a community of practice […];
>
> [6] *Embodiment of standards*. Modified by scope and often by conflicting conventions, infrastructure takes on transparency by plugging into other infrastructures and tools in a standardized fashion;
>
> [7] *Built on an installed base*. Infrastructure does not grow *de novo*: it wrestles with the "inertia of the installed base" and inherits strengths and limitations from that base […];
>
> [8] *Becomes visible upon breakdown*. The normally invisible quality of working infrastructure becomes visible when it breaks […]' (Star and Ruhleder, 1996, p. 113).

On this conception, the word 'infrastructure' is not used for large-scale technical installations, nor is it — as in public policy discourse — used for such installations *in their capacity of providing* a support service, but is rather used for the *integration* of resources in 'local practices'.

The argument is muddled, however, and needs unpacking. Several distinctly different lines of reasoning are entwined: (1) the concept of 'infrastructure' is a '*relational*' concept; (2) 'infrastructure' '*emerges*' as the result of a 'gestalt shift'; (3) technical resources 'become', 'occur', or 'emerge' as 'infrastructure', and can only be considered as such when enacted as part of 'organized practices'; and (4) different practices, different conceptions of infrastructure. What makes the argument

[11] At this place in the first version of their article, Star and Ruhleder (1994, p. 253) boldly stated 'that infrastructure is [!] fundamentally and always a *relation*, never a thing'. But it is incomprehensible to say that 'an infrastructure *is* a *relation*, not a thing'. On one hand, when we refer to something as an 'infrastructure', we are referring to something *in* its relation to something else. On the other hand, it is surely the *concept* of 'infrastructure', not the railroad system or the water system, that is 'relational' in that it (logico-grammatically) presumes some 'superstructure'.

muddled is, primarily, that these propositions are implicitly taken to be identical, which they obviously are not. Let us consider them in turn.

First, Star and Ruhleder argue that 'infrastructure appears only as a relational property, not as a thing stripped of use'. The concept of 'infrastructure' should not simply be understood as a notion of large-scale technical artifacts but as a 'fundamentally relational concept': 'It becomes infrastructure in relation to *organized practices*', that is, in as much as 'it' from the point of view of some (identifiable) 'organized practices' 'sinks into an invisible background'. In other words, something — *anything*, really — is an 'infrastructure' if it is in such a relation to something else that it serves the function of a resource that is routinely and unproblematically taken for granted: 'It is something that is just there, ready-to-hand, completely transparent'.

Now, it is (logico-grammatically) indisputable that something cannot be said to be an 'infrastructure' without its being an infrastructure *of* something else, just as something cannot be said to be 'supportive' without being supportive of something else or 'a means' without being a means for some end. One could thus also say that 'infrastructure' is a transitive noun. To that extent, the notion of a 'relational concept' is clear enough, although it is a rather overwrought way of expressing the obvious.

Second, there is a sense in which one can say that, when applying a figure-ground gestalt shift, one makes what was the ground 'emerge' as focus. Thus, one may say that when one shifts attention from the computing system to the organized practices supporting it, as did Kling et al., one thereby makes these otherwise taken-for-granted phenomena 'emerge'. Thus, one may say with Star and Ruhleder that 'infrastructure emerges', as a result of inversion' (1996, p. 113). But infrastructures 'emerge' only in that they become objects of attention and, in that particular sense, 'visible'. In other words, the gestalt shift is an analytic move. It is not the ground that shifts; it is *the analyst's attention*. Nor is it the infrastructure that 'emerges' or resources that 'become' infrastructure; it is the analyst who reconceives his or her object of attention. There is surely a temporal dimension to the analyst's shift of attention but not to something's being infrastructure. Does the moon 'emerge' from the sky when an astronomer trains her telescope on it? The talk about the ground emerging as a focus is ultimately an elaborate way to call for the study of the mundane or ordinary — a call that is absolutely key for CSCW — but at the same time not itself revolutionary for CSCW or for the study of practice (and by extension what practitioners themselves are focusing on) within CSCW. That said, the call has played an important and useful political role for justifying this kind research.

Third, Star and Ruhleder state that 'It [?] becomes [!] infrastructure in relation to organized practices'. If 'it' here refers to some technical installation, which in context seems the most likely interpretation, the proposition may mean different things: the installation is only ('it becomes') an infrastructure to the extent that it is incorporated into organized practices; *or* the technical installation is only ('it becomes') an infrastructure *when* actually used as such by organized practices. It is tautology to say that a technical installation is only an infrastructure to the extent that it is incorporated into organized practices. If human civilization ceased to exist, mechanical or electronic structures would not be infrastructures, just as tools would not be tools but just material objects. It may be appropriate to remind us that a technical installation is only an infrastructure to the extent that it has been incorporated into organized practices, but it is a source of confusion to talk about tools and infrastructures as having a temporal dimension. But while it is tautology to say that a chair is only a chair for a life form for which sitting in chairs is a routine occurrence, it is nonsense to say, following Engeström, that the chair is only a chair *when* occupied and thus ceases to be a chair *when* it is not being used, e.g., while its owners are absent or asleep in their beds. In the same way, a hammer does not cease to be a hammer *when* lying on the workbench or in the tool box or *when* it is being manufactured or is on display in the hardware store. A hammer of course ceases to be a hammer when melted as scrap in a steel plant, but apart from that, 'tool-ness' does not have a temporal dimension. Being a tool is not a process or an activity; it does not have duration. The question 'When is an Infrastructure?', while it may serve to direct attention to the need to study instances of actual practice, is ultimately, unintelligible.

Fourth, consider again the proposition, 'It becomes infrastructure in relation to *organized practices*'. There is a third possible interpretation, namely, that the given installation is only an infrastructure for the particular organized practices by which it is a taken-for-granted resource, in contrast to organized practices that, for instance, build or maintain it. It makes obvious sense to say that a technical installation is only an infrastructure 'in relation to organized practices'. Notice, however, that the notion of a "relational" concept here is used differently than in the sense discussed above (the infrastructure/superstructure relation), namely in the sense that the identity and extension of the infrastructure is determined by ('in relation to') certain organized practices that thereby stand as the 'focal' entity, the unit of analysis (the role played by the 'focal' computing system in Kling et al.). — But it is another source of confusion to reinterpret 'in relation to' as '*relative to*'. To take the water system example: 'Within a given cultural context, the cook considers the water system a piece of working infrastructure integral to making dinner; for the city planner, it becomes a variable in a complex equation' (Star and Ruhleder, 1996, p. 113). Here, the water system is considered an infrastructure for the cook ('within a given cultural context'), whereas for the city planner it is a parameter in the overall planning task (and presumably for the plumber an artifact to maintain or reconfigure). On that view, we cannot talk about the water system as an infrastructure spanning these *different* practices. But that is of course a completely arbitrary conceptual imposition. The simple fact that citizens of all stripes, consumers, planners, technicians, etc. are able to engage in sensible debates about the water system or the power system is simply ignored. While the cook considers the water system 'a piece of working infrastructure', the city planner in her work surely conceives of the contemplated extensions to the water system as extensions to the *same* water supply infrastructure (next to the power and transportation infrastructures), just as the plumber, in implementing some of the local extensions, considers those pipes and fittings as elements in the *same* infrastructure. The water system is simply ordinarily conceived of as *one* infrastructure, by virtue of the fact that it is a (large) system of hierarchically configured components that are mechanically connected and designed to work in a reasonably dependable causal manner (ensuring the flow of water). That is, the system has functional unity. It is thus the same system they are dealing with; they are just doing different things with it. Their practices are quite different but nonetheless interlinked by the functionally unitary system. However, by imposing a radically 'relational' (or rather *relativistic*) notion of 'infrastructure', Star and Ruhleder officially rule out any talk of the water system as an infrastructure for practitioners other than water consumers.

Let us summarize. To a large extent, the muddled argument offered by Star and Ruhleder is surely simply an indication that this was the very first attempt to formulate a research program for investigating computer-based information infrastructures spanning distinctly different work practices. The 'infrastructural inversion' was proposed as a way of foregrounding or focusing on the practices and conflicts of interest that might otherwise have remained unrecognized or, as they preferred to express it, 'invisible'. But it does so at a high cost. The program outlined by Star and Ruhleder — predicated on the notion that 'infrastructure' is a 'relational' or relativistic or even a temporal concept — only seems to work because it makes a virtue of the ambiguity afforded by entwined lines of argument. The result is ambiguity in almost all sentences in which the word 'infrastructure' occurs in the very text by Star and Ruhleder (1996). If it is accepted that 'infrastructure appears only as a relational property, not as a thing stripped of use' (p. 112), or that 'Information infrastructure is not a substrate which carries information on it, or in it, in a kind of mind-body dichotomy' (p. 118), what then is meant by 'infrastructure' in expressions such as 'a large-scale information infrastructure' (pp. 112, 131), 'very large scale systems such as the US National Information Infrastructure' (p. 117), 'large-scale information and communication infrastructures' (p. 129), or 'computing infrastructures, including gophers, FTP sites, etc.' (p. 131)? — Having deprived themselves and the rest of us of using 'infrastructure' in the ordinary sense, they obviously cannot cope without using it in exactly that way. The same semantic oscillation can be observed in Bowker and Star's *Sorting Things Out* (1999). For example, take the statement tghat '[Infrastructural] inversion is a struggle against the tendency of infrastructure to disappear (except when breaking down)' (p. 34). In which sense of 'infrastructure' can it said to be able to 'disappear' and 'break down'? Using the term in both senses — in the ordinary as well as in the 'inverted' sense — is a source of the ambiguity that hobbles infrastructure studies. If we, following Star and Ruhleder as well as Star and Bowker use 'infrastructure' to denote some technical installation *in its being* 'transparent', taken-for-granted, 'disappeared', or 'invisible', then we are at a loss for words to describe that which 'emerges' when 'breakdown' occurs, namely, that installation as an infrastructure in the ordinary sense.

Worse, however, as a result of the 'inversion', the term 'infrastructure' can be used to mean just about anything. This licenses not just semantic drift but a conceptual landslide. For example, according to Star and Bowker 'information infrastructures' 'provide the tools — words, categories, information processing procedures — with which we can generate and manipulate knowledge' (Star and Bowker, 1995, p. 41). Words, categories, and procedures as 'infrastructures'? This is to stretch the notion of 'infrastructure' to the breaking point. This conceptual slide becomes even more obvious in the extensive discussion devoted to 'infrastructural inversion' in Bowker and Star's *Sorting Things Out* (1999, pp. 33). Presented as an example of 'Scientific inversions of infrastructure', Bowker and Star mention the collection *The Right Tools for the Job: At Work in Twentieth-Century Life Sciences* (edited by Clarke and Fujimura, 1992).

> 'The purpose of this volume was to tell the history of biology in a new way – from the point of view of the materials that constrain and enable biological researchers. Rats, petri dishes, taxidermy, planaria, drosophila and test tubes take center stage in this narrative. The standardization of genetic research on a few specially-bred organisms (notably drosophila) has constrained the pacing of research, and the ways the questions may be framed, and has given biological supply houses an important, invisible role in research horizons. While elephants or whales might answer different kinds of biological questions, they are obviously unwieldy lab animals. While pregnant cow's urine played a critical role in the discovery and isolation of reproductive hormones, no historian of biology had thought it important to describe the task of obtaining gallons of it on a regular basis. Adele Clarke (1998) puckishly relates her discovery, in the memoirs of a biologist, of the technique required to do so: tickle the cow's labia in order to make her urinate. A starkly different view of the tasks of laboratory biology emerges from this image. It must be added to the processes of stabling, feeding, impregnating, and caring for the cows involved. The supply chain, techniques and animal handling methods had to be invented along with biology's conceptual frame; they are not accidental, but constitutive. ¶ Our infrastructural inversion with respect to information technologies and their attendant classification systems follows this line of analysis.' (Bowker and Star, 1999, p. 36).

In the quoted passage, are 'rats, petri dishes, taxidermy, planaria, drosophila and test tubes' the (inverted) 'infrastructure'? Does 'infrastructure' then simply mean the infinite assortment of *stuff* upon which a practice, any practice, relies? If so, 'infrastructural inversion' then simply means focusing on the (mundane) practicalities of a given practice: methods, techniques, materials, tricks of the trade from the point of view of the history of their development and integration. Such a focus is of course most useful for the purposes of studying the mundane practicalities of cooperative work, but do we have call what we thus focus on '*infrastructure*' and thereby lose the ability to talk clearly and systematically about — exactly! — large-scale technical installations? More than that, do we, in order to be able to focus on the practicalities of work in a world of large-scale technical installations, have to abandon what is *specific* to large-scale technical installations, as the semantic conflation implied by the inversion would suggest? We suggest that the very methodological move of 'infrastructural inversion' tends to spin out of control.

The 'infrastructural inversion' is a source of considerable confusion and presses researchers into contortions where anything (not just petri dishes and bovine urine but also words and categories) that is used as resources in some sense in an organized practice can be seen as an *infrastructure* for just that practice. But at the same time, and as a result of the advocated 'inversion', Star and Ruhleder are themselves unable to apply that language to their case. The 'decentralized technologies' they address in their study and that motivate their conceptual analysis are characterized by spanning multiple and often very different practices. The setting they studied was, in their own words, characterized by 'communities of practice with very different approaches to computing infrastructure', 'very different practices, technologies and skills', and so on. Given that, and given the 'relational' conception they advocate (something is only an 'infrastructure' 'in relation to' particular 'organized practices'), there is no reason at all for them to even try to use the notion of 'infrastructure' in analyzing the case. For *which* practice is what they characterize as an 'infrastructure' in fact an infrastructure (in the inversed sense)? What is the focal entity by means of which the scope of the infrastructure is defined? In short, Star and Ruhleder's proposed interpretation of the concept of 'infrastructure' cannot be applied to the kind of problem it was originally designed to handle.

Now, a less radical relational notion of 'infrastructure' may be possible. Different practices typically rely on different infrastructures. The chef, in his work, relies on, *inter alia*, the water system that yields clean running water but also electrical power for cooling and heating food items, deliveries and removal of refuse, and so on just as the city planner in her planning work relies on resources such as drawing archives, and the plumber in his maintenance work relies on the resources such as tools and materials at hand in his van. — Leigh Star may have been suggesting just that a few years later when she argued that the ordinary understanding of infrastructure gets complicated 'when one begins to investigate large-scale technical systems in the making, or to examine the situations of those who are not served by a particular infrastructure':

> 'For a railroad engineer, the rails are not infrastructure but topic. […] One person's infrastructure is another's topic, or difficulty. […] So, within a given cultural context, the cook considers the water system as working infrastructure integral to making dinner. For the city planner or the plumber, it [!] is a variable in a complex planning process or a target for repair:' (Star, 1999, p. 380).

That is, one group's support structure is another group's everyday work of design, maintenance, and upgrade (Ribes and Finholt, 2007). This much is clear. This pragmatist definition of 'infrastructure' is sufficient to forestall endless discussions of 'what is really infrastructure' and instead directs the research to examine the intersection of multiple organized practices: what is supporting the work of somebody and who is sustaining those relationships (Ribes and Lee, 2010)? But notice the role the innocuous pronoun 'it' plays in the passage by Star quoted above: 'it' ('the water system') is now referred to as a self-evident entity with well-defined boundaries. The role played by the ordinary notion of 'infrastructure' has now been taken over by the concept of 'system'. Of course, in the case of a water system, identifying and delimiting the focal entity poses no problem; but what is the 'system' when we are trying to investigate 'decentralized technologies' used in multiple organized practices across wide geographical distance? — We have been taken on a very long detour, only to arrive back where we started. What is the criterion of determining the focal entity?

Finally, a question is pleading to be raised: Why this insistence on taking the ordinary term 'infrastructure' through these inversion somersaults? One answer is that Star and Ruhleder — as well as the rest of us — are struggling to understand and articulate a relation between our practices and our technical artifacts that is particularly acute when it comes to large-scale distributed systems based on computing technology. For while computational artifacts, such as spreadsheets and word processors, can be compared to and largely understood as machines, on par with power looms and automatic gear shifts, and while complex computational artifacts such as airline reservation systems and accounting systems can be compared to and understood as machine systems, on par with newspaper printing presses, it is difficult to do so for the kinds of machinery that are explored here. The complex computational artifacts that are being addressed here span local practices, typically with diverging standards and policies of data curation and different preferences for data sharing, but they also, and most importantly, incorporate, in computational form, standardized coordinative protocols such as data representation metrics, notations, classification schemes, etc. Hence the insistence that 'information infrastructures' are not just computers connected with cables and routers but somehow also encompass standards and policies and practices of their maintenance. This concern is then further strengthened by the fact that these complex computational artifacts often evolve over time in an open-ended process. The ordinary use of the term 'infrastructure', especially as used in public policy discourse, seems to meet these concerns quite well, as it can be used to express a complex of 'the technical' and 'the social' (as in 'the city's transportation infrastructure'). The problem with this, in the context of the development of computing technologies for these kinds of application, is that it, by conflating technical artifacts and the practices in which they are used, forestalls the necessary clarity with respect to *what* is to be designed for *which* practices. It can be (and has been) useful to use terms like 'man-machine system', 'human-computer interaction', 'socio-technical system', 'socio-materiality', and so on, so long as and *only* so long as we are still able to distinguish and articulate the artifact to be designed from the setting in which it is used. And for that purpose, we need to be able to distinguish, as clearly as possible, the *computational representation* of objects, procedures, protocols, notations, classifications, etc. from the objects, procedures, protocols, notations, classifications, etc. of the *practices* in which the computational representations are applied. If we use the same word, e.g., 'infrastructure', for both aspects, we will have great difficulties making progress (for a more elaborate discussion, cf. Schmidt and Bansler, 2016).

Subsequent efforts to apply and further develop the concept of 'infrastructure' have provided ample demonstration of these difficulties, as the ambiguities and contradictions that have beset the 'infrastructure' discourse from the very beginning continue to hamper us at every other turn.

4 'Information infrastructures' 2.0

Over the last two decades an ambitious attempt to develop a systematic and comprehensive approach to 'information infrastructures' has been undertaken by a network of (primarily Norwegian) researchers comprising Ole Hanseth, Eric Monteiro, Gunnar Ellingsen, and many others (e.g., Hanseth et al., 1996; Hanseth and Monteiro, 1998; Hanseth and Lundberg, 2001; Rolland and Monteiro, 2002; Ellingsen and Monteiro, 2003; Hanseth and Lyytinen, 2004; Ellingsen and Røed, 2010; Hanseth and Lyytinen, 2010; Monteiro et al., 2013).

In all this, Hanseth et al. draw upon and try to unite the 'infrastructure' movements discussed above, on the one hand, the public policy discourse on 'information infrastructures' (e.g., McGarty, 1992; Smarr and Catlett, 1992) and the related information systems literature on organizational 'information infrastructures' (e.g., Weill and Broadbent, 1998), and on the other, the 'inversion' tradition initiated and represented by Kling et al. and Star et al. In doing so, they try to develop a unified conceptualization informed by the 'actor network theory' of Michel Callon and Bruno Latour.

All in all, this tradition has resulted in a very rich body of literature that bridges from ethnographic studies to conceptual work and tries to address a very diverse spectrum of 'infrastructures', from the Internet at large to domain-specific 'infrastructures' to 'infrastructures' servicing particular local practices, and the research questions driving the research reach from the policy and management issues of identifying opportunities and anticipating impact to issues of designing and implementing large-scale technical facilities under conditions of practical contingencies. In the course of its development, this tradition has produced a range of in-depth studies of the role of large-scale computational infrastructures in complex cooperative work settings, such as studies of corporate Electronic Data Interchange (EDI) implementations (Hanseth and Monteiro, 1997; Hanseth and Braa, 2001); Enterprise Resource Planning (ERP) systems (Hanseth and Braa, 2001; Hanseth et al., 2001); electronic patient record (EPR) systems and similar IT-based healthcare systems in a wide spectrum of clinical practices (Hanseth and Lundberg, 2001; Ellingsen and Monteiro, 2003, 2006; Ellingsen and Røed, 2010; Aanestad and Jensen, 2011; Larsen and Ellingsen, 2012; Silsand and Ellingsen, 2014); surveyor support in a maritime classification company (Rolland and Monteiro, 2002; Monteiro and Rolland, 2012); IT support for environmental monitoring in subsea oil and gas production (Parmiggiani et al., 2015), and so on.

The overarching conceptualization of 'information infrastructures' is that they are characterized by developing in a way entirely different from other technical systems, in that they are a characterized by being 'enabling, shared, open, socio-technical, heterogeneous, and [an] installed base' (Hanseth and Monteiro, 1998, p. 10), or a '*shared, evolving, heterogeneous installed base of IT capabilities among a set of user communities*' (Hanseth and Lyytinen, 2004, pp. 207, 208, 213). That is, an 'information infrastructure' cuts across local practices; it is not strictly speaking *designed*, or only designed embryonically, but is rather an evolving 'installed base' encompassing a vast number of technical components of different kinds. In exploring these issues, this tradition highlights the tension between standardization and flexibility, the tension between the global and the local, and the tension between the inertia of the installed base and the dynamically changing technologies and practices that depend on that installed base.

This impressive portfolio of studies contributes much needed studies of economically vital collaboration technologies in actual use and provides a critical corrective to the main-stream program in CSCW that focuses on supporting small-group interaction (Monteiro et al., 2013).

There is, however, a deep ambiguity in its use of the term 'infrastructure'. In accordance with their original and overriding commitment to public policy and managerial discourses concerning 'information infrastructures', Hanseth et al. use the term 'information infrastructures' in more or less the same way as it was used when the very notion was launched in the US (with a big bang) around 1990. In fact, in their widely cited paper entitled 'Developing Information Infrastructure' (1996), as well as in their unpublished but also widely cited book manuscript (1998, pp. 45-49), Hanseth et al. followed McGarty's characterization of the concept of 'infrastructure' (McGarty, 1992), remarking that he 'gives a rather extensive and precise definition of [information infrastructures] with the following keywords: shareable, common, enabling, physical embodiment of an architecture, enduring, scale, and economically sustainable' (Hanseth et al., 1996, p. 409; Hanseth and Monteiro, 1998, pp. 45-49), just as they joined Smarr and Catlett (1992) in conceiving of 'information infrastructures' as 'computer networks *with associated services*' (Hanseth et al., 1996, p. 409; Hanseth and Monteiro, 1998, p. 43 (Emphasis added)). That is, they used the term 'information infrastructures' as it was used in public policy discourse: a large-scale technical facility conceived of, from the point of view of society at large, as an information-provisioning *service*.

In accordance with this perspective, they 'do not see an infrastructure as some kind of purified technology, but rather in a perspective where the technology cannot be separated from social and other non-technological elements, i.e. as an actor-network' (Hanseth and Lundberg, 2001, p. 349). In other words, on this view 'information infrastructures' 'are not pure technical artifacts, but complex heterogeneous actor-networks' (Hanseth and Braa, 2001, p. 263). In the context of public policy discourse and, related to this, in the context of management studies and social studies of technology, this is sufficiently clear. In fact, this use of the term 'infrastructure' is in accordance with the ways it is ordinarily used. Ambiguity, however, wells up nonetheless, and does so in three ways.

First, there is a perennial problem with the criterion of inclusion. Hanseth and Lyytinen, for instance, echo the notion of 'information infrastructures' as defined by Hanseth and Monteiro (1996) and reiterated by Hanseth and Lyytinen 2004, but then also distort it, when they state that

> 'we will define an [Information Infrastructure] as *a shared*, *open* (and unbounded), *heterogeneous* and *evolving* socio-technical system (which we call *installed base*) consisting of a set of IT

capabilities[12] and their user [!?], operations and design communities' (Hanseth and Lyytinen, 2010, p. 4).

Here the concept of 'information infrastructure' begins to stumble. In so far as an 'information infrastructure' is conceived of as a shared, open, heterogeneous, and evolving socio-technical system consisting of a set of IT capabilities *and* their operations and design communities, we are still within the framework of the public policy discourse or the organizational IT management discourse. We are supposedly still talking about an 'infrastructure' as a *support* structure. But when the authors include 'user communities' as part of the 'infrastructure', is the 'infrastructure' now supporting itself, levitating as if by magic, or is it doing self-service, perhaps? The concept is no longer taken as 'relational', as a concept that *presumes* a superstructure for which it provides support, but is rather taken as a concept of *a thing in itself*, as synonymous with, say, 'a socio-technical system'. — The tendency to use 'infrastructure' as synonymous with 'socio-technical system' is also visible in Hanseth and Lundgren's article on 'work oriented infrastructures' in a radiology clinic (2001):

> 'We also include in the infrastructure the institutionalized communication forms used: the request/response communication, the daily meetings, and the ad-hoc conversations. This infrastructure is supported by a more general one consisting of transporters, trolleys, shelves, tables, personal callers, phones and fax machines, secretaries, other support staff (medical assistants), PACS, RIS and their computer and network infrastructure […], etc.' (Hanseth and Lundberg, 2001, p. 355)'[13]

Including 'ad hoc conversations' is no slip of the pen. It is a deliberate move:

> 'Seeing orders, reports, images, meetings and ad-hoc conversation as infrastructure is in conflict with a narrow, and rather conventional, understanding of infrastructure as just material structures like roads, cables (for telephone or electric power transmission), water pipes, etc. But we want to look at the orders and reports as well as the immaterial phenomena such as meetings and conversations as infrastructure because
>
> - they constitute together the foundation upon which the collaboration and division of labour between radiologists and clinicians rest,
> - the different elements are linked together in the sense that each of them is based upon the existence of the others, and the role of each is defined in terms of how this role fits together with and links with the other elements' roles.' (Hanseth and Lundberg, 2001, pp. 355).

Yes, there is no reason to restrict the use of the term 'infrastructure' to 'material structures'. In fact, as argued, in ordinary language we do not impose such a restriction. It is certainly legitimate to use the term 'infrastructure' to denote not only a material structure but also the support offered to another system by an organized effort *by means of* that structure, that is, to talk about a socio-technical system *as a service*. This is how the term is ordinarily used in public policy discourse and the rational point of saying that the concept of 'infrastructure' is 'relational'. And it is,

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12 'We denote an IT capability as the possibility and/or right of the user or a user community to perform a set of actions on a computational object or process. […] IT capabilities are viewed here s*olely as engineered artifacts*' (Hanseth and Lyytinen, 2010, p. 2).

13 PACS: Picture Archiving and Communication System; RIS: Radiology Information System.

of course, an open issue whether it is helpful to talk about the socio-technical setting of a particular cooperative work practice as an 'infrastructure', rather than simply a 'material setting' or, say, an 'ordering system'. But without clarity about the point of using the very term 'infrastructure' and about the criteria of what is included and what is not, the use of the concept of 'information infrastructure' is dodgy and easily ends in a vicious circle. — So, are cables and routers and the electronic circuits of running software 'infrastructures' *in the same sense* as digital images or stacks of paper with orders? And are these material structures 'infrastructures' *in the same sense* as, for instance, 'immaterial phenomena' such as meetings or conversations? Are they simply 'infrastructures' because they *in some sense can be said to be* involved in the cooperative effort in question? Would that not be to substitute metaphor for concept? Imagery and orders, for instance, may certainly be said to be part of the infrastructure of radiology work but they can hardly be said to evolve in the same sense as, say, an EPR system. What is gained by transforming the concept of 'infrastructure' into an abstract category on par with, for instance, 'resource' or 'useful stuff', and conceiving of 'the motley of artifacts and materials of our lives as instances of such an all-encompassing category' (Schmidt and Bansler, 2016)?

Second, in order to avoid the impending ontological avalanche, clear criteria of inclusion and exclusion are necessary. Describing some facility as an 'infrastructure' is an analytic operation: We highlight the *specific* relation of dependence/support, and in so doing we include under 'infrastructure' that which is considered to be *specific* to the relation from the point of view of what is supported (a superstructure of applications or society at large or a particular cooperative work arrangement). The concept of 'infrastructure' should be used with great care. Thus, in the case of the cooperative work arrangement of radiology clinic, it might be relevant to include orders, reports, images, etc. as 'infrastructure', in so far as these types of artifact are essential to the specific practices of the radiological clinic. But are these ad hoc conversations *specific* to these practices? Can something as transitory as ad hoc conversations be said to be part of an 'infra*structure*', in any sense of the word? Does it make sense to include under 'infrastructure' phenomena that occur contingently and sporadically? It is, we submit, an analytic problem of the first order to determine what is included as essential to this particular setting, and what is not.

And third, these ambiguities and terminological slides are perhaps rooted in the very concept of 'infrastructure' as appropriated by Hanseth et al. from the public policy discourse of the early 1990s, from which Hanseth et al., as mentioned, derived their conception of 'information infrastructure' as a 'shared, evolving, heterogeneous installed base of IT capabilities'. The exemplars discussed in the texts founding this tradition are the Internet (in which Hanseth et al. include email and the WWW) as well as EDI, health care systems, etc. (Hanseth et al., 1996; Hanseth and Monteiro, 1998; Hanseth and Lyytinen, 2004, 2010). Let us consider the Internet. In which sense, can it be said to be 'evolving' and 'heterogeneous'? This is not at all evident. What are the criteria of sameness (and hence also change) presumed when talking about evolution and heterogeneity? In the context of a technical discourse (as opposed to public policy discourse), the criterion of inclusion would be the suite of Internet protocols (TCP/IP, etc.), so that machines (hosts, routers, laptops, mobile devices, printers, CNC machines…) running TCP/IP and thus having an IP-number are included. That, we submit, would make the Internet very well defined and not heterogeneous at all. The same would apply to email or the WWW. Defined by protocols such as POP, IMAP, and SMTP, and HTTP and HTML, respectively, these are well-defined infrastructures. Of course, protocols may change and new protocols may be added, but this is hardly qualitatively different from updating any other multi-user system.

According to Hanseth et al., information infrastructures are 'heterogeneous' in that they 'are more than "pure" technology, they are rather *socio-technical networks*'. Thus, 'Infrastructures are heterogeneous concerning the qualities of their constituencies. They encompass technological components, humans, organizations, and institutions' (Hanseth and Monteiro, 1998, p. 43). Or in similar words, 'information infrastructures are at any moment of time *heterogeneous*: they contain components of multiple sorts — diverse technological components as well as multiple non-technological elements (individual, social, organizational, institutional etc.) that are necessary to sustain and operate the infrastructure' (Hanseth and Lyytinen, 2004, p. 215). The reason for this conception is the (unsurprising) observation that 'An information system does not work […] if not the users are using it properly' (Hanseth and Monteiro, 1998, p. 43). That is, the heterogeneity Hanseth et al. find in their studies is a manifestation of their methodological stance according to which they reject distinguishing between 'the technical' and 'the social'.[14] The heterogeneity is an artifact of their insistence on extending the notion of 'infrastructure' to include 'components of multiple sorts'. One result of this stance is that ambiguity is unrestrained. When they, for example, say that 'components are connected in complex ways and they change constantly' and that 'clean interfaces between layers of the architecture are critical', or when they talk about 'protocol stacks' and 'variations of heterogeneity as a result of the architectural layering' (Hanseth and Lyytinen, 2004, p. 215) —the scope of these observations is quite blurred. In the context of technical design, the ensuing ambiguity seems quite unwieldy.

In sum, then, the conceptual difficulties that emerge in this tradition seem to stem from trying to make the same conceptual apparatus bridge from a public policy discourse to management discourse to a technical design discourse.

5 'Cyberinfrastructures'

By the turn of the century, the movement to build 'information infrastructures' to support scientific research work had gained momentum. What had been but a vision when the plans for NSF's 'collaboratory testbed program' were drafted and debated in the early 1990s (e.g., Cerf et al., 1993), was now solid experience from a large

[14] 'Actor network theory views society as a completely interwoven socio-technical web. It consists of a highly heterogeneous network of actors, institutional arrangements, textual descriptions, work practices and technical artefacts' (Hanseth and Monteiro, 1997, p. 185).

number of testbeds and evaluation studies (for a very useful overview, cf. Finholt, 2003). To take stock of what had been achieved and what the prospects were, NSF published, in the course of the three years 2003 to 2005, about 30 workshop reports and similar studies on the experiences with building and using cyberinfrastructures in various scientific disciplines: Atmospheric Sciences, Biological Sciences, Chemistry, Earth Sciences, Engineering Design, Engineering Research, Environmental Research, Geoscience, Humanities, Materials Research, Mathematical Sciences, Ocean Sciences, Physical Sciences, Polar Science, and Social Sciences.[15]

As part of this, quite impressive, assessment exercise, the term 'collaboratory' was superseded by the term 'cyberinfrastructure' and was thereby brought into line, terminologically at least, with the broader movement engaged in building 'information infrastructures'. The term 'cyberinfrastructure' was coined in the early 2000s by a 'Blue Ribbon' panel formed by the NSF on the future of scientific computing in a publication colloquially referred to as the 'Atkins Report' (Atkins et al., 2003). With the added push of funding from the NSF specifically for research related to 'cyberinfrastructure', the term grew in prominence and subsequently joined the developing 'infrastructure' lexicon.[16]

The main push for 'cyberinfrastructure' research at that time, and still today although to a lesser degree, was for the development and use of high-performance computing (fast internetworked) and complementary applications and services for scientific work. At this time, however, the notion of 'infrastructure' was closer to the original notion of a technical infrastructure in that it is actually a material substrate:

> 'The charge to the Panel is premised on the concept of an advance infrastructure layer on which innovative science and engineering research and education environments can be built. […] The newer term *cyberinfrastructure* refers to infrastructure based upon distributed computer, information and communication technology. If *infrastructure* is required for an industrial economy, then we could say that *cyberinfrastructure* is required for a knowledge economy' (Atkins et al., 2003, p. 5).

The *Atkins Report* did mention in passing the importance of investigating sociological aspects of cyberinfrastructure for success: 'Much of the effort under way to use cyberinfrastructure for collaborative research is not giving adequate attention to sociological and culture barriers to technology adaption that may cause, failure, even after large investments' (Atkins et al., 2003, p. 12). Nevertheless, social aspects were not explicitly called out as part of the cyberinfrastructure:

> 'The base technologies underlying cyberinfrastructure are the integrated electro-optical components of computation, storage, and communication that continue to advance in raw capacity at exponential rates. Above the cyberinfrastructure layer are software programs, services, instruments, data, information, knowledge, and social practices applicable to specific projects, disciplines, and communities of practice. Between these two layers is the *cyberinfrastructure* layer

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[15] For an index, see http://www.nsf.gov/cise/aci/reports.jsp.

[16] It should be noted that there is a compatible and overlapping research program both in Europe and in the United States around the concepts of e-Research and e-Science (Jirotka et al., 2013), but as our focus here is on notions of 'infrastructure' per se, we do not address that literature here.

of enabling hardware, algorithms, software, communications, institutions, and personnel. This layer should provide an effective and efficient platform for the empowerment of specific communities of researchers to innovate and eventually revolutionize what they do, how they do it, and who participates.'(Atkins et al., 2003, p. 5).

But a few years later, the notion of 'cyberinfrastructure' underwent the same semantic slide we have already seen. In 2006 and 2007, the NSF sponsored two workshops bringing together prominent researchers interested in cyberinfrastructure (Edwards et al., 2007; Cummings et al., 2008). The direct impact of these workshops and resulting reports is open to debate; however, they are indicative of an almost simultaneous push forward in both the 'information infrastructure' and 'infrastructural inversion' approaches to cyberinfrastructure research.

In its understanding of the idea of 'cyberinfrastructure', the report *Understanding Infrastructure: Dynamics, Tensions, and Design*, written by Paul Edwards, Steven Jackson, Geof Bowker, and Cory Knobel (2007), draws explicitly on the work of Star and Ruhleder and defines 'cyberinfrastructures' as:

> 'the set of organizational practices, technical infrastructure and social norms that collectively provide for the smooth operation of scientific work at a distance. All three are objects of design and engineering; a cyberinfrastructure will fail if any one is ignored.' (Edwards et al., 2007, p. 6).

On this view, then, 'cyberinfrastructures' are a 'set of organizational practices, technical infrastructure and social norms'. Again, this is not quite intelligible. As we have seen, one can certainly, in the context of public policy discourse, talk of the 'transportation infrastructure' of a country, in reference to the technical infrastructure and the organization of its operation, since the scope of the entity is defined by the given social unit for which this entity is a resource ('country'). But in the case of 'cyberinfrastructures', how is 'scientific work' distinct from 'the set of organizational practices, technical infrastructure and social norms'? That is, there does not seem to be a social unit — 'scientific work' — of which it makes sense to say that it relies on a 'set of organizational practices, technical infrastructure and social norms'.[17] Here the 'infrastructural inversion' seems to have lost sense of what is what. Nevertheless, the Edwards et al. report pushes slightly past earlier framing of infrastructure as 'relational' and as existing 'in relation to organized practices' by bringing back in the notion of 'systems':

> 'The growth, consolidation, and splintering phases of the historical model mark a key transition from homogeneous, centrally controlled, often geographically local systems to heterogeneous, widely distributed networks in which central control may be partially or wholly replaced by coordination.
>
> In general, and specifically in the meaning of the cyberinfrastructure framework, *infrastructures are not systems*. Instead, they are networks or webs that enable locally controlled and maintained systems to interoperate more or less seamlessly. […] Thus we define a spectrum running from systems (centrally organized and controlled) to networks (linked systems, with control

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[17] Edwards et al., mainly discuss the notion of 'social norms' in terms of the different norms of different scientific domains with respect to data sharing, but there is no explicit discussion about norms as part of what defines 'cyberinfrastructures'.

> partially or wholly distributed among the nodes) to webs (networks of networks based primarily on coordination rather than control).' (Edwards et al., 2007, pp. 11 f.).

That is, 'infrastructures' are not 'systems', for they are constituted by 'coordination', as opposed to 'central control', but they are still conceived of as heterogeneous 'networks of systems', each having different control structures and stakeholders. Here, then, we see a shift whereby the notion of 'coordination', a hierarchy of coordination really, becomes central to the idea of 'cyberinfrastructure' and where 'infrastructures' are conceptually, though not geographically or politically, bounded by the notion of 'systems'. That is, in spite of the nod to Star and Ruhleder, the problem of identifying the focal entity that first Kling and then Star and Ruhleder tried to address (in different ways) is bypassed by Edwards et al. as they, ultimately, anchor the notion of 'cyberinfrastructure' in 'systems'. On one hand, 'cyberinfrastructures' are conceived of as 'organizational practices, technical infrastructure and social norms' and, on the other, as 'heterogeneous, widely distributed networks in which central control may be partially or wholly replaced by coordination'. In short, it was obviously as difficult for this report to pin down what was meant by 'cyberinfrastructure' as it was for the Atkins report.

Whereas the report by Paul Edwards et al. (2007), built upon the 'infrastructural inversion' approach, another NSF workshop, held soon afterwards with a different set of prominent researchers, namely Jonathon Cummings, Tom Finholt, Ian Foster, Carl Kesselman, and Katherine Lawrence, resulted in a report that represents another approach to studying 'cyberinfrastructure': *Beyond Being There: A Blueprint for Advancing the Design, Development, and Evaluation of Virtual Organizations* (Cummings et al., 2008). Researchers in this vein, like others before them, faced confusion about the conceptual separation between the notions of 'virtual organizations' and 'cyberinfrastructures'. The report opens by stating:

> 'A virtual organization (VO) is a group of individuals whose members and resources may be dispersed geographically and institutionally, yet who function as a coherent unit through the use of cyberinfrastructure (CI). A VO is typically enabled by, and provides shared and often real-time access to, centralized or distributed resources, such as community-specific tools, applications, data, and sensors, and experimental operations.' (Cummings et al., 2008, p. v)

The notion of 'cyberinfrastructure' as that which enables 'virtual organizations' to remain coherent is iterated several times, but at the same time the notion of 'cyberinfrastructure' itself remains rather hazy. In fact, despite the stated decisive role ascribed to cyberinfrastructures, the report does not define what is meant by 'cyberinfrastructure'. However, the report does go on to state that

> '[virtual organizations] may be known as or composed of systems known as collaboratories, e-Science or e-Research, distributed workgroups or virtual teams, virtual environments, and online communities.' (Cummings et al., 2008, p. v)

The definitions are rather circular since some of the terms that 'virtual organizations' are supposed to be 'known as', such as 'collaboratories' or 'e-Science', also happen to be used as *synonyms for cyberinfrastructures themselves*. In a way, like the term 'infrastructure' began to refer not only to the substrate but the superstructure (services included), 'cyberinfrastructure' began to be considered as not only that which supports 'virtual organizations' but in fact to *be* 'virtual organizations'.[18]

While both of these workshops and subsequent reports had different but overlapping antecedents, that is, US information sciences and US organization science, respectively, they also had shared interests in contextualizing the 'big iron' of high-speed computing in terms of socially situated use and actual work practices. This progression towards prioritizing social aspects was in part due to experiences in computing demonstrating that attending to organizational issues was critical to the success of the cyberinfrastructure mission in supporting science (Finholt, 2003; Finholt and Birnholtz, 2006; Foster and Kesselman, 2006). Socio-technical researchers, building in part on earlier work on collaboratories (Finholt and Olson, 1997; Finholt, 2002) and also on the work of Star and Ruhleder (1996) and Star (2002), were quick to heed the call to explore the concerns and social structures related to cyberinfrastructure (e.g., Karasti et al., 2006; Lawrence, 2006; Lee et al., 2006; Ribes, 2006).

Taking a Latourian turn, researchers 'followed the network' and found that, in order to understand cyberinfrastructures, the larger ecosystem of organizational formations and concomitant systems also needed to be studied (e.g., Pollock et al., 2007; Bietz et al., 2010; Monteiro et al., 2013; Ribes, 2014; Cohn, 2016).

However, despite the reasonableness of expanding the scope of cyberinfrastructure investigations to include the organizations that cyberinfrastructures both support and rely upon, the concept of 'cyberinfrastructure', and by extension the concept of 'infrastructure', became extremely convoluted. By this time, 'infrastructure' was conceived of as including, in addition to the technical substrate, services that overlay the technical substrate; skilled staff; organized practices; social norms; virtual organizations; and — in the vein of infrastructural inversion — anything that routinely and unproblematically supports any organized practices.

6 'Infrastructuring'

The latest turn in the life of the concept of 'infrastructure' in CSCW and nearby areas occurred as researchers in the mid-2000s undertook another 'infrastructural inversion'. It will be remembered that Star and Ruhleder, in deconstructing the concept of 'infrastructure', or rather re-constructing it as a 'relational' one, went so far as to make the term 'infrastructure' a process term ('When is infrastructure?' Star and Ruhleder, 1996). This radical inversion then inspired researchers to construct the neologism 'infrastructuring':

> 'Bringing the long-term perspective and infrastructure work to the forefront of priorities creates a need for change in approaches to information systems design and technology development,

[18] In fact, one of the authors of this chapter contributed to this controversial expansion (Bietz and Lee, 2009; Bietz et al., 2012).

particularly large-scale collaboration infrastructures. […] Theoretical challenges suggest moves from technologies as high-tech devices towards more inclusive conceptualizations of thickly interwoven socio-technical infrastructures encompassing mundane technologies and practices and information systems design from one-time technology development towards ongoing processes of infrastructuring. Together these openings challenge us to explore *designing for infrastructuring*, i.e. how to design for the blurring of borders between use and design, for ongoing changes, ease of maintenance, and tailoring of flexible and adaptable systems.' (Karasti and Baker, 2004, p. [8]).

Similarly, also with a view to 'blurring the borders between use and design', Pipek and Wulf use the notion of 'infrastructuring' to 'subsume *all* activities that contribute to a successful establishment of usages under the term "infrastructuring" to avoid confusion with classic notions of design as design-before-use performed by professional designers' (Pipek and Wulf, 2009, p. 450). They later further specify that they 'use the term infrastructuring to distinguish ourselves from notions of design that only refer to professional, or to put it better, professionalized design activities':

> 'It is the degree of professionalization with regard to (technical) competencies that leads to the distinction between users and designers. Based on this distinction, traditional design methodologies in IS prioritize the designers' perspective in a way that obstructs the perception of the users' contributions to the improvement of infrastructures. However, the users' perspective on developing IT infrastructure is actually broader. It includes the transition from old to new routines and usage patterns, and it is more diverse. While product-related choices in the application domain may seem straightforward to the designer, any organizational unit and any individual actor confronted with new systems has to find ways to integrate them into existing work practices.' (Pipek and Wulf, 2009, p. 457).

That is, 'infrastructuring' is proposed as a shorthand way of referring to the social, organizational, educational, and technical processes (design and redesign, implementation and introduction, adaptation and adoption, combination and recombination) through which complexes of technical artifacts become integrated into practices as taken-for-granted technical resources. It is meant as a placeholder for a host of interdependent and intersecting issues that only with difficulty can be investigated separately, if at all. And sure enough, the move to rally around 'infrastructuring', rather than 'infrastructure', seems to have provided new space for researchers to investigate the processes and practices involved in the evolution of infrastructures.

Such conceptual moves are often useful in scientific work, but they have a price. The introduction of a particular technical term for such loose heuristic use may lead the innocent or credulous to believe that a coherent research program or even *a theory* has been established when in fact nothing of the sort has happened. It may thus forfeit the very purpose of introducing it. Whether this will happen to the notion of 'infrastructuring' is to be seen, but the risk is obvious.

Anyway, the conceptual problems we have discussed concerning the different uses of the concept of 'infrastructure' are already visible in these programmatic articles. It is, for example, striking that the 'infrastructural inversion' approach that has been invoked to justify using the term 'infrastructure' as a verb (or rather a verb in its gerund form: 'infrastructuring') is immediately abandoned again and forgotten when, for example, Karasti and Baker refer to 'large-scale collaboration infrastructures' in one of the ordinary senses of 'infrastructure' (technical resource or socio-technical service) or when Pipek and Wulf use terms such as 'e-infrastructure', 'IT infrastructure', etc. in the ordinary sense of technical installations. Again, the issue of how to identify and delimit the focal entity that occupied Kling et al as well as Star and Ruhleder has been abandoned. This is especially obvious when Pipek and Wulf propose to 'subsume *all* activities that contribute to a successful establishment of usages under the term "infrastructuring"'. It is thus not clear if the technical resources that Pipek and Wulf have in mind when they investigate 'infrastructuring' are of the same kind as or are comparable to the 'large-scale collaboration infrastructures' Karasti and Baker are referring to. It is not even clear if they use the term 'infrastructure' to refer to a large-scale technical resource as opposed to the array of artifacts and resources available in a particular work setting:

> 'In our framework, the work infrastructure of a worker or organization is *the entirety of devices, tools, technologies, standards, conventions, and protocols on which the individual worker or the collective rely* to carry out the tasks and achieve the goals assigned to them. These elements are interconnected mainly in two ways: either in a technological sense that the functioning and utility of elements depends on other elements, or through use-based ties motivated by a shared interest of users or shared organizational aspect (work task, department, etc.). Dependencies may be transitive […]. While our general definition does not exclude non-IT devices, we consider IT devices and technologies to play a crucial role in the ensemble of tools and technologies.' (Pipek and Wulf, 2009, p. 455 (Emphasis added)).

There may be much to be gained by such an inclusive approach: 'the entirety of devices, tools, technologies, standards, conventions, and protocols on which the individual worker or the collective rely to carry out the tasks and achieve the goals assigned to them'. But then the very term 'infrastructure' gets in the way. What unites all these entities is merely the fact that they somehow, in some fashion, belong to the ensemble of artifacts and techniques upon which practitioners can be said depend in their work. This approach then faces the same methodological problems faced by the 'information infrastructure' approach as discussed above.

7 Using the concept of 'infrastructure': Proceed with caution!

We have traced a multitude of paths that meander and sometimes cross. The notion of 'infrastructure' has shifted, expanded, and developed in manifold ways over time. In many ways, the CSCW and IS communities have been circling around the concept of 'infrastructure' without defining or otherwise determining its point or its boundaries. What is striking in the use of the term 'infrastructure' in CSCW and vicinity is not only that the term is used quite variably. What is perhaps more striking is that the various authors do not seem to realize this. Star et al. refer to Kling et al. and Hanseth et al. refer to Kling et al. and Star et al., and subsequent authors refer to this disparate body of literature in varying combinations. But what is most striking is that the term 'infrastructure' is being used for distinctly different purposes and to denote distinctly different phenomena.

Let us summarize. We can distinguish at least four different discourses and related meanings of the term 'infrastructure' in this literature:

- 'infrastructure' as something that somehow provides essential support for something else; 'infrastructure' here is broad, encompassing, and extremely ambiguous with very little or no distinction between what is or is not included or excluded in 'infrastructure';
- 'infrastructure' as an assemblage of artifacts (and perhaps even activities and 'users') in operation as providing support and/or service to some social system (nation, city, industry, firm, research community, organized practice); 'infrastructure' here is also very broad and ambiguous — including any material artifact that supports a practice or organization;
- 'infrastructure' as technical structure or installation or material substrate ('networked computing') conceived of in terms of its structure *and* the services it provides to some social system: infrastructure and superstructure;
- 'infrastructure' as technical structure or installation or material substrate ('networked computing') conceived of in terms of its structure: the material interdependencies of its components and processes; in the case of computing technologies, these processes include regular electronic or optical pulses, protocols, messages, etc.

As we have tried to demonstrate, this range of meanings is a bridge too far. If by 'infrastructure' we may mean either a technical installation, or an assemblage of stuff, or even an assemblage of both artifacts *and* their users, then we would not know what we are talking about, nor would anybody else.

We therefore recommend that the semantic landslide triggered by the 'infrastructural inversion' be halted. One can talk about 'infrastructure' in *the narrow sense* of a technical structure or installation ('networked computing') —computing infrastructures as running code (running over networked computing devices) and the representations of running code in the form of programs, protocols, and interfaces. One may then talk about the Internet as defined by the suite of protocols as a specific infrastructure, just as one may focus on other infrastructures defined by other protocols, such as HTTP, IMAP and SMTP, or the proprietary protocols and interfaces at higher 'levels' such as organizational information systems or 'social media'.

One can also talk about 'infrastructure' in *a broader sense* of a technical structure *in operation*, that is, *as providing some service*, giving support, etc. 'Infrastructure' in this broader sense thus basically means the same as 'socio-technical system', in that any talk about a technical structure *in operation* presumes the competent organized practices of its operation and maintenance. — But it is here crucial that we remember that when we talk about 'infrastructure', we are engaged in an operation of abstraction in which we highlight the relation between the technical structure and its superstructure. While it is critically important to investigate the organized practices that operate and maintain a technical infrastructure and its technical components, it is a source of massive confusion to *categorize* as part of the infrastructure, *on par with technical components*, the activities, interactions, skills, people etc. required for the infrastructure to operate. After all, when we refer to a hammer as a useful tool, we do not categorize the arm holding it or the man wielding it, as part of the hammer; however, when designing or selecting a hammer we may very well consider the strength or preferences of the prospective hammerer. This designation of what is and is not part of the hammer is a matter of conceptual clarity and not a matter of saying that the hammerer or the method and qualities of hammering do not matter.

However, one may also, in the context of studying a particular work practice, address the ways in which the various computational infrastructures are adopted and incorporated in that practice. In the context of such practice-centered studies, one may talk about *heterogeneous* complexes of technical infrastructures (e.g., the Internet suite of protocols; HTTP, IMAP and SMTP; SQL-based organizational databases connected via CGI; ERP systems such as SAP R3, etc.) as configured in the particular application context, and how they are integrated with the whole range of assorted artifacts, materials, and processes pertinent to that practice. It is here crucial, however, that the focal entity, *the practice*, is clearly identified, for without that, any attempt at comparative analysis and reasoned generalization will be critically hampered.

8 Implications and conclusions

Although used in manifold, often contradictory ways, the notion of 'infrastructure' has served a useful purpose in that it serves to frame and focus the issue of understanding computational artifacts in the larger practical context of their use. Notions such as 'infrastructuring' and 'infrastructure-as-virtual-organization' are used to enable and encourage the growing ranks of researchers in 'infrastructure' studies to explore how people actually use or develop computing technologies in a larger context.

The importance of this becomes evident when one considers that the historic biases of the IS and CSCW fields towards research projects that lend themselves to *post hoc* evaluation of entire readily deployable prototypes has driven early research in those areas toward efforts to develop novel, effectively discrete artifacts that support a constrained set of practices. In fact, large-scale computing systems, especially those that transcend local practices and connect otherwise disconnected practices, have tended to be marginalized in CSCW (Monteiro et al., 2013). Studies of infrastructure present a necessary challenge to CSCW because such studies are preoccupied with infrastructures that are created to regulate, connect, and intersect with local practices. Now, thanks to the contributions from infrastructure studies, this has more recently given way to research focusing not only on the use of existing technical infrastructures but also on how infrastructures are developed in relation to specific work practices, and how infrastructures are sustained over time including through leveraging other, related infrastructures.

The gamut of traditional and infrastructure approaches necessarily deal with notions of embeddedness — as both a product and a resource (Bietz et al., 2010) — and consider stakeholders (Lee et al., 2010) and sources of innovation in infrastructure to be manifold and more diverse than traditional notions of information technology design would accommodate (Pipek and Wulf, 2009). In order to take more seriously the situatedness of infrastructure development in particular work contexts — and to begin to reconcile global notions of infrastructure with CSCW studies of locally grounded work practices — research in Europe has coined concepts such as 'work-oriented infrastructure' to highlight how infrastructures are 'developed to support specific work tasks' (Hanseth and Lundberg, 2001) and 'work infrastructure' to highlight 'how the technologies undergoing design, and the design process itself, are embedded in an existing work environment' (Pipek and Wulf, 2009). This work lay the ground work for more recent work on 'appropriation infrastructure' which is yet another trope to show how grass roots 'usages' become embedded in larger infrastructures.

Investigating notions of the sustainability of infrastructure has resulted in a variety of overlapping notions such as the practices of 'aligning' and 'leveraging' actors across groups, organizations, and infrastructures (Bietz et al., 2010; Bietz et al., 2012; Vertesi, 2014); designing for graceful obsolescence (Cohn, 2013); resolving differing temporalities or rhythms of stakeholders (Steinhardt and Jackson, 2014); and investigating the work and technologies that sustain the availability of core resources and services over time (Ribes, 2006). This latter work in the US represents a mélange of practice-centered work and more STS-style conceptual explorations or some combination of those.

All in all, what studies of infrastructure have indeed accomplished, and that very successfully, is to create a space in which researchers can take seriously the practices and wider technical and organizational milieu in which computational artifacts are created and used.

In sum, what emerges from our critical investigation of the vicissitudes of the concept of 'infrastructure' over the last 35 years is that the various attempts to develop the concept of 'infrastructure' apply a perspective that is complementary to important strands of CSCW research. The ('indigenous') research program of CSCW explores collaboration technologies from the point of view of local work practices (Schmidt and Bannon, 2013) and conceives of technologies as necessary but contingent complements of such practices, 'practice' here being constituted by the norms, rules, and conventions to which practitioners are observably committed. The study of locally situated practices can actually span a fair number of concerns because practices are not discrete entities; there are families of practices, with variations and overlapping characteristics. Even so, while CSCW derives is strength from its focus on actual, locally-situated practices — the focus on the local is also CSCW's weakness.

Branches of infrastructure research offer a necessary corrective to the focused emphasis in CSCW on the local. Infrastructures, after all, can impose regulatory regimes on local practices (administrative workflow systems, production planning and control systems, healthcare information systems, cyberinfrastructures, etc.). At the same time, infrastructures not only provide constraints to local practice but also provide resources for the creation of new practices and artifacts and for the creation of new infrastructures themselves. If we see infrastructures as providing regulatory and other constraints as well as resources for local practice the question of how to approach the relationship between local practice and infrastructure becomes pressing. The investigation of infrastructure and local practice can be approached and scoped in a number of ways such as:

- by focusing on a particular social setting, researching practices (in the Star and Ruhleder sense) or a family of practices (e.g., the work of nurses at Clinic X, or the clinical work of nurses and doctors at Clinic X at *this* address); in this case, we work from the family of practices outward and across to multiple applications or systems;
- by focusing on a particular class of social settings and researching practices or of a family of practices (e.g., the clinical work in oncology, or clinical work in general); in this case, we work again from the family of practices outward and across to multiple applications or systems; in this example, we scale up to look at multiple local settings;
- by focusing on a particular technical structure and researching the practices they enable and support, including those practices that may be otherwise unrelated; the unit of analysis is here the web of practices that intersect a technical system or kinds of component of a technical system such as data structure, data collection, protocol, portal (web interface), application, or instrument;
- by focusing on a particular class of technical structures; this applies the same approach as for focusing on a particular technical structure but, in this case, we scope a particular technical structure across multiple settings to explore differences and commonalities between technical structures and the webs of practices they enable and support;
- by focusing on coordination among infrastructure-spanning practices and technical structures, researching management and coordination practices across heterogeneous, distributed "systems of systems"—these heterogeneous systems of systems frequently lack central control, and research thus tends to focus on system, and perhaps infrastructure-spanning practices, artifacts, and coordination; in this type of work, artifacts and practices may have characteristics of being local *and* global simultaneously or serially and of being pertinent and useful in multiple workflows and in practical time frames or temporalities.

This list is not intended to be a checklist or a directive, but rather as means to make sense of the landscape of how studies of infrastructure are attempting to transcend local concerns with concerns that have to do with the conceptual, geographic, and temporal reach of technical structures that have been described as 'infrastructure'. Indeed, studies often combine elements of the above and we do not call for mutual exclusivity, only awareness.

While the importance of the relationship between the local and the global have already been pointed to in previous research (Ribes and Finholt, 2007) and suggested in the notion of 'embeddedness' (Star and Ruhleder, 1996; Bowker and Star, 1999), we here call for further exploration and a great deal more articulation of the specific artifacts that are embedded, and, furthermore, of the actual practices that are undertaken in order to embed these artifacts and keep them embedded. In this way, infrastructure studies can offer a useful corrective for CSCW so that local work practices are studied but also transcended. The point is, of course, not to abandon or ignore work practice but rather to not only *situate* work practices within a larger context but also to actually understand the *dialogic and emergent relationship between* work practices and the practices and artifacts that are part of a larger socio-technical milieu — however that milieu is scoped.

The slipperiness of 'infrastructure' concepts has been understandable in what was a rapidly developing area, but now, some decades in, clarifications are necessary for the further articulation of differences within studies of infrastructures so that we might ensure that we are comparing like with like or at least being purposeful and circumspect when we are comparing phenomena that are not the same. Further conceptual clarity will not only allow the definition of subareas and spin-offs as demanded by research and design but might also enable the discovery of nuances in how practices play out within and across the context of larger socio-technical frames. We are not arguing for a singular approach to the study of infrastructures — far from it. What we are calling for is for infrastructure scholars to (a) clearly define what is meant by 'infrastructure' for each study; (b) clearly explicate the focal entity and hence the criteria of inclusion; (c) delineate the scope and limits of the set of phenomena (including infrastructure) actually being studied; and (d) explicitly articulate the relationship of the myriad artifacts, techniques, and practices under study to the infrastructure as defined. Whether those artifacts and practices are conceived of within, across, or outside of the infrastructure in question is of significant consequence for future studies. Greater empirical, conceptual, and analytical precision is necessary for the continuing advancement of computer supported cooperative work itself as well as the study and support of massively proliferating technical infrastructures.

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