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The Rationalities behind the Adoption of Cyberinfrastructure for e-Science in the Early 21st Century U.S.A.

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The Rationalities behind the Adoption of Cyberinfrastructure for e-Science in the Early 21st Century U.S.A.

BY

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DEDICATION

for all my interview participants, and the men and women who usher in cyberinfrastructure in the early 21st century.

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The Rationalities behind the Adoption of Cyberinfrastructure for e-Science in the Early 21st Century U.S.A.

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Based on grounded theory and thematic analysis of 70 in-depth interviews conducted over 32 months (from November 2007 to June 2010) with domain scientists, computational technologists, supercomputer center administrators, program officers at the National Science Foundation, social scientists, policy analysts, and industry experts, this dissertation explores the rationalities behind initial adoption of cyberinfrastructure for e-science in the early 21st century U.S. This dissertation begins with Research Question 1 (i.e., how does cyberinfrastructure's nature influence its adoption process in early 21st century U.S.?) and identifying four areas of challenging conditions to reveal a lack of trialability/observability (due to the participatory/bespoke nature), a lack of simplicity (due to the meta/complex characteristic), a lack of perceived compatibility (due to the disruptive/revolutionary quality), and a lack of full control (due to the community/network property). Then analysis for Research Question 2 (i.e., what are the rationalities that drive cyberinfrastructure adoption in early 21st century U.S.?) suggests that there are three primary driving rationalities behind adoption. First, the adoption of cyberinfrastructure as a meta-platform of interrelated technologies is driven by the perceived need for computational power, massive storage, multi-scale integration, and distributed collaboration. Second, the adoption of cyberinfrastructure as an organizational/behavioral practice is driven by its relative advantages to produce quantitative and/or qualitative benefits that increase the possibility of major publications and scientific reputations. Third, the adoption of cyberinfrastructure as a new approach to science is driven and maintained by shared visions held by scientists, technologists, professional networks, and scientific communities. Findings suggests that initial adoption by pioneering users was driven by the logic of quantitative and qualitative benefits derived from optimizing cyberinfrastructure resources to enable breakthrough science and the vision of what is possible for the entire scientific community. The logic was sufficient to drive initial adoption despite the challenging conditions that reveal the socio-technical barriers and risky time-investment. Findings also suggest that rationalization is a structuration process, which is sustained by micro individual actions and governed by macro community norms simultaneously. Based on Browning's (1992) framework of organizational communication, I argue that cyberinfrastructure adoption in the early 21st century lies at the intersection of technical rationalities (i.e., perceived needs, relative advantages, and shared visions) and narrative rationalities (i.e., trialability, observability/communicability, simplicity, perceived compatibility, and full control).

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CHAPTER ONE: INTRODUCTION

Cyberinfrastructure is a rapidly emerging facilitator of large-scale and distributed science in the early 21^{st} century. By using Rogers' (2003) definition of an innovation, cyberinfrastructure (CI) can be conceptualized as having three distinct yet interrelated dimensions: 1) it is an object (i.e., a meta-platform of interrelated technologies and processes around a network of supercomputers) (Atkins et al., 2003), 2) it is a practice (i.e., a scientist's transition from simply working with local personal computers with his/her own data in a laboratory to connecting to supercomputers, aggregated datasets, remote instruments, distributed colleagues, etc.) (Lee, Dourish, & Mark, 2006), and 3) it is an idea (i.e., a shift in discovery science from theoretical and/or experimental methods to simulation, visualization, and modeling techniques on large-scale and multi-scale datasets in digital forms) (Getov, 2008). The three dimensions co-influence each other in the adoption and implementation process. Atkins and colleagues (2003) maintain that CI is revolutionizing research and education in science and engineering across multiple disciplines in the early 21^{st} century United States.

Rice and Webster (2002) define adoption as "allocation of resources to acquire an innovation" (p. 193). The resources required for cyberinfrastructure adoption primarily include time, knowledge, and funding. A central challenge, spurred by the unique nature of cyberinfrastructure, is that the innovation of cyberinfrastructure and its development in the early 21st century are different from many traditional innovations in the past. With a pro-innovation bias, this dissertation argues that in order to fully optimize the cyberinfrastructure being developed today, we need more domain scientists (i.e., disciplinary scientists) to adopt and implement CI to conduct scientific research. In other words, I approach this topic with the hope that cyberinfrastructure will become a widely diffused and adopted innovation in science and society in the future.

