

Research Commentary

Digital Infrastructures: The Missing IS Research Agenda

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Since the inauguration of information systems research (ISR) two decades ago, the information systems (IS) field's attention has moved beyond administrative systems and individual tools. Millions of users log onto Facebook, download iPhone applications, and use mobile services to create decentralized work organizations. Understanding these new dynamics will necessitate the field paying attention to *digital infrastructures* as a category of IT artifacts. A state-of-the-art review of the literature reveals a growing interest in digital infrastructures but also confirms that the field has yet to put infrastructure at the centre of its research endeavor. To assist this shift we propose three new directions for IS research: (1) theories of the nature of digital infrastructure as a separate type of IT artifact, *sui generis*; (2) digital infrastructures as *relational* constructs shaping all traditional IS research areas; (3) paradoxes of *change* and *control* as salient IS phenomena. We conclude with suggestions for how to study longitudinal, large-scale sociotechnical phenomena while striving to remain attentive to the limitations of the traditional categories that have guided IS research.

Key words: generativity; digital infrastructure; control points; IT artifact; IS research agenda

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1. Introduction

In the 20 years of ISR's existence, pervasive digitalization of organizational life has become the "new" reality (Yoo 2010). Understanding the antecedents and consequences of this phenomenon, commonly referred to as *digital convergence*, forms a significant opportunity for information system research. The IS field traditionally has attended to the interactions between specific classes of information technology and their social and organizational effects. Yet, its top journals largely have remained silent about the impact of the one class of IT artifacts—*digital infrastructures*—that underlies digital convergence.

Infrastructure in general can be defined as the basic physical and organizational structures needed

for the operation of a society or enterprise, or the services and facilities necessary for an economy to function (Wikipedia). Accordingly, digital infrastructures can be defined as the basic information technologies and organizational structures, along with the related services and facilities necessary for an enterprise or industry to function. These infrastructures can be further defined with respect to the entity being supported or enabled as global, national, regional, industry, or corporate infrastructures. Morphologically, digital infrastructures can be defined as shared, unbounded, heterogeneous, open, and evolving sociotechnical systems comprising an installed base of diverse information technology capabilities and their user, operations, and design communi-

ties (Hanseth and Lyytinen 2010). Accordingly, these infrastructures cannot be defined through a distinct set of functions (unlike specific systems), or strict boundaries (unlike applications). In contrast, they are characterized by dynamism and longevity and are relational in nature. Overall, digital infrastructures herald a new stage in the evolution of IT, reflecting the fact that IT has become deeply socially embedded, is coordinated through diverse sociotechnical worlds and numerous standards, and is most visible during breakdowns (Star and Ruhleder 1996). To wit, infrastructures can best be comprehended by analyzing processes of embedding capabilities and standards in organizational practices, which enable new social behaviors and/or regulations (Edwards et al. 2007, pp. 5 and 6).

In this commentary we build a case for the pivotal role of digital infrastructures in shaping the future uses of IT. We posit that the IS field cannot continue to ignore their significance. To this end we characterize the nature and growth of digital infrastructures and show their orphaned status in IS research. We also clarify the need to theorize about the evolution of digital infrastructures in ways that recognize the salience of the paradoxes of change and control. We finish by observing the need to approach the topic with theoretical and methodical elasticity that will push IS scholars outside their comfort zones.

2. Digitizing and Digitalization

Since the 19th century, the way people live has been shaped by the infrastructures of modernity: steam, rail, and electricity (Arthur 2009, Edwards et al. 2007). The 20th century added information infrastructures including telephone, radio, and TV. For over a century the separate industries offering associated services remained surprisingly stable despite huge technological evolution. This was largely due to the analog and inflexible nature of the underlying technologies: Devices, storage media, and transmission formats were all unique for each service. Consequently, the industries were subject to excess inertia. Tight couplings between the service model and underlying technological capabilities implied that significant technological improvements did not challenge the dominant service model. For example, when the telecommunications industry replaced manual

switching—first with electromechanical machines and later with fully digitized switches—the service model remained the same. Over time the single purpose nature of the services and the high fixed cost of the infrastructure lead to the concentration of ownership and control, the need for mass markets, and a strong regulatory hand further reinforcing industry boundaries and stability. Overall, the structures, practices, and business models in these industries were mutually dependent on the characteristics of the technological and the related social infrastructures that organized, delivered, and sustained the technical capabilities and services over time and space.

The computer emerged as the greatest information technology of the 20th century and carried within it the seeds of radical change. Computers came with the revolutionary idea of *digitizing*—the process of converting analog signals into a digital form, and ultimately into binary digits (bits). Because all digital information assumes the same form, it can, at least in principle, be processed by the same technologies. Consequently, digitizing has the potential to remove the tight couplings between information types and their storage, transmission, and processing technologies—potentially shattering the dominant service model and the stability of the industrial organization. However, the full-scale use of digital technologies to these ends calls for new social connections and cognitive models that accompany each new infrastructural technology. Therefore, we need to distinguish carefully *digitizing*—a technical process—from *digitalization*—a *sociotechnical process* of applying digitizing techniques to broader social and institutional contexts that render digital technologies infrastructural.

2.1. From Digitizing the Cow Paths to Unleashing Generativity

Due to the limited capabilities of early digital equipment and the inertia of prevailing social infrastructures, it is not surprising that extant tight sociotechnical couplings were not immediately broken down by the early waves of digitizing. Rather, the first “digital” services were equivalents of existing analog functionality, built and organized in ways aligned with existing social and technical infrastructures. For example, inventory control processes were

first digitized pretty much “as is,” only later evolving into the enterprise resource planning behemoths that truly transformed organizational control. Early “*digitizing of the cow paths*” was motivated by lower cost or improved service and led to multiple quantitative changes of a similar kind, e.g., analog LPs to digital CDs, analog 1G to digital 2G mobile phones, etc.

The inherent flexibility of digitizing was unleashed and digital technologies made truly infrastructural once the power of cheaper, smaller, and more powerful computers escaped from corporate backrooms, and more neutral general-purpose digital networks (e.g., the Internet) emerged. Then digital devices became capable of communicating, storing, and processing many types of information (*device convergence*), and the same network could support just about any information service (*network convergence*). Once the momentum for such digitalization reached a tipping point (Hughes 1987), the reshaping of social infrastructures followed (*industry or market convergence*). Within two decades, boundaries between content providers, advertising agencies, telecom and pay-TV operators, computing companies, and device manufacturers became blurred. Increasingly heterogeneous bundles of services encroached on established business models while previously separate infrastructures commingled. Recorded music, TV, and books have all had to yield to radical digitalization from the 1980s, 1990s, and 2000s, respectively. This in turn provoked regulators to tailor their approaches to facilitate or to constrain the process of convergence.

Due to the new phenomenon of generativity¹ produced by extensive digitization, digital infrastructures “are built on the notion that they are never fully complete, that they have many uses yet to be conceived of, and that the public and ordinary organizational members can be trusted to invent and share good uses” (Zittrain 2008, p. 43). The extended markup language’s (XML) capability to embed new sociotechnical practices, based on agreed-upon data standards, illustrates such generative properties—for example, creating “automated” publishing across diverse media or supporting the

integration of business transactions across diverse organizations. Now, XML based document type definitions (DTDs) can be defined locally, yet they can simultaneously relate to global standards emerging within and between industries. This generativity adds unforeseen properties to information systems, such as the capability to recombine data sources and to semi-automatically generate, assemble, and redistribute content. The associated increase of metadata is also creating new industries, such as the search industry.

Generativity allows individuals, groups, and organizations to cocreate services, applications, and content. These services can, thanks to fully digital infrastructures, in principle, combine any information, behaviors, or states available on the network. This affords radically new business models (e.g., eBay or Netflix), and incumbent organizations have had to yield to these new entrepreneurs who, untethered from prior social infrastructures, continuously seek opportunities to harness the flexibility of digitizing. A new kind of unbounded *service divergence* has emerged, enabled by (a) lower costs and global reach encouraging wide participation in service production and distribution (e.g., open source), and (b) new market conditions created by multisided markets. The outcome has been a hitherto unimaginable variety of new services: search, e-commerce, social networking, information sharing and pooling, gaming, video production and music distribution, just to name a few. The previously tight interlocking of services, technologies, and stable industry organization has rapidly morphed into a dynamic tapestry of unforeseen dependencies among content, devices, networks, and social compositions. This has resulted in fast shifting trajectories among coevolving digital infrastructures and new forms of social and institutional order, which have significantly widened struggles around who will control of the creation and offering of new information-based services. In this context, the term *digital convergence* denotes the wide-ranging effects of the organic growth of digital infrastructures, the processes by which they come about, and the inseparability of digital infrastructures from new forms of social infrastructure.

Apple’s iPad exemplifies this change. The device is a sophisticated digital platform seamlessly integrated with the iTunes store from which music, videos,

¹ Generativity denotes the ability of any self-contained system to create, generate, or produce a new output, structure, or behavior without any input from the originator of the system (Wikipedia 2010).

movies, applications, magazines, and books can be downloaded. The combination of the iPad *qua* device and the iTunes *qua* infrastructure radically redefines forms of control through device standards, storage medium, and transmission formats and blurs the boundaries between media, computer, software, and telecom industries. As a result, Apple exerts new forms of control by coordinating the evolution of the platform for both developing and delivering entertainment and new services.

2.2. Digital Infrastructure: The Orphan of the IS Field

Traditionally, the IS field has focused on IT governance and system development in well-bounded organizational contexts, along with studying IT's effects on individuals, groups, organizations, and markets (Sidorova et al. 2008). The recent wave of digitizing, however, is transforming the nature of IT and shifting the focus to service ecologies, new experiences, and new forms of human interaction. Yet, this fundamental shift has remained but weakly examined (Yoo 2010), and the field has, with some exceptions, isolated itself from research that extends beyond organizational or industry boundaries.

Our content analysis² of the articles published in ISR during its first 20 years reveals that a mere 2% of articles are attentive to infrastructural issues. We found only five articles (~1% of the total) with infrastructural issues as their primary focus, including the late Star's and Ruhleder's (1996) groundbreaking analysis of the evolution of a digital research infrastructure. Others include calls for more research on platforms and on heterogeneous and distributed environments, or analyses of network externalities. Despite the slim number of articles, there is evidence of increasing interest because all but two of the articles were published in ISR's second decade. The sparse attention to infrastructural issues is not

confined to ISR, as our review of MISQ gave similar results (Tilson et al. 2010). This lack of interest can be partially explained by the scarcity of good published exemplars and the huge challenges in studying large-scale complex phenomena unyielding to IS scholars' preferred research techniques. Another reason is the weak theoretical understanding of digital infrastructure as a new *type of IT artifact*.³ Also notable is the general dearth of empirical and theoretical analyses of digital convergence (Herzhoff 2009). Most theorizing has been left to other fields—to economists (network effects, information asymmetry, two-sided markets, patterns of technological change) (Arthur 2009, David 2005, and Shapiro and Varian's work) and to legal scholars (forms of information creation and distribution, intellectual property and control) (Lessig 2001, Zittrain 2008, and Benkler's work).

Until recently this omission could have been deemed acceptable. Historically, the effects of IT were confined to administrative processes within business functions and to the governance of essential industrial relationships. Accordingly, corporate digital infrastructures could be assumed to be relatively isolated and stable, and issues of infrastructural change could be analytically and operationally decoupled from the ongoing issues of IT design, use, and governance. This assumption has, however, become under increasing attack as digital convergence accelerates. As corporate information infrastructures become fully digitalized (and thus embedded in industry and global infrastructures), new generative dynamics emerge, affecting the social and technical infrastructures (Brynjolfsson and Saunders 2009). For example, mobile services and social networking are changing how firms interact with customers, employees, suppliers, or manufacturing processes by transforming interactions into "connect-and-coordinate," as opposed to "command-and-control" forms.

3. Digital Infrastructures: An IS Research Agenda

The received concept of digital infrastructure has been primarily shaped by research into earlier infrastructures of modernity like the electricity grid (Hughes

² A total of 399 research articles dealing directly with phenomena of interest to the IS field were published in ISR between March 1990 and December 2009 (there were also 71 introductions, editorials, and other miscellaneous articles). We evaluated all 470 abstracts using a methodology broadly similar to that used by Orlikowski and Iacono (2001) in their search for the IT artifact in the first decade of ISR articles. Our goal was to identify articles that focused on infrastructure and related issues.

³ Exceptions in IS include studies by Geoffrey Bowker, the late Claudia Ciborra, Paul Edwards, Ole Hanseth, Jannis Kallinikos, Kalle Lyytinen, Eric Monteiro, the late Susan Leigh Star, and JoAnne Yates.

1987). This stream emphasizes digital infrastructure as a stable enabling mechanism, needed to ensure competitiveness as reflected in the “*information super highway*” term coined by Al Gore. This view emphasizes connectivity and pervasive access as well the stable characteristics of heterogeneous physical equipment. Therefore, proponents of this view focus on technical standards to ensure interconnectivity across transoceanic fiber optics, local loops, etc., and on universal protocols such as TCP/IP for steering data across such physical infrastructure. They also point to the need to regulate networks to establish a long-term perspective (Lyytinen and King 2006). The well-known argument that commoditization of digital technology (e.g., Carr) will eventually transform corporate IT into a utility is a direct logical extension of such a perspective.

Although the features described above apply to digital infrastructures, we need to recognize pivotal differences that make digital infrastructures generative. These include its recursive nature, scalability, flexibility, and the varying substance of the material (data) being “transported.” First, traditional infrastructures rely on tight functional couplings between the underlying technical capabilities and the service delivery model. Unlike digital infrastructures, they are not *recursively* organized—electricity and water utilities cannot generatively create new infrastructure businesses to challenge incumbents. Second, digital infrastructures are extremely *scalable*, as their components can be upgraded or replaced (e.g., routers and transmission equipment) with relative ease and low cost. This leads to regular leaps in performance, exceptional growth, and radically decreasing costs not offered by physical infrastructures (Brynjolfsson and Saunders 2009). Third, the inherent flexibility of digitizing has led to a radical widening of the reach and scope of digital infrastructures in ways not possible with physical infrastructures. Digital infrastructures possess *upward flexibility* in that they, in principle, are open to the creation of any application or service making use of its lower level communications and storage capabilities (Tilson 2008). Furthermore, infrastructures possess the potential for *downward flexibility* in that a wide range of digital or physical networks potentially can provide the required interconnectivity and other functions. This flexibility is made possible by the malleability of software implementing the

logic laid down in layers over the physical layer of interconnected hardware. The potential for upward or downward flexibility, however, can be restricted by sociotechnical and regulatory arrangements (e.g., traffic restrictions imposed by mobile telecom operators). Nevertheless, the widespread adoption of the Internet protocol suite has led to a divisive break in the tight coupling between services and underlying networks. Digital infrastructures are now far less limited in the ways their capabilities can be recombined, with one infrastructure forming a foundation for services or even for other infrastructures—the Internet itself is but a network of connected networks tied together by its core protocols and is oblivious to the services and other platforms, like the World Wide Web, that it supports. This unique property has had the disruptive effect of redistributing control away from the owners of the physical assets. Rather, as noted individuals, groups, or organizations can now cocreate services and applications limited only by their own abilities to envision desirable properties, to succeed in development, and to enroll others. This shift allows for rapid and dynamic reconfiguration of behaviors (David 2005, Tilson 2008) using gateways or functional abstractions (Ciborra et al. 2000, Hanseth and Lyytinen 2010). Accordingly, control over access and behaviors in application or service ecologies have become a new means to exercise control. This is exemplified by Apple’s iTunes platform at the epicenter of a new ecology of devices, content, applications, users, and developers. This contrasts sharply with earlier analog and “cow-path” infrastructures, where control was all but synonymous with the ownership of physical assets.

Finally, digital infrastructures transfer bits—a singular universal material that assumes the most diverse meanings. In this sense, data play a significantly different role in digital infrastructures than, say, a car in relation to transportation infrastructures or an electron in relation to an electrical grid. Simply, digital data have unique properties not found in physical infrastructures (Kallinikos et al. 2010). Use of digital infrastructures by users, machines, and communities requires institutions negotiating and arranging the meaning of the bits that are traversing the networks. A new breed of layered interoperable standards and common definitions of application

and service interfaces are essential for the infrastructure's use and growth. YouTube video, for example, engages shared video encoding standards that allow not only viewing video but also complementary processes of annotation, reappropriation, remixing, and altering of original encodings, either by humans or machines, creating an ever-expanding space of meaning creation, negotiation, and standardization. This has resulted in the exponential growth in digital data and metadata (human-made tags and automatically generated indices). This production, repackaging and reappropriation of data and metadata, and the related negotiation and standardization processes become a constant recursive computational rendition of multiple "realities," whereby each stage leaves more of the analog to be digitized and subjected to further tagging and reappropriation (Kallinikos 2006).

In summary, the unique properties of digital infrastructures and their effects are becoming fundamental in understanding the effects of digitalization. Consequently, we argue, they have become essential in guiding IS scholarship. Digitalization of information industries provides ample evidence of how transformative these effects are, as well as clues that research on the interplay between dimensions of change and control will be vital in developing an understanding of future IT uses in organizational contexts. Research on the nature, design, and evolution of these infrastructures should start by capturing the sociotechnical infrastructural dynamics of specific cases and the study context, but it should strive toward more generalizable models that can provide guidance to designers, managers, and policymakers.

3.1. The Paradoxical Nature of Digital Infrastructure

While digital infrastructures can appear durable for a time, their inherent scalability and flexibility fosters extraordinary growth in scale and scope. New combinations of services and capabilities can be produced at unprecedented speed. As noted, this tilts the nature of digital infrastructures toward generativity and forges novel sociotechnical relationships during ongoing use. This blurs organizational boundaries and triggers constant rivalries for creating new control points. If and when control is solidified for a time, this blurring creates a new "iteration" of a

contingently stable sociotechnical configuration. Thus, the tension between digitally enabled flexibility and the constraints imposed by prior investments, design decisions, and associated forms of control remains a focal research challenge: how can we understand the dynamics and outcomes of generative change associated with digital infrastructures?

Building on this foundation, we review two broad challenges related to the drivers of generativity—the issues of change and control (Ciborra et al. 2000). We approach them as a *duality* (Farjoun 2010) in that digital infrastructures need to be organized in ways that are simultaneously stable and flexible as well as offering both control and autonomy. Moreover, we assume that high levels of flexibility are essentially outcomes of stable technological and social mechanisms involving apparently paradoxical elements. Infrastructures appear as stable only "*when oppositional tendencies are brought into recognizable proximity through reflection, or interaction*" (Ford and Backoff 1988). These phenomena involve a variety of contradictory elements, inviting attempts to make sense of digitalization by simplifying reality into polarized either/or distinctions articulated as tensions that conceal their complex interrelationships. Accordingly, we focus in the following sections on (a) the paradoxical nature of change in digital infrastructures, and (b) the paradoxical nature of control in digital infrastructures. By analyzing these paradoxes we raise pivotal questions about the benefit of focusing IT research on single levels of analysis and through the use of fixed categories. This raises another question: Do we need to relax key assumptions about the nature and levels of analysis preferred in IS research in the face of the increased fluidity, tensions, and dynamics brought by digital infrastructures?

3.1.1. The Paradox of Change. Generativity can be viewed as the fruit of an urge to harness the possibilities enabled by the flexibility of digitizing. We consider that viewing infrastructural change as essentially paradoxical is necessary for building explanations of how generativity emerges and for understanding the dynamics of digitalization. The *paradox of change* is defined by the opposing logics of stability and flexibility that operate across infrastructural layers and components. On one hand, digital infrastructures need to be stable to allow "enrollment" of

new artifacts, processes, and actors; on the other, it must possess flexibility to allow unbounded growth.

The paradoxical nature of change follows directly from our characterization of digital infrastructures as unbounded, evolving, shared, heterogeneous, and open installed bases of capabilities (Hanseth and Lyytinen 2010). Here *stability* is defined through the installed base and its ossified nature and content in terms of social and technical components and their connections. The *change* is enabled and constrained by the very stability of these sociotechnical formations; only a stable installed base allows new connections to be created. After all, there has to be something to connect to, and the means of connecting must be predictable. Without such a stable technical foundation, providing upward and/or downward flexibility is not possible. Related social stability is needed to reach and disseminate agreements about necessary interfaces, data definitions, and their evolution. Void of stability, generativity is curbed, and change will halt.

Conversely, stability can be bolstered only by allowing flexibility. The broadening and deepening of the ecologies through variation at the “edge” and across layers bolsters the stability of infrastructures. If the social compositions exhibit similar flexibility (e.g., in terms of standards creation and governance) and avoid imposing undue restrictions (e.g., overregulation), the infrastructural base remains stable. Nevertheless, the flexibility always has the potential to undermine social stability (and, consequently, technical stability), as it *blurs* organizational and industrial boundaries through digital convergence and divergence. Highly invested meanings, roles, and lines of responsibility can be wiped out, and related technical competencies and capabilities can be undermined in an instant.

These highly dynamic, intricate, and paradoxical effects are central to our argument for why digital infrastructures are such an important topic. The paradox invites us to adopt a fresh stance on how change in digital infrastructures is driven by the dialectic of stability and flexibility and how it affects uses of IT in corporate environments. This stance contrasts with a majority of IS research in organizational contexts that foregrounds either stability or flexibility, but avoids recognizing the paradox. In software engineering, for example, component stability is in

the foreground (Hanseth and Lyytinen 2010), and change at the component level viewed as an exception; while at the enterprise level, change as “digital options” is brought to the fore at the cost of stability (Sambamurthy et al. 2003).

3.1.2. The Paradox of Control. Opposing logics around centralized and distributed control (or individual autonomy) play an equally important role in the evolution of digital infrastructures. This *paradox of control* brings into consideration the strategic actions of heterogeneous actors and their preferences on modes of control related to change. These considerations shape the services deployed, ownership of data and their definitions, control of critical resources (e.g., APIs), and the appropriation of value.

The use of information systems has historically been intimately linked to the needs and abilities of organizations to exercise control (Beniger 1986, Yates 1989). The broad set of affordances that come with IT, however, signify new opportunities for rethinking organizational command and control. As processes can now be digitally modeled, monitored, and controlled, the shift of the intelligence and control to the edge has simultaneously loosened and tightened organizations’ abilities to exert control. Laterally networked PCs in the late 1980s softened centralized control (Malone et al. 1987). Mobile technologies possess the paradoxical possibilities of both tighter and looser organizational control at the individual level (Sørensen 2011). There is also evidence that problems in realizing organizations’ desires to control lead to increased infrastructural drift, where systems “*deviate from their planned purpose for a variety of reasons often outside anyone’s influence*” (Ciborra et al. 2000, p. 4). At the societal level the opportunities for massive repurposing of content leads incumbents to reassert control through new legislation and digital enforcement (e.g., tight copyright, DCMA, attacks on net-neutrality). All of this reflects the paradox of both more and less control (Lessig 2001, Zittrain 2008).

The critical issue is, how do actors establish generative platforms by instituting a set of control points acceptable to others in a nascent ecosystem? The notion of a control point involves defining and controlling a set of connections in a sociotechnical system that largely determine the behaviors and

constraints for other elements in the system. The control point concept captures both aspects of control—centralization/decentralization of certain rights and access to “stipulate” specific behaviors—and thus provides a finer granularity for discussing new paradoxical regimes of control. Apple’s iTunes platform, for example, represents a “different” balance of controls, enabling on one hand a generative platform supporting millions of users and hundreds of thousands of applications, while on the other hand exercising strict control over application approval, payment terms, architectural rules, and many aspects of the internal operations of applications. Yet, iTunes thrives, in part, due to this balance of control providing a stable and flexible low-cost entry for a large number of developers to innovate—even though developers share a somewhat “love-hate” relationship with the infrastructure’s restrictions.

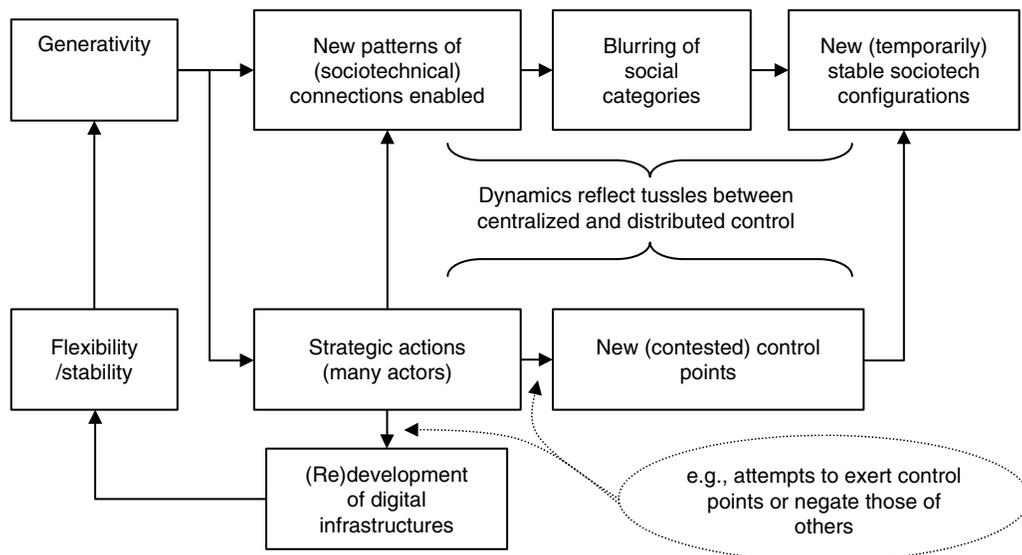
Digitization’s convergent and divergent effects lead to conflicts between existing and emerging control regimes. This results in tussles, i.e., intense rivalries among divergent interests within and between the system’s governing infrastructure, services, regulation, and use (Clark et al. 2005, Herzhoff et al. 2010). A dynamic is established where the constant change in sociotechnical configurations impels tussles that drive further change as actors seek to establish new control points or to prevent others from doing

so. This constant jockeying to create preferred control points interacts with the need to find a generative balance between stability and flexibility.

Control points and tussles can be interpreted as midlevel constructs, which enable fine-grained characterization of the dynamics of control paradox. Given the characteristics of generativity, and the complexity of the legal, architectural, social, and economic dimensions involved in tussles, the relationships between generativity and control remain poorly understood. This opens an opportunity for the IS field to lead the way in analyzing the relationships between the paradoxes of change and control and, in due course, formulating prescriptions for designers, managers, and policymakers.

An important theme emerging from our discussion is the role of generativity and the subsequent emergence of new forms of control. For example, the ability to define an API serving as the “obligatory passage point” can be viewed as a control point both decentralizing and centralizing access, while at the same time both regulating behavior and enabling access. The evolution of contingently stable sociotechnical formations thus depends on the definition and placement of control points within digital ecologies, as well as on the ways they are challenged by the dynamics of generativity (Figure 1).

Figure 1 Conceptual Model of the Sociotechnical Dynamic of Digital Infrastructures



3.2. Digital Infrastructures and the Core of IS Research

Digital infrastructures are a new species of IT artifact. They render industries and products increasingly information based and reshape industrial organization and services as industries undergo comprehensive digitalization. This transformation is now taking place at a rate and with a scope that no longer allows the taking of traditional IS approaches and research questions for granted. Neither can IS research confine itself to the study of infrastructural artifacts in isolation but must extend investigations into the traditional core of the discipline. To this end, Table 1 identifies key issues in studying digital infrastructures (see row 1) and reviews emerging general IS research directions due to increased digital convergence organized along the five major IS research themes identified by Sidorova et al. (2008).⁴

Several kinds of effects on information systems development can be expected. The increasing number of digital ecosystems and capabilities will change the components from which applications and services can be developed (e.g., mapping options from Google). It will also enrich the social dimension as well as complicate the technical one. This affects the methodologies employed in developing and managing the evolution and integration of systems (or services). Furthermore, digital infrastructures enable alternative social and technical mechanisms for the creation of applications (see second row of Table 1).

Our earlier discussion highlights the potential for radical effects upon industries and their boundaries. These changes have already revolutionized individual and group coordination as well as the consumption and creation of information and media. It is, therefore, reasonable to assume that digitalization will continue to have profound effects at all levels of analysis (see rows 3 through 7). In addition, the emergence of self-creating and self-organizing social assemblages, incorporating both individuals and agents of traditional organizations, represent important new forms of organizing that go beyond the idea of hierarchical control. The relative fixity of the social and technical infrastructures of yesteryear meant that IS researchers

could assume a stable foundation for studying phenomena located at a specific level of analysis. The emergence of generative digital infrastructures makes such assumptions increasingly problematic, e.g., the proliferation of cloud services will enable groups, and organizational units to adopt and adapt technologies not sanctioned by their superiors. All it takes is a free dropbox.com account for sharing documents, or a credit card to open an Amazon Web Services account. Increased flexibility and sophistication in the individual and organizational appropriation of digital services shifts the research agenda beyond conceptions of singular technology adoption at one level. Individuals' adoption strategies for managing multiple personal tools and new ways of group working enriched by digital services are inextricably intertwined—there is similar mutual shaping between group and organizational levels. While we do not suggest that all IS research must cut across all levels of analysis, the effect on the adoption and use of IT means that the nomological networks developed around a particular phenomenon at one level must incorporate constructs that would have been assumed as a stable contextual backdrop in the past. While examining the infrastructural effects at each level of analysis (see Table 1) will undoubtedly prove insightful, our aims go deeper. Proposed investigations make sense only if we invest more in theorizing the nature and impact of the digital infrastructures and work towards richer conceptualizations of IT uses that cut across multiple levels of analysis and multiple contexts.

4. Concluding Remarks

Nearly 15 years ago a paper by Star and Ruhleder (1996) emphasized the importance of approaching IT artifacts as unique and complex infrastructural formations. Although their study did not gather many followers in the decade that followed, it can now be regarded as a harbinger of things to come. We are now observing the cascading effects of digital infrastructures as special types of IT artifacts, *sui generis*, with IT tearing down the old analog world and its associated social infrastructures. As we have shown, this calls for (1) deeper theoretical work on the notion of infrastructures, (2) new theoretical lenses to understand the paradoxical nature of change and control in digital infrastructures, and (3) better understanding

⁴ We assume the listed issues are self-explanatory and for brevity do not expand them significantly here.

Table 1 New Research Directions for the IS Field Triggered by Digital Infrastructures

Paradox of change	Paradox of control
<p>Infrastructure</p> <ul style="list-style-type: none"> ● Development and funding of digital infrastructures (DI) <ul style="list-style-type: none"> —Factors promoting/impeding change —Suitable coordination mechanisms —Upward and downward flexibility conceptualizing the paradox of change ● Key social and technical elements affecting change and stability of DI <ul style="list-style-type: none"> —Effects on generativity —Mutual effects of control and change ● Key architectural forms and principles 	<ul style="list-style-type: none"> ● Key social and technical elements affecting control within DI <ul style="list-style-type: none"> —Infrastructural change through; control points, architectural control, forms of control, and tussles —Commercial actors shaping the design and evolution of DI/platforms and associated ecosystems —The role of public policymakers and regulation —The role of individuals and small groups ● The effect of technical standards and standardization processes on the evolution of DI
<p>Development</p> <ul style="list-style-type: none"> ● Influence of generative ecosystems on methodologies, IT architectures, requirements discovery, systems integration, and maintenance ● Influence of generative DI on; actor constellations, requirements, and timing of service development ● Upward and downward flexibility as characterization of the evolution of DI; impact on evolution patterns ● Role of service ecosystems for IS professionals and their careers 	<ul style="list-style-type: none"> ● Sociotechnical control points and tussles as catalysts for revealing salient aspects of DI evolution ● Conceptualizing and planning for change in DI ● Choosing between alternative DI platforms, e.g., as real options ● DI-based IT architectures affecting generativity through the balance of change and control paradoxes ● Free and open software leveraging the evolution of DI
<p>Individual</p> <ul style="list-style-type: none"> ● Understanding individuals engaging in patterns of use across multiple devices and services while adapting to dynamically changing service ecologies ● Individual impact of flexibility on work processes, e.g., work/leisure balance ● Individual effects of dynamic shifts between service convergence and divergence ● Dynamic patterns of group formation, e.g., mobile working, itinerant workers, click-working 	<ul style="list-style-type: none"> ● Individuals dynamically adapting to the control paradox ● Users seeking to cede or retain control over devices and service options ● Attempts to subvert control ● Implications for content ownership and privacy of services provided remotely DI ● Conceptualizing the control paradox for dynamic group formations
<p>Group</p> <ul style="list-style-type: none"> ● Dynamic group capabilities for remote collaboration, sharing, visualization, and awareness maintenance ● Impact of information service options on group decision processes, and the quality of decisions ● Conceptualizing dynamics of new forms of emerging collaborative networks and innovation platforms 	<ul style="list-style-type: none"> ● Challenges of the control paradox on understanding of groups, e.g., negotiation of tools used, or management principles ● Conceptualizing tensions between centralized support and decentralized group support, e.g., through cloud services ● Understanding tussles in collaborative networks in terms of control point dynamics
<p>Org.</p> <ul style="list-style-type: none"> ● Understanding IT ecosystem dynamics strategy, governance, investment, organization, operations, and strategy in IT function ● Ensuring reliability, availability, and security in complex service ecologies ● Understanding dynamic crowds engaged in collective intelligence a blurring of boundaries between groups, organizations and markets 	<ul style="list-style-type: none"> ● Identifying factors affecting the strategic high ground in gaining control of generative service ecosystems ● Conceptualizing organizational actions in terms of tussles ● Sociotechnical control points and tussles and the harnessing of global crowds
<p>Market</p> <ul style="list-style-type: none"> ● Dynamic platforms affecting interorganizational collaboration ● Capturing and sharing economic externalities in dynamic ecosystems ● Vulnerabilities and security issues of DI 	<ul style="list-style-type: none"> ● Understanding partner power to select platform or features of a platform, e.g., real options ● Standards agreement, implementation and coordination, and the associated changes to power balances and tussles ● Technological and market-based control points

of the ways in which infrastructural change shapes IT governance, IS development, and promotes new effects across all levels of analysis.

This infrastructure-turn calls us to critically review the categories that have so far helped us make sense of the sociotechnical reality we study. As old worlds and connections disappear, we need to invent new concepts, relationships, and vocabularies by keeping our concepts and models fluid and open to new analyses. Our emphasis on investigating mutual dependencies between digital infrastructures and received categories also leads us to question the established categories and look for their limitations. The concept of digital infrastructure is in this regard especially challenging, as it is a relational notion, which cuts across and integrates concerns at multiple levels and across multiple temporal scales. Theory building using notions of contradiction (Poole and Van de Ven 1989) provides some purchase for establishing initial understanding of these interrelationships. The established social categories of individuals, groups, etc. therefore need to be approached with sensitivity. For example, is it possible to conceive of individual users without understanding infrastructural relations that define what it means to be a user? Similarly, some topics, such as virtual teams, are void concepts without a connection to infrastructural capabilities. Table 1 includes some consideration of cross-category topics.

We thus see parallels between the destabilization of industrial structures and the destabilization of academic boundaries. Ongoing digitalization challenges the separation of disciplines, for example, between communication and media studies, information systems, and telecommunications engineering—three disciplinary fields associated with the interrelated content, code, and physical infrastructure layers (Lessig 2001). The final challenge is to augment traditional case studies and sectorial quantitative studies with dynamic, multilevel, and longitudinal analyses to better grasp infrastructural change. This can lead to better understanding of what factors, events, and actions generate different outcomes and possibly to prescriptive advice on the design, evolution, and utilization of digital infrastructures (Tilson 2008).

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