Defining Cyberinfrastructure for Communication, Organizational, and Diffusion Research: Interactions and Characteristics

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Abstract

This paper explores the interactions layers and defining characteristics of the phenomenon of cyberinfrastructure, an emerging sociotechnical system that enables large-scale research using aggregated computational resources and combined datasets through the Internet, high-performance networks, and local machines to mine publicly-funded datasets accumulated over time. We argue that cyberinfrastructure possesses four key layers: information and communication layer, science and research layer, macro structures layer, micro interactions layer. Further, we describe cyberinfrastructure with four pairs of distinctive characteristics: participatory/bespoke, meta/complex, disruptive/revolutionary, and community/network. These layers and pairs are not meant to be exclusive and exhaustive categories, but merely potential analytical 'cuts' through the complex phenomenon of cyberinfrastructure. Nonetheless, we argue that these layers and characteristics provide an initial model and framework to describe future large-scale communication networks, information infrastructure, and virtual organizations. Continuing funding for cyberinfrastructure development support suggests a bet on the future and antenarrative of cyberinfrastructure. (146 words)

Introduction

It has been almost a decade since the concept of "cyberinfrastructure" for large-scale science and engineering was officially introduced in the United States in 2003 in the Atkins Report (Atkins et al., 2003). Around the same time, the concept also emerged in Europe but it took on the label of "e-science" (Hey & Trefethen, 2005; Schroeder & Fry, 2007), with an emphasis on the distributed scientific work the infrastructure enables. Since then, "cyberinfrastructure" and "e-science" has taken on other more inclusive labels (inclusive of social sciences, humanities, business, etc.), such as "e-Research infrastructures" (Schroeder, 2007, p. 1), "e-Infrastructure" (Hey & Trefethen, 2005, p. 817), "information infrastructures" (Bowker, Baker, Millerand, & Ribes, 2010; Turner, Bowker, Gasser, & Zacklad, 2006, p. 93), as well as "collaboratory" (Olson, Zimmerman, & Bos, 2008), which emphasizes the social and "collaborative" dimensions of this new kind of science. Over the years, since the official established on the "Office of Cyberinfrastructure" within the U.S. National Science Foundation (NSF) in 2006 (Seidel, Muñoz, Meacham, & Whitson, 2009), the development of cyberinfrastructure has received steady funding, investments, and attention (Edwards, Jackson, Bowker, & Williams, 2009; Kee & Browning, 2010).

Cyberinfrastructure is impacting scientific fields, such as biomedicine (Buetow, 2005), meteorology (Droegemeier et al., 2004), geosciences (Keller, 2003), bioinformatics (Li et al., 2006), library sciences (Goldenberg-Hart, 2004), and many others. Freeman, Crawford, Kim, and Muñoz (2005) contend, "past efforts in supercomputing and high performance networking are being subsumed into a broader, integrated vision of a more capable, ubiquitous, and accessible cyberinfrastructure" (p. 682). Burn and Barnett (1999) call this the transition from "laboratory science to in silico e-science" (p. 48). Cannataro and Talia (2004) predict that the development of cyberinfrastructure will eventually move from data storage and advanced computation to a "pervasive, worldwide knowledge management infrastructure" (p. 56). Getov (2008) maintains that this innovative deployment of cyberinfrastructure to conduct science, e-science, "is increasingly being adopted as one of the most successful modern methods for experimental scientific discovery" (p. 30). The emergence, development, adoption, and diffusion of cyberinfrastructure are exciting.

We believe that the phenomenon of cyberinfrastructure is of interest to communication and organizational researchers interested in studying innovation adoption and diffusion. In the adoption and diffusion literature, Rice and Webster (2002) define *adoption* as "allocation of resources to acquire an innovation" (p. 193). Relatedly, Rogers (2003) defines *diffusion* as "the process by which an innovation is communicated through certain channels over time among the system members". From a broader view, Rabin and Brownson (2012) argue that diffusion is passive, untargeted, unplanned, and uncontrolled. They state, "Diffusion is part of the diffusion-dissemination-implementation continuum, and it is the least focused and intense approach" (p. 25).

In this paper, the questions we attempt to answer are: "*What is cyberinfrastructure in the research context of innovation adoption and diffusion? How can communication and organizational researchers connect with this emerging phenomenon with existing theoretical perspectives?*" In order to achieve this goal, we first summarize one of several possible historical sketches of CI emergence in the US. This section signals the significance of cyberinfrastructure and the large-scale collaborative efforts that have converged in relatively recent history. Second, we provide a brief overview of the various CI definitions in the literature, with an emphasis on its communication and organizational dimensions in addition to its obvious technical nature. This section presents cyberinfrastructure as a socio-technical system that is suitable for communication and organizational research. Third, we provide a framework on how the phenomenon of cyberinfrastructure can be distinguished by its key pairs of characteristics and interaction layers that could help connect with communication and organizational research. These pairs and layers describing cyberinfrastructure are not meant to be exclusive and exhaustive categories, but merely potential analytical ‘cuts’ through the complex phenomenon of cyberinfrastructure. Finally, we discuss the implications of our framing and conclude with some future research directions.

The Emergence of Cyberinfrastructure in the Early 21st Century U.S.: One Version of the Historical Sketch

In this section, we list one sequence of the major historical events and projects that contributed to the emergence of cyberinfrastructure in the U.S. Atkins and colleagues (2003) explain that the concept of infrastructure emerged in the 1920s to collectively refer to “the roads, power grids, telephone systems, bridges, rail lines, and similar public works that are required for an industrial economy to function” (p. 5). Freeman (2007) maintains further that the concept of infrastructure in reference to labs, equipment, support personnel, etc., for conducting science did not become commonly used until the 1950s with the establishment of an NSF-sponsored polar studies facility in Antarctica. However, he suggests that the accurate starting point of CI development was in the 1960s, when the NSF financially supported the establishment of academic computing centers on several U.S. campuses. The unique nature of these academic computing centers was that they were open to the general scientific community and not limited to specific projects. This allowed numerous faculty and students access to the facilities created with NSF funding.

In the 1980s, NSF did two things that further strengthened the foundation of today’s cyberinfrastructure development. First, NSF invested in the creation of the first supercomputer centers in the country (Atkins, et al., 2003; Freeman, 2007), which started the vision of the open scientific community in the early 1980s. Through its Supercomputer Centers Program, NSF established five supercomputer centers across the U.S. between 1985 and 1986. These centers include San Diego Supercomputing (SDSC) at the University of California at San Diego; National Center for Supercomputing Applications (NCSA) at the University of Illinois at Urbana-Champagne; Pittsburgh Supercomputing Center (PSC), a joint effort of Carnegie Mellon University and the University of Pittsburgh together with Westinghouse Electric Company; the Cornell Theory Center at Cornell University; and the John von Neumann Center at Princeton University (NSF, 2009). However, the NSF decided to support fewer centers, and the Cornell and Princeton centers ceased to receive NSF funding in 1997 (Markoff, 1997). The remaining three centers continue to be the leading supercomputer centers in the present development of cyberinfrastructure in the U.S.

Second, NSF invested in distributed computing experiments and programs in late 1980s. Freeman (2007) documented the Coordinated Experimental Research (CER) Program started in the late 1980s as one of the most important programs during that time. In fact, many basic concepts in distributed computing that are important to current cyberinfrastructure development came out of CER.

Perhaps the most recent and familiar development is the creation of the Internet. Kahin and Jackson (2007) claim the term ‘cyberinfrastructure’ was initially used as a shorthand for “Internet–based information infrastructure” (¶ 1). Leiner et al. (2009) credit the beginning of the Internet to ARPANET (Advanced Research Projects Agency Network), a network established by the Defense Advanced Research Projects Agency (DARPA) in the 1960s. Freeman (2007) documented another critical beginning of the Internet as David Farber's distributed computing project at the University of California, Irvine, in the early 1970s, a project funded by NSF. Later, the project developed into Theory Net and then CSNet in the 1970s, and then NSFNET in the 1980s (Comer, 1983; Freeman, 2007; Jennings, Landweber, Fuchs, Farber, & Adrion, 1986). In the 1990s, along with the deployment of NSF supercomputer centers in the country, NSFNET eventually became the Internet we know today.

The revolutionary turning point of cyberinfrastructure emergence traces to 1999. According to Avery (2007), one of the earliest and most successful cyberinfrastructure projects, the Open Science Grid, was created. During that year, domain scientists working on large-scale projects in physics and astronomy in conjunction with computer scientists (with prior experience in distributed computing) came together and discussed the development of a grid-based computing infrastructure to facilitate data-intensive experiments in physics and astronomy. Shortly after the initial conception, three pioneering grid projects were funded: Particle Physics Data Grid (funded by the Department of Energy in 1999), GriPhyN (funded by the National Science Foundation in 2000), and the International Virtual Data Grid Laboratory (funded by the National Science Foundation in 2001). Due to the significant overlap of human and institutional representations in these projects, they began to consolidate resources and merge efforts by creating a national-scale grid cyberinfrastructure called the Trillium Consortium in 2002. In the following year, the consortium grew steadily and created the Grid3 prototype cyberinfrastructure project to support disciplines beyond physics and astronomy. It ran 1,000 concurrent applications successfully in October/November 2003.

Trillium continued to expand for two more years with recruitment of more domain and computer scientists interested in this new development. This expansion led to additional funding from the National Science Foundation and the Department of Energy (DOE) for the official establishment of the Open Science Grid (OSC) on July 20, 2005, while funding for the Trillium consortium (and its three inception projects) expired in 2006. OSC is in stable operation. In fact, it has recently received another round of funding from NSF and DOE from 2012 to 2016 (OSC, 2012).

As a result of grassroots cyberinfrastructure projects and their increasing impacts on scientific discovery in recent years, the NSF established the Office of Cyberinfrastructure (OCI) in 2006 to further this development through its funding (Seidel, et al., 2009). OCI's website states, "The Office of Cyberinfrastructure coordinates and supports the acquisition, development and provision of state-of-the-art cyberinfrastructure resources, tools and services essential to the conduct of 21st century science and engineering research and education." In other words, OCI's mission is to create a cross-directorate cyberinfrastructure for science and engineering research and education in the U.S. It administered budgets of about $185 million in 2008, $200 million in 2009 (NSF, 2010), $215 million in 2010, $214 million in 2011, and $236 million for 2012 (NSF, 2012).

The first NSF OCI's flagship cyberinfrastructure project is the TeraGrid (2001-2011), which Zimmerman and colleagues (Zimmerman, 2007; Zimmerman & Finholt, 2006; Zimmerman, Krause, Lawrence, & Finholt, 2008) have extensively documented. The TeraGrid gives domain scientists access to "computational resources, primarily in the form of supercomputers, large amounts of storage space, visualization services, fast networks, and software" (Zimmerman & Finholt, 2007, p. 241) needed to conduct large-scale research. TeraGrid began in 2001, and Zimmerman and Finholt (2008) provide a detailed account of its historical development. The idea behind the TeraGrid was to create partnerships to provide combined resources and services to scientists through tools and environments they were already using (Catlett, Beckman, Skow, & Foster, 2006).

TeraGrid was a consortium based on eleven partner sites, including National Center for Supercomputing Applications (NCSA), San Diego Supercomputer Center (SDSC), Pittsburgh Supercomputing Center (PSC), University of Chicago/Argonne National Laboratory (ANL), Texas Advanced Computing Center (TACC), Indiana University, Purdue University, Oak Ridge National Laboratory (ORNL), the Louisiana Optical Network Initiative (LONI), the National Institute for Computational Sciences (NICS), and the National Center for Atmospheric Research (NCAR). The TeraGrid supported more than 10,000 scientists across (XSEDE, 2011) more than 200 American universities, in a wide range of scientific research, including molecular biosciences, astronomical sciences, chemical and thermal systems, atmospheric sciences, earth sciences, computer and computation research, etc. By establishing such diverse partnerships and supporting an array of scientific research nationwide, NSF obliquely makes the claim that cyberinfrastructure is a technological platform with vast applications, thus justifying the investment.

In 2011, TeraGrid concluded and transitioned into a new project called XSEDE (The Extreme Science and Engineering Discovery Environment), which is funded by the US NSF for 2011-2016 and $121 million (XSEDE, 2011). XSEDE includes ten of the original 11 partners (excluding LONI) and welcomed six new partners: Center for Advanced Computing - Cornell University, Ohio Supercomputer Center - The Ohio State University, Rice University, Shodor Education Foundation, Southeastern Universities Research Association, University of California Berkeley, and the University of Virginia.

As previewed, the first section of this paper is to provide a brief overview of one story of cyberinfrastructure emergence. The second section of this paper will present the key definitions of the concept of cyberinfrastructure. The purpose of this definitional section is to frame cyberinfrastructure as a socio-technical system beyond its obvious technical characteristics.

The Various Definitions of Cyberinfrastructure: Towards a Socio-Technical Conceptualization

Cyberinfrastructure is an emerging and complex phenomenon. In order to provide a comprehensive background, we drew from definitions proposed by NSF documents, scientists, technologists, and social scientists who have written about cyberinfrastructure. We begin with the document that prompted the U.S. NSF to establish the 'Office of Cyberinfrastructure'. In the Atkins Report, Atkins, Droegemeier, Feldman, Garcia-Molina, Klein, Messerschmitt, Messina, Ostriker, and Wright (2003) to describe an "infrastructure based upon distributed computer, information, and communication technology" (p. 5). More specifically, they explain:

> 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 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. (p. 5)

Although this definition is full of technical references, it concludes an emphasis on the empowerment on the research community to potentially generate a revolution on science and engineering.

Furthermore, Stewart (2007) provides a similar definition: "Cyberinfrastructure consists of computing systems, data storage systems, advanced instruments and data repositories, visualization environments, and people, all linked together by software and high performance networks to improve research productivity and enable breakthroughs not otherwise possible" (¶. 3). Although Stewart focuses on the technical aspects of cyberinfrastructure, he did suggest that 'people' plays a key role in this highly technical infrastructure.

In addition to the specialized technologies, Hai (2004) suggests that cyberinfrastructure also includes email communication, net meetings, personal and organizational web pages with information and data, online digital libraries, and common search engines such as Google. The inclusion of these technologies suggests that an important aspect of cyberinfrastructure and the science enabled by cyberinfrastructure is to be powered by everyday communication and organizational activities engaged by people involved in it.

While cyberinfrastructure appears highly technical in nature, challenges from its non-technical dimensions have long been recognized. David (2004) is among one of the first to argue that the 'soft' foundations of cyberinfrastructure may be the hardest challenges to effectively enable cyberinfrastructure-enabled collaboration. He persuasively argues,

> Success in realizing the potential of e-Science - and other global collaborative activities supported by the 'cyberinfrastructure'- if it is to be achieved, will more likely be the resultant of a nexus of interrelated social, legal and technical transformations. The socio-institutional elements of a new infrastructure supporting research collaborations - that is to say, its supposedly 'softer' (non-engineering) parts - are every bit as complicated as the hardware and computer software, and, indeed, may prove much harder to devise and implement.

David's recognition of the social and organizational challenges brings attention to the need to think about the human aspects of cyberinfrastructure, even in its infancy, so the investment and efforts that go into its development will not be wasted.

Towards generating a sophisticated analytic lens to understand the social and organizational complexity of cyberinfrastructure, Lee and colleagues (2006) propose the concept of "human infrastructure". They define this concept as "the arrangements of organizations and actors that must be brought into alignment in order for work to be accomplished" (p. 484). They further elaborate, "Human infrastructure in large cyberinfrastructure projects is a vast series of overlapping traditional organizations, consortia, loosely organized groups, and networks" (p. 488). In their seminal piece on defining the notion of human infrastructure of cyberinfrastructure, they focus on describing "the social conditions and activities that constitute the emergence of infrastructure" (p. 484). More recently, Allison and colleagues (2012) in geoscience echoes, "Principal challenges are less technical than cultural, social, and organizational. Before we can make data interoperable, we must make people interoperable" (p. 13563).

In an interdisciplinary review of CI literature, Kee and colleagues (2011) synthesize and propose the following definition:

> Taken together, cyberinfrastructure is data intensive, computationally powerful, large-scale, distributed, hierarchical, interoperable, and with second-order growth over time. It consists of specialized and general hardware, high-performance computing applications and information and communication technologies, human and nonhuman agents, all interacting and connecting through multidimensional networks. This platform facilitates technologically generated virtual environments and socially generated virtual organizations that orient people, data, and technology towards common goals. Cyberinfrastructure leads to increased productivity, breakthrough innovations, and paradigmatic revolutions. Simplistically, cyberinfrastructure is an empowering network of advanced technologies; meta/data; and collaborative people and groups. (p. 164)

This synthetic definition shows how CI works as a socio-technical system (Hughes, 1989; Jirotka, Procter, Rodden, & Bowker, 2006; Zimmerman, 2007) of people and technology that is effective only when it 'interacts'. Given the paper's constant emphasis on "cyberinfrastructure" (instead of e-science, collaboratory, etc.), a potential risk is to appear to be technologically deterministic in our position. However, Leonardi and Barley (2008) maintain that it is possible to place an emphasis on the materiality of an organization without being technologically deterministic. We regard both the human and material dimensions of cyberinfrastructure as equally important. In fact, the focus of this paper is to highlight the human dimension in the interplay between the social arrangements and material technology in the context of cyberinfrastructure. Therefore, we turn to a discussion on the characteristics we argue to connect with research literature in communication and organizational studies.

Characteristics and Layers: Potential Analytical 'Cuts' for Communication and Organizational Research on Cyberinfrastructure Adoption and Diffusion

In this section, we discuss four layers of cyberinfrastructure conceptualized for cyberinfrastructure adoption and diffusion research as well as four pairs of interrelated characteristics that define cyberinfrastructure. As a preview, the four layers are the information and communication layer, the scientific and research layer, the macro structures layer, and the micro interactions layer. The four pairs of characteristics are participatory/bespoke, meta/complex, disruptive/revolutionary, and community/network. These layers and pairs describing cyberinfrastructure are not meant to be exclusive and exhaustive categories, but merely potential analytical 'cuts' through the complex phenomenon of cyberinfrastructure.

Given the acknowledgement of the people and technology in the conceptualization of cyberinfrastructure, Kee, Cradduck, Bloggett, and Olwan (2011) argue to further frame cyberinfrastructure based on its technical layers and social processes. Therefore, we propose another way to breakdown and categorize the key components of cyberinfrastructure for communication and organizational researchers interested in studying cyberinfrastructure adoption and diffusion. The four categories more easily connect the topic of cyberinfrastructure to existing literature on innovation diffusion and adoption in communication and organizational research. The four categories are as follows:

Information and Communication Layer: The information and communication layer includes single computers, the Internet, the Web, and commonplace information and communication technologies (concurrently used by scientists for non-research purposes). This can also be understood as the general layer. This layer relates to the ICT Succession Theory (Stephens, 2007; Stephens, Sørnes, Rice, Browning, & Saetre, 2008) and a huge body of literature on information and communication technologies.

Scientific and Research Layer: The scientific and research layer includes advanced instruments, simulation tools, visualization environment, high-performance computing applications, algorithms, and large data storage systems (mainly used for research purposes). This can also be referred to as the niche and specialized layer. Given its capabilities to support creation, modification, and manipulation of digital data, information, and artifacts via sophisticated and computational technologies and simulations, cyberinfrastructure can be framed as what Leonardi and Bailey (2008) term ‘transformational technologies’. This layer will be the most challenging dimension of cyberinfrastructure adoption and diffusion, therefore, the central focus of the discussion. In other words, cyberinfrastructure adoption, as conceptualized in this paper, is largely about the adoption of the scientific and research layer, although some discussion on the role of the information and communication layer is also included.

Macro Structures Layer: The macro structures layer includes social networks, teams, organizations, institutions, communities, fields, disciplines, and other macro entities and networks that tie people together because of common characteristics, goals, purposes, and relationships. These macro structures usually maintain existing practices and cultures among the people involved, beyond the confine of time and space. This is similar to the notion of a ‘virtual organization’ in cyberinfrastructure literature (Bird, Jones, & Kee, 2009; Foster, Kesselman, & Tuecke, 2001), ‘invisible college’ in traditional diffusion literature (Estabrooks et al., 2008; Gmür, 2003; Lievrouw, 1989; Rogers, 2003), and Structuration Theory’s notions of rules and resources (DeSanctis & Poole, 1994; Giddens, 1984). The macro structures provide the environmental context in which cyberinfrastructure adoption and diffusion is analyzed and understood.

Micro Interactions Layer: The micro interactions layer includes individual personnel, experts, subjective mentalities (i.e., interpretations, meanings, thoughts, intentions, motivations, decisions), and personal behaviors (i.e., habits, activities, communications), conformities to/deviations from practices and cultures that contribute to the evolution of the macro structures discussed in the previous paragraph. This is similar to the notion of systems of interactions

(DeSanctis & Poole, 1994; Giddens, 1984). The micro interactions reflect the actual behaviors of cyberinfrastructure adoption at the personal level.

As explained earlier, ‘cyberinfrastructure’ is a metaphorical term built on a more familiar term, ‘infrastructure’, which emerged in the 1920s to refer to a collection of roads, highways, bridges, rail lines, power grids, telecommunication systems, and other public services and technologies necessary to support and develop the industrial economy. In the 21st century, cyberinfrastructure is the collection of general computer technologies, information and communication technologies, specialized supercomputers, high-performance computing applications, teams, organizations, institutions, disciplinary practices, cultures, interactions, individual experts, subjective decisions, and personal behaviors that all converge to facilitate and advance scientific discovery and the knowledge economy. This emerging phenomenon can be described by four pairs of defining characteristics we will discuss next.

First, cyberinfrastructure is a *participatory/bespoke* innovation. CI tools are often built by domain scientists and computational technologists working jointly on funded projects. They often submit grant proposals together to foreseek funding to investigate scientific problems by building CI tools. In other words, both groups commit to building CI for specific scientific problems before the tools actually exist. Cyberinfrastructure is a participatory innovation because unlike most traditional/commercial innovations, domain scientists participate as users in the development and design of a tool to be developed and built by computational technologists. It requires long-term collaboration and ongoing interaction during the process of building the tools.

As alluded to, cyberinfrastructure is also a bespoke innovation because the tools are often custom-made, based on particular theoretical and methodological assumptions, with the intent for participating scientists to address their unique scientific problems and research questions. These problems and questions are often referred to as the grand challenges of science. In this early phase of development, no two CI tools are identical. Therefore, the participatory and bespoke qualities go hand-in-hand for cyberinfrastructure as an innovation. At the same time, remaining in a permanent beta phase (Neff & Stark, 2004) is a natural state of cyberinfrastructure tools. The decision to adopt cyberinfrastructure is made before an innovation is built, which is a different type of adoption decision than those with traditional innovations that are mass-produced and can be bought off-the-shelf. The participatory/bespoke qualities, along with the long beta phase, complicate the traditional notions of observability and trialability (Rogers, 2003) to promote adoption because potential adopters do not get to ‘observe’ or ‘try it out’ before a formal commitment for adoption is made. What they can observe in their peers’ projects may not be the tools they will develop or reinvent during their own CI projects.

Second, cyberinfrastructure is a *meta/complex* innovation because it refers to an abstract cluster of technologies and processes that support large-scale scientific work. Because of this range of technologies and processes, CI adoption and implementation reflects the emerging view of combinatorial and sequential use of technologies (Stephens, 2007; Stephens, Sørnes, Rice, Browning, & Saetre, 2008) instead of the media substitution hypothesis, which suggests you substitute one technology for another (Krugman, 1985). Research shows that wholesale media substitution has not occurred in organizations (Rice, Grant, Schmitz, & Torobin, 1990; Rice & Shook, 1990). In fact, there are significant values in sequential and simultaneous use of technologies. People do not always give up paper technologies for digital technologies (Rice & Schneider, 2005). In practice, people use both paper and digital technologies to complement each other when performing organizational tasks. In other words, a new innovation adds to an existing repertoire of technologies in organizations. Because CI as a technological platform involves a range of hardware and software, it is also highly complex. The meta and complex qualities go hand-in-hand for cyberinfrastructure.

Third, cyberinfrastructure is a *disruptive/revolutionary* innovation. It is disruptive (as opposed to a sustaining innovation) since it causes a shift in a field or industry and disrupts an existing model of work or business (Christensen, 1997). The term 'radical' innovation (Rice, 2009) can also be used to characterize CI. Due to the computational power of CI resources and high-performance computing applications, domain scientists are now able to do science at a speed and scale that was never possible before. This capacity gives CI a high degree of relative advantage (Rogers, 2003) and perceived usefulness (Davis, Bagozzi, & Warshaw, 1989) over traditional models of scientific work. However, because CI is revolutionary, the learning curve is high, which disrupts the organizational temporality (Ballard, 2007; Ballard & Seibold, 2000, 2004) and organizational workflow (Van der Aalst & Van Hee, 2004). The tension between the benefits (i.e., relative advantage, Rogers, 2003; perceived usefulness, Davis et al., 1989) on one hand and the costs (i.e., time spent learning due to its perceived complexity, Rogers, 2003; its lack of perceived ease of use, Davis et al., 1989; and a lack of perceived compatibility with existing knowledge and organizational arrangements, Rogers, 2003; and very low trialability, Rogers, 2003) on the other hand presents a competition for temporal, intellectual, and financial resources that become sunk costs that cannot be recovered if an adopted CI project fails upon execution or completion. This tension complicates cyberinfrastructure adoption decisions.

Finally, cyberinfrastructure is a *community/network* innovation. Social influence (Fulk, Schmitz, & Steinfield, 1990; Stephens & Davis, 2009) and interpersonal communication in social networks (Rice, 2009; Rice, et al., 1990; Rogers, 2003) have been identified as drivers of innovation diffusion and adoption. However, cyberinfrastructure is a large-scale innovation, and its adoption leads to a community of users sharing the same resources. On one hand, data contribution to the community repository for reuse is good for all as public goods and collective benefit. On the other hand, more users in queue for the community instruments means slower processing for those involved. Furthermore, new users sometimes make changes to existing settings on shared resources without knowing the potential impacts of their changes. This behavior is similar to what Rice and Rogers (1980) call "reinvention". New changes that work for some may negatively impact the workflows of others. There are a variety of social influences with a mix of utilities and norms (Kraut, Rice, Cool, & Fish, 1998). This mixed self-interest of existing users can impact the social influence and interpersonal communication processes surrounding cyberinfrastructure diffusion and adoption.

As a review, the four layers are the information and communication layer, the scientific and research layer, the macro structures layer, and the micro interactions layer. The four pairs of characteristics are participatory/bespoke, meta/complex, disruptive/revolutionary, and community/network. Through these analytical 'cuts' through the complex phenomenon of cyberinfrastructure, we argue that these layers and characteristics provide an initial model and framework to describe future large-scale communication networks, information infrastructure, and virtual organizations.

Implications & Conclusion: Some Suggestions for Taking Up Cyberinfrastructure Adoption in Innovation Diffusion Research.

So how do we make sense of all of these? What can cyberinfrastructure's history of emergence, socio-technical definitions, as well as its characteristics and layers suggest new directions for innovation adoption and diffusion research in communication and organizational research? We suggest the following three.

First, studying cyberinfrastructure adoption and diffusion helps describe future large-scale information infrastructure. CI movement from grassroots community efforts towards a more organized and federally funded program, such as in the cases of TeraGrid and XSEDE in the US, suggests that CI movement may be evolving from bottom up effort into a more top town program. Thus, adoption and diffusion research can draw from the emerging field of dissemination and implementation science (Brownson, Colditz, & Proctor, 2012) about building and sustaining large-scale programs and efforts. Proctor and Brownson (2012) maintain that *dissemination* is an active approach with the goal of spreading innovations to "target audience via determined channels using planned strategies" (p. 261). Dearing and Kee (2012) explain that *implementation* explores "what happens after adoption occurs, especially in organizational settings. Implementation is one stage (after awareness and adoption, and before sustained use) in the over-time process of diffusion" (p. 56). Recently, Hunsinger (2010) observes that cyberinfrastructure is moving from an organic and innovative organization (i.e., bottom up) form he calls 'nomadic science' to a controlled and centralized organization (i.e., top down) he calls 'royal science'. This observation signals a need to move beyond what Rabin and Brownson (2012) describes as passive, untargeted, unplanned, and uncontrolled innovation diffusion to what we would like to argue for: an active, targeted, planned, and controlled program of cyberinfrastructure dissemination and implementation. Given CI's participatory/bespoke and disruptive/revolutionary characteristics, one potential fruitful research focus is on individual, organizational, and community capacity assessment and capacity building for adoption and implementation towards building a future large-scale information infrastructure.

Second, studying cyberinfrastructure adoption and diffusion gives us a sense of future large-scale communication networks. CI emergence out of inter-organizational collaborations, consortia, communities, as well as its meta/complex and community/network characteristics suggest that CI presents a case for exploring the recursive relationships between the macro structures and the micro interactions layers in a large community of practice and complex system. In other words, the sociological theory of structuration (Giddens, 1984) can potentially shed lights on the adoption mechanisms and diffusion processes in the communication networks of cyberinfrastructure. More specifically, one potentially fruitful approach is to conceptualize three levels of communication networks and recursive relationships: individuals and organizations, organizations and consortia/communities, and consortia/communities and individuals. This approach can consider framing the context of cyberinfrastructure as an emerging moral community (Browning & Shetler, 2000) with complex networks. Furthermore, this approach can also integrate the notion of concurrent and sequential uses of technologies to accomplish work (Stephens, et al., 2008). This approach utilizing both a structurational perspective and technology concurrencies/sequences more fully capture the complexity of the relationships and networks, and how adoption and diffusion researchers can take these complex context of organizations, consortia, and networks into understanding individual, organizational, and inter-organizational adoption decisions in a complex ecology of technologies and media.

Third, studying cyberinfrastructure adoption and diffusion implies understanding the adoption and diffusion of its associated social and organizational practices in the form of future large-scale virtual organizations. Shirky (2009) argues, "Revolution doesn't happen when society adopts new technologies—it happens when society adopts new behaviors" (p. 160). In order for cyberinfrastructure to revolutionize science and engineering, one of NSF's key items is its funding agenda is to develop effective virtual organizations enabled by cyberinfrastructure. This is evident in NSF's establishment of the VOSS (Virtual Organizations as Sociotechnical Systems) program under the Office of Cyberinfrastructure since 2008. Castell (2011a, 2011b) uses the metaphor of "flow" as an powerful analytic frame to understand the forces that make up today's society. He argues that various "flows", including financial capital, foreign direct investments, labor immigrations, technological know-how, production, information, culture, etc., give rise to the networked society we live in. Similarly, McPhee and colleagues (McPhee & Iverson, 2009; McPhee & Zaug, 2009 (reprinted from 2000)) use the same metaphor to explore the communicative constitution of organizations. They argue that membership negotiation, self-structuring, activity coordination, and institutional positioning are the four communicative flows that give rise to organizations.

In the case of cyberinfrastructure and its associated virtual organizations, *membership negotiation* refers to who are considered members of cyberinfrastructure projects and who has access to cyberinfrastructure resources from across the country via the Internet. *Self-structuring* refers to cyberinfrastructure policies and project proposals that help a wide range of participants, distributed organizations, and the larger communities to self-structure towards a stated goal. *Activity coordination* refers to what distributed participants and virtual groups do on a daily basis to coordinate their cyberinfrastructure related activities, sometimes deviating from what one would do if acting in total accordance with self-structure policies and documents. *Institutional positioning* is how organized groups, virtual organizations, larger communities, and funding agencies collectively communicate cyberinfrastructure to an external audience, including the congress, the scientific community at large, and the public. In addition to treating these four flows as distinct, another potentially fruitful direction is to study how McPhee's four flows overlaps and in pairs (Browning, Greene, Sitkin, Sutcliffe, & Obstfeld, 2009) give rise to organizations and its complexity.

In this paper, we set out to answer two questions: "*What is cyberinfrastructure in the research context of innovation adoption and diffusion? How can communication and organizational researchers connect with this emerging phenomenon with existing theoretical perspectives?*" In order to achieve this goal, we first summarized one of several possible historical sketch of CI emergence in the US. This section signals the significance of cyberinfrastructure and the large-scale collaborative efforts that have converged in relatively recent history. Second, we provided a brief overview of the various CI definitions in the literature, with an emphasis on its communication and organizational dimensions in addition to its obvious technical nature. This section presents cyberinfrastructure as a socio-technical system that is suitable for communication and organizational research. Third, we provided a framework on how the phenomenon of cyberinfrastructure can be distinguished by its key pairs of characteristics and interaction layers that could help connect with communication and organizational research. These pairs and layers describing cyberinfrastructure are not meant to be exclusive and exhaustive categories, but merely potential analytical 'cuts' through the complex phenomenon of cyberinfrastructure. Finally, we discussed the implications of our framing and conclude with some the paper with some future research directions. Although cyberinfrastructure is still in its infancy, continuing funding for cyberinfrastructure development support suggests a bet on the future and antenarrative (Barge, 2004; Boje, Rosile, & Gardner, 2007) of cyberinfrastructure.

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