In a state of the art review of information systems research, Orlikowski and Iacono (2001) frame technological artifacts as "those bundles of material and cultural properties packaged in some socially recognizable form" (p. 121). They propose to organizational researchers to theorize about technological artifacts and then treat these theories as central in their research, beyond looking simply at the effects, context, and capabilities of technologies. Inspired by this call to theorize about technology and to include the initial findings in a study, I derived four pairs of interrelated CI characteristics from early analysis of pilot data, theoretical memos, and literature; these four pairs help frame this dissertation's organization.

First, cyberinfrastructure is a *participatory/bespoke* innovation (Atkins et al., 2003; Kee, Cradduck, Blodgett, & Olwan, in press). CI tools[1] are often built by domain scientists and computational technologists[2] 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.

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[1] The term "tools" will be used to also refer to applications, computer programs, codes, and similar technological elements of CI from this point onwards.

[2] In the literature of cyberinfrastructure studies, computational technologists are sometimes loosely referred to as computer scientists. In this dissertation, I will use "technologists" to emphasize their role of building 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. 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), as discussed in Chapter 2, 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 (Atkins et al., 2003; Kee et al., in press). 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 (Atkins et al., 2003; Kee et al., in press). 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, 2004a) 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 (Atkins et al., 2003; Kee et al., in press). 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 adoption and implementation. 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 adoption and implementation.

SCOPE OF THE PROJECT

The introduction thus far presents cyberinfrastructure as an innovation with three distinct yet interrelated dimensions (i.e., an object, a practice, and an idea) and four pairs of unique qualities (i.e., participatory/bespoke, meta/complex, disruptive/revolutionary, and community/network) that complicate traditional understanding of innovation adoption. The four pairs of qualities will guide the first part of the dissertation and the interrelated dimensions will guide the exploration of the second part of this dissertation. While there is a wealth of research and knowledge on innovation adoption since Ryan and Gross's (1943) hybrid seed corn study of Iowa farmers in the 1940s, cyberinfrastructure is an innovation that deserves new research attention for several reasons.

First, as discussed thus far, the nature and development of cyberinfrastructure in the early 21st century make it a different innovation from traditional innovations. This is an opportunity to study the adoption of a different category of innovation. Second, the National Science Foundation established the Office of Cyberinfrastructure in 2006 (Seidel, Muñoz, Meacham, & Whitson, 2009) to fund and facilitate cyberinfrastructure develop across the U.S. As I will review in Chapter 3 in more details, the serious financial and intellectual investments (Edwards, Jackson, Bowker, & Williams, 2009) in cyberinfrastructure signal that CI is an innovation with tremendous significance. Cyberinfrastructure is not just a random new thing that has not been studied. It is a forcefully emerging phenomenon that deserves serious research attention.

This dissertation project seeks to investigate the adoption of cyberinfrastructure in the early 21st century U.S. Due to cyberinfrastructure's relative infancy, this dissertation project examines adoption as it takes place during the *innovation development process*, when "actors ranging from individual entrepreneurs and collaborative users through governmental agencies and corporations attempt to identify needs and/or problems, conduct research on the ways to solve these problems, develop the innovation, and commercialize or otherwise promote it" (Rice, 2009, p. 491). Because adoption is complex during this very early phase among what Rogers (2003) calls 'innovators' (the first 2.5 percent of adopters in a social system), the goal is to understand their rationalities for adoption and the challenging conditions they face in their sustained adoption before cyberinfrastructure has become common place.

Drawing from a wealth of innovation adoption literature, a study of CI represents an opportunity to investigate innovation adoption with an emerging and multi-dimensional perspective. In addition to adopting Rice and Webster's (2002) conceptualization of adoption as being intertwined with diffusion and use, this project also includes development and implementation (Leonardi, 2009a) along with appropriation (DeSanctis & Poole, 1994; Leonardi, 2007) as a complete adoption process. In other words, adoption in this dissertation is not simply a decision point. Cyberinfrastructure adoption is an ongoing process sustained by its development, use, appropriation, implementation, and diffusion.

The purpose of this research project is to develop a theoretical framework, grounded in the participatory/bespoke, meta/complex, disruptive/revolutionary, and community/network nature of cyberinfrastructure, to understand the rationalities that drive innovation adoption in the new landscape of cyberenvironment and media ecology. Toward that goal (an integrated theoretical framework), this project addresses two research questions: First, how does cyberinfrastructure's nature influence its adoption process in the early 21st century U.S.? I draw upon Fulk and colleagues' (1990) argument that rationality represents "sense-making… created *after* the occurrence of the behavior. In this case, it is to interpret the behavior retrospectively rather than to direct the choice prospectively" (p. 123, emphasis original). Second, what are the rationalities that drive cyberinfrastructure adoption in the early 21st century U.S.? Then, findings from these two research questions will be juxtaposed with existing literature to develop a preliminary framework of cyberinfrastructure adoption in the early 21st century U.S.

Developing a preliminary framework to describe and explain adoption is a challenging task given that CI development involves multiple stakeholder groups. To address the complexity, this project includes experiences, opinions, and perceptions from the following six groups of stakeholders: (1) domain scientists who use cyberinfrastructure to conduct research, (2) computational technologists who build and provide user-support for cyberinfrastructure tools, (3) administrators of supercomputer centers and research laboratories that provide local management and national leadership in building a nation-wide infrastructure, (4) directors and program officers at the National Science Foundation (NSF, especially in the Office of Cyberinfrastructure) who facilitate the allocation of governmental funding to support cyberinfrastructure projects and developments, (5) social scientists and policy experts who have been involved in cyberinfrastructure projects and are sensitive to the social, organizational, and political dimensions of cyberinfrastructure adoption and implementation, and (6) computing experts from commercial industry that have insights about academic and scientific computing. A diverse collection of stakeholder groups allows robust triangulation of the findings drawn from a wide range of voices and interests.

Atkins and colleagues (2003) proposed that the NSF should establish the Office of Cyberinfrastructure because of the bottom up and grassroots efforts they observed across the U.S. In 2006, NSF formally established the Office of Cyberinfrastructure to coordinate this national development (Seidel et al., 2009). The timing of this data set and dissertation project is significant. Theoretically, this dissertation captures self-motivated adoption decisions before cyberinfrastructure reached critical mass (Markus, 1987) in the diffusion process. This is an important point in the diffusion process to study innovation adoption because Rogers (2003) contends that the opinion leaders of an innovation are often the early adopters in a population. The technical and narrative rationalities behind their cyberinfrastructure adoptions will likely drive the remaining diffusion process. Particularly, findings from this dissertation may have implications for cyberinfrastructure deployment (Dunning, Berman, & Boisseau, 2006), and they may provide useful insights for promoting adoption to optimize and maximize NSF's investments in building a national cyberinfrastructure for unprecedented speed and scale of scientific discovery.

CHAPTER TWO: LITERATURE REVIEW

This dissertation project integrates literature from innovation adoption and organizational communication in the context of cyberinfrastructure. It examines CI as a multidimensional innovation with four pairs of qualities that influence its adoption process. In this chapter, I seek to accomplish two goals: (1) provide a specific context for cyberinfrastructure, and (2) provide a literature review on innovation adoption theories and rationality in the context of organizational communication. In order to accomplish these goals, I will first provide a historical context for the emergence of cyberinfrastructure, an overview of e-science enabled by cyberinfrastructure, and a review of the definitions of cyberinfrastructure. The four pairs of qualities discussed in the introduction will be highlighted at the end of the historical overview of cyberinfrastructure development in the U.S. Second, I will review key factors of innovation adoption and technology implementation based on leading theories, including Diffusion of Innovations Theory (Rice, 2009; Rogers, 2003), Technology Acceptance Model (Bagozzi, Davis, & Warshaw, 1992; Davis, 1989), Social Influence Model (Fulk et al., 1990; Fulk, Steinfield, Schmitz, & Power, 1987), and ICT[3] Success Theory (Stephens, 2007; Stephens et al., 2008). Third, I will discuss rationality in organizations and explore how they operate to influence the way people communicate about situated innovations and technologies-in-practice.

THE EMERGENCE OF CYBERINFRASTRUCTURE IN THE U.S.

In this section, I list one sequence of the major historical events and projects that contributed to the emergence of cyberinfrastructure in the U.S. Atkins and colleagues

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[3] ICT stands for ‘information and communication technologies’, the original focus of this theory. ICT is the acronym the theorist used to describe her theory in the original article.

(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 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 during the time of data collection for this dissertation in 2008 (and foreseeable future).

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 2005 to further this development through its funding. 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, and $219 million for 2010 (NSF, 2010).

NSF OCI’s flagship cyberinfrastructure project is the TeraGrid, which Zimmerman and colleagues (Zimmerman, 2007; Zimmerman & Finholt, 2006; Zimmerman & Finholt, 2007; Zimmerman & Finholt, 2008; 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).

Today, TeraGrid is 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 supports about 4,000 scientists across about 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. However, as stated in the Introduction, in order to fully optimize the cyberinfrastructure developed today, we need more domain scientists (i.e., disciplinary scientists) to adopt and implement cyberinfrastructure in order to conduct scientific research. This pro-cyberinfrastructure bias led to the second research question to explore the rationalities behind adoption.

According to the sequence of events presented in this section, cyberinfrastructure can be framed as both an evolution and revolution. It is an evolution of earlier technological development funded by NSF. However, the Trillium consortium, OSC, and TeraGrid demonstrate that the cyberinfrastructure model drastically changed how science can be conducted by creating a robust and powerful grid infrastructure. It is drastically different from traditional science because these projects combine distributed datasets, supercomputing resources, and disciplinary experts in a common platform to produce science at an unprecedented scale and speed. In this sense, cyberinfrastructure is revolutionary (Atkins et al., 2003). As such, its *disruptive/revolutionary* natures are important to consider when looking at the question of adoption. Furthermore, the example of the Trillium consortium in 1999 demonstrates the *participatory/bespoke* natures of cyberinfrastructure in that it was created by domain scientists and computer scientists who came together to create a new technological platform mainly to investigate specific new scientific problems. The later example of TeraGrid exemplifies the *community/network* natures of cyberinfrastructure because it is built by a community of technologists (from 11 independent supercomputer centers) and multidisciplinary scientists from various universities. The next section reveals the *meta/complex* nature of cyberinfrastructure by exploring its definition.

THE DEFINITION OF CYBERINFRASTRUCTURE AND E-SCIENCE

Cyberinfrastructure is an emerging term proposed by 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)

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). Furthermore, 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.

Cyberinfrastructure has also taken on other labels, such as e-infrastructure in the United Kingdom (Hey & Trefethen, 2005; Meyer & Dutton, 2009; Meyer, Schroeder, & Dutton, 2008) and e-research infrastructure in Australia and Europe (Eccles et al., 2009; Jankowski, 2009; Schroeder, 2007). It has often been discussed in relation to a similar concept of *collaboratory*, which emphasizes the distributed collaborations supported by cyberinfrastructure (Olson, Zimmerman, & Bos, 2008).

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). 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).

E-science refers to science enabled by cyberinfrastructure (Jankowski, 2007; Schroeder, 2007). It is often understood as the science supported by advanced computing technologies (De Roure & Hendler, 2004). Besides ‘e-science’, CI-enabled science has also been referred to as ‘telescience’ (Lievrouw & Carley, 1990), ‘cyberscience’ (Nentwich, 2003), ‘large-scale science’ (Johnston, 2004), and ‘enhanced science’ (Jankowski, 2007) in the literature. 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).

One example of e-science and cyberinfrastructure at the international scale is the Enabling Grids for E-sciencE (EGEE) documented by Bird, Jones, and Kee (2009). In 2007, EGEE processed about 44 millions jobs (a job is approximately a run of a single program to process data with duration of about 8 to 12 hours) for high energy physics experiments. In 2009, EGEE accessed about 20 petabytes of data (about 4 million DVDs) and 80,000 CPUs across hundreds of sites. In the same year, the EGEE infrastructure regularly ran at least 100 applications and served more than 10,000 scientists worldwide. From an organizational standpoint, EGEE is noteworthy because it supported more than 200 virtual organizations of scientists working together in 2009. Some virtual organizations involved more than 2,000 scientists at a time. The example of EGEE demonstrates the way cyberinfrastructure is revolutionizing science at a scale that makes it an innovation that deserves research attention. This example also illustrates the meta/complex and community/network natures of cyberinfrastructure.

In some way, the definitions cited above for cyberinfrastructure heavily emphasize the categories of hardware and software. The notion of ‘people’ in the conceptualization of cyberinfrastructure is under-developed in the definitions presented thus far. However, the notion of infrastructure in the sciences has become more than simply the “tubes and wires” (Ribes & Bowker, 2008, p. 311) that allow it to operate. Ribes and Finholt (2009) argue that a CI without people is not a CI at all. This can be seen in the vision of Atkins et al. (2003), in which they charged CI to be “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 in it ” (p. 5). The argument advanced by Ribes and Finholt (2009) and the vision proposed by Atkins et al. (2003) offer a core of CI that includes a notion of the people and communities involved in implementing it and the payoffs for their efforts on it, as well as the social and organizational arrangements that support its implementation.

One of the most cited attempt to theorize the social and organizational aspects of cyberinfrastructure is the work by Lee, Dourish, and Mark (2006). They introduce the concept of the ‘human infrastructure’ of cyberinfrastructure by defining ‘human infrastructure’ as “the arrangements of organizations and actors that must be brought into alignment in order for work to be accomplished” (p. 484) in the context of CI-enable scientific work. This conceptualization is similar to what Olson, Malone, and Smith (2001) call coordination in Coordination Theory. They use the concept of ‘human infrastructure’ as an analytic lens to examine the organizational arrangements that enable large-scale distributed work in CI projects. Also included are the social activities and conditions that give rise to cyberinfrastructure. This important lens 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’. Leonardi and Barley (2008) maintain that it is possible to place an emphasis on the materiality of an organization without being technologically deterministic. Although this dissertation acknowledges a pro-innovation bias as noted earlier, I regard both the human and material dimensions of cyberinfrastructure as equally important. The focus of this dissertation is on the interplay between social arrangements and material technology in the context of cyberinfrastructure adoption.

Given the acknowledgement of the people and technology in the conceptualization of cyberinfrastructure, Kee, Cradduck, Bloggett, and Olwan (in press) argue to further frame cyberinfrastructure based on its technical layers and social processes. Therefore, I propose another way to breakdown and categorize the key components of cyberinfrastructure for the purpose of this research project. The four categories more easily connect the topic of cyberinfrastructure to existing literature on innovation adoption and organizational communication, which emphasize the social aspects. 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 et al., 2008) discussed later.

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 central focus of this dissertation research when the notion of cyberinfrastructure adoption is discussed. In other words, cyberinfrastructure adoption, as conceptualized in this study, 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 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 and implementation 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. Cyberinfrastructure is at the forefront of the nation’s agenda because of its potential impact on the information economy and knowledge society.

As previously stated, the first part of this literature review provides a specific context for cyberinfrastructure. In the preceding paragraphs, I first provided a historical context for the emergence of cyberinfrastructure, then an overview of e-science enabled by cyberinfrastructure, and finally a review of the definitions of cyberinfrastructure. The discussion provided details to illustrate the participatory/bespoke, meta/complex, revolutionary/disruptive, and community/network characteristics of cyberinfrastructure. The purpose of the first part of the review is to establish cyberinfrastructure as a unique context and case for studying innovation adoption in organizations. In the second half of the literature review, I will explore literature on innovation adoption and implementation in organizational context. These constructs are important because they are the way in which the four layers of CI (i.e. information and communication layer, scientific and research layer, macro structures layer, and micro interaction layer) come about.

INNOVATION ADOPTION & IMPLEMENTATION

There is a huge body of literature on innovation adoption and implementation. Research on the adoption and spread of innovation has a long history of about 110 years (Dearing, 2008). In June 2008, Rice (2009) located 29,000 citations on Google Scholar for ‘Diffusion of Innovations’. Exactly two years later, Google Scholar yielded 43,300 references with the same search phrase. Similar terms also yielded high results: ‘innovation adoption’ 14,200 results, ‘technology adoption’ 46,800 results, ‘innovation implementation’ 3,650 results, and ‘technology implementation’ 19,900 results. Therefore, the following section is only a modest review of the key theories on innovation/technology adoption and implementation. I draw particularly from Diffusion of Innovations Theory (Rice, 2009; Rogers, 2003), Technology Acceptance Model (Bagozzi et al., 1992; Davis, 1989), Social Influence Model (Fulk et al., 1990; Fulk et al., 1987), and ICT Succession Theory (Stephens, 2007; Stephens et al., 2008). This section will begin with a brief discussion of adopter categories, followed by classic factors of adoption/implementation.

Adopter Categories and Diffusion Process

According to Rogers (2003), there are five types of adopters of innovations, and their usual distributions are indicated by the percentages after the categories, based on the percentages associated with standard deviations of the normal curve of innovation adoption: innovators (2.5 percent), early adopters (13.5 percent), early majority (34.0 percent), late majority (34.0 percent), and laggards (16.0 percent). Innovators are usually venturesome. They have the ability to understand and apply complex technical knowledge. They are also able to cope with high degree of uncertainty. Early adopters usually have the greatest degree of opinion leadership in most systems and are usually respected by their peers. The early majority adopts the innovation just before the average member of a system does. However, they may deliberate for some time before completely adopting a new idea. The late majority is usually skeptical of the innovation. Adoption may be both an economic necessity for them and the result of peer pressure. Laggards tend to be suspicious of innovations and change agents. They are also usually lagging far behind awareness-knowledge of a new idea.

As mentioned in the Introduction, this project examines adoption as it takes place during the *innovation development process*, when “actors ranging from individual entrepreneurs and collaborative users through governmental agencies and corporations attempt to identify needs and/or problems, conduct research on the ways to solve these problems, develop the innovation, and commercialize or otherwise promote it” (Rice, 2009, p. 491). In this dissertation, although the focus is on adoption, it is conceptualized as related to emergence, development, deployment, and implementation simultaneously in the innovation development process. I discuss in more details in the methodology section (Chapter 3) the way I distinguished these stages.

Classic Factors and Mechanisms In Innovation Adoption/Implementation

Within the literature on innovation adoption and technology implementation, the best known theory is Rogers' (2003) Diffusion of Innovations (DOI) theory. DOI theory is highly influential in social science research (Browning & Sørnes, 2004). In fact, Rice (2009) reports that DOI Theory is "the most cited, summarized, and applied communication theory" (p. 489). Recent updates of DOI theory include Rice's (2009) theoretical extension of DOI in media effects; Greenhalgh and colleagues' (2004) model of evidence-based innovation diffusion and sustainability in health service organizations; Rice and Webster's (2002) integrated model of communication technologies and new media adoption, diffusion, and use; Valente's (1995) review of network models of DOI; Moore and Benbasat's (1991) comprehensive scale development for adoption of information technology innovation, and Venkatesh et al's (2003) attempts to link eight models, including DOI theory, to create a unified theory of technology acceptance and use.

As more innovations are introduced to the society, more studies are being undertaken to increase our understanding of technology adoption and implementation. The next section begins a review based on Rogers' (2003) original framework of classic innovation attributes and adoption factors, juxtaposed with recent diffusion literature and useful models that are relevant to the case of cyberinfrastructure. As a preview, these factors include relative advantage, perceived compatibility, perceived complexity/simplicity, observability/communicability, trialability, and social influence/communication network.

Relative Advantage. Rogers (2003) proposes and defines *perceived relative advantage* as "the degree to which an innovation is perceived as being better than the idea it supersedes" (p. 229). He points out that this advantage is often conceived of as financial profitability, social prestige, and other perceived gains by potential users. Similar to the notion of perceived relative advantage, Davis and colleagues (1989) propose that the key predictor of computer technology adoption in organizational setting is *perceived usefulness,* defined as “the prospective user’s subjective probability that using a specific application system will increase his or her job performance within an organizational context” (p. 985). They maintain that the most important predictor of users’ innovation adoption at the workplace is the perceived usefulness of the system in improving job performance, which is then likely to lead to extrinsic rewards (such as pay increases and promotions). Both constructs suggest that a potential adopter will likely adopt an innovation if it is perceived as relatively useful and more advantageous than an existing one at bringing some forms of gain in a social and organizational context.

The construct of relative advantage has a substitution assumption, in the sense that a new technology is adopted to replace an existing technology. However, technologies and media are becoming increasingly integrated (Rice & Webster, 2002) and mixed (Rice, Hiltz, & Spencer, 2004) in today’s organizations. Stephens (2007) proposes the ICT Succession Theory to explain how technologies are (or can be) used in succession and/or combination to facilitate effective and efficient communication in the workplace. She maintains, “Maximizing modalities through complementary successive ICT use increases the effectiveness and efficiency of task completion for persuasion, status, information, and problem-solving tasks” (p. 496). This proposition calls attention to the importance of redundancy through complementary and successive use of different ICTs. For example, the use of an email message to follow-up with a co-worker after a phone call establishes redundancy. This redundancy could increase the chances for successful accomplishment of a persuasion, status, information, or problem-solving task at work.

By adopting Stephens and colleagues' (Stephens, 2007; Stephens et al., 2008) combinatorial perspective, the notion of relative advantaged could be extended to consider redundancy (through simultaneous and/or sequential use of multiple technologies) as a form relative advantage. In other words, adopting and using multiple redundant technologies is relatively more advantageous than using a single technology in the traditional sense. This view is relevant to a study of cyberinfrastructure adoption because CI involves multiple technologies and processes. They form what Lievrouw (2006) refers to as "constellations or 'clusters' of interrelated or complementary innovations" (p. 252). A new piece may be adopted into a cluster in order to make the aggregate relatively more advantageous than the existing make-up. In that sense, a new piece of technology is not adopted to replace the old. Furthermore, the adoption of the 'Scientific and Research Layer' of cyberinfrastructure with supercomputers (as explained earlier as the central focus of this dissertation) does not imply that commercial desktops and personal computers will be replaced. In fact, CI adopters continue to work with commercial computers along with their specialized use to supercomputers.

Perceived Compatibility. Rogers (2003) contends that *perceived compatibility* is "the degree to which an innovation is perceived as [being] consistent with the existing values, past experiences, and needs of potential adopters" (p. 240). He points out that the contexts through which compatibility is evaluated include social values and cultural beliefs, information and ideas presently held by potential adopters, and the needs and situations that could be addressed by the innovation considered. Moore and Benbasat (1991) argue that "the inclusion of 'needs' is considered to be a source of confounding with **Relative Advantage**, as there can be no advantage to an innovation that does not reflect an adopter's needs" [emphasis original] (p. 199). They suggest dropping reference to 'needs' from the construct of perceived compatibility. Furthermore, Rogers argues that the sequence of need and awareness-knowledge of a new idea is inconclusive. He suggested that an adopter's sense of need could be the result of awareness-knowledge. However, Hassinger (1959) argues the opposite. Hassinger maintains that the notion of need comes before adoption.

Rogers' (2003) original conception of perceived compatibility appears to have an adopter-centered assumption, with an argument for compatibility with social norms and community/organizational/cultural practices. More recently, Stephens (2007) argues, "Complementary successive ICT use increases the likelihood that communicators will reach their audience" (p. 497). She points out that people have different preferences for and access to ICTs. Using only one ICT to reach an intended audience can limit one's likelihood of reaching the target audience. However, by using complementary ICTs in a successive manner, especially if the ICTs match the preferences and access patterns of the intended audience, the likelihood of getting the message across is higher than using a single ICT. Therefore, innovation adoption may be influenced by perceived compatibility of the communication preferences and work habits of a target audience with his/her channels of choice. In the case of cyberinfrastructure, the adoption of CI (or an element of it) could be an attempt to match a respected colleague's research approach, or interdisciplinary or cross-institutional research projects in order to gain the opportunity to collaborate with him/her. This argument adds a relevant other-centered interpretation of Rogers' notion of perceived compatibility.

Perceived Complexity/Simplicity. The construct of *perceived complexity* is defined as "the degree to which an innovation is perceived as relatively difficult to understand and use" (Rogers, 2003, p. 257). Rogers explains that although complexity may not be as important a factor as relative advantage and compatibility, it can be a barrier to adoption. A high degree of complexity can lead to a high degree of frustration among potential and new adopters, in addition to rejection, discontinuance, and misuse of the innovation. In a recent update of DOI theory, Dearing (2009) modifies the notion of complexity and uses the reversed term of ‘simplicity’. Similar to the notion of simplicity, Davis and colleagues (1989) propose that the factor of *perceived ease of use* refers to “the degree to which the prospective user expects the target system to be free of effort” (p. 985). All these constructs suggest that the simplicity and high usability of an innovation increase the likelihood of adoption. In order to remain consistent with a positive relationship between factors and adoption likelihood, I will primarily use the term ‘simplicity’ to refer to the related constructs reviewed here.

Observability/Communicability. Rogers (2003) posits the notion of *observability* to refer to “the degree to which the results of an innovation are visible to others” (p. 258). He argues that equipment (i.e., computer hardware) tends to get adopted faster than programs (i.e., computer software) because equipment is usually more visible and observable than programs. Rice (2009) pairs observability and communicability together, emphasizing the notion that the degree to which the results of an innovation are communicable to potential adopters increases the likelihood of adoption. Moore and Benbasat (1991) propose to combine the notions of observability and communicability to ‘result demonstrability’. Collectively, they suggest the more observable, visible, communicable, and demonstratable an innovation and its results, the higher the likelihood of adoption.

Trialability. The notion of *trialability* is defined as “the degree to which an innovation may be experimented with on a limited basis” (Rogers, 2003, p. 258). Rogers point out that trialability is an important factor because when a potential adopter tries out an innovation, he or she gives meaning to it in the process of figuring out how it works. More importantly, trialability allows a potential adopter to try an innovation and return to the pre-existing situation without much cost. S/he can try out components so that there are no huge initial costs and consequences. In other words, trialability reduces uncertainty and risks, increasing likelihood of trial adoption. Although trialability is conceptually unique as discussed, Moore and Benbasat (1991) argue that perhaps trialability and observability are not two separate factors, but could be treated as the same.

Social Influence/Communication Network. In new and ambiguous situations, people tend to rely on social comparisons to make decisions (Fulk et al., 1990; Stephens & Davis, 2009). CI adoption is one such situation where social influence is likely to play a significant role. Salancik and Pfeffer (1978) initially explained job attitudes in terms of *social information* – "information about past behavior and about what others think" (p. 224). Fulk and colleagues (1990; 1987) apply Salancik and Pfeffer's (1978) social information processing model to the study of media use in organizations. Their attempt represents a critique of the traditional rational choice model of media use (Stephens & Sætre, 2004). More specifically, they posit that a worker's technology and media use behavior will be a function of attitude toward communication technology and media use, perceived requirements of the communication tasks to be performed, social information (i.e., attitudes, statements, behaviors of salient coworkers and/or supervisors about the technology/media), and individual differences. Rice (2009) treats social influence as part of the persuasion process or as part of the communication channel aspects. He makes explicit that these social/network influences can affect one's perceptions of the attributes of an innovation as discussed earlier. Therefore, the role of social influence/communication networks as diffusion mechanisms are important to review with innovation attributes in this section.

While Fulk and colleagues (1990; 1987) acknowledge the influence of communication technology and media characteristics (Daft & Lengel, 1986) on a worker's behavior, they add to the traditional perspectives with the social influence and social information processing perspective. The emphasis on social information is important because information through interpersonal and diffusion networks (i.e., what neighbors say about an innovation, Rogers, 2003) and social influence (i.e. utility and norms, Kraut et al., 1998) were found to be sources of persuasion in a diffusion process. The notion of communication network is especially important when considering how opinion leaders can drive innovation diffusion in a social system (Valente, 1995; Valente & Davis, 1999). The social emphasis of the social information influence model is relevant given the participatory and community nature of cyberinfrastructure. This model has been empirically tested and criticized (Rice & Aydin, 1991; Rice et al., 1990), and conceptually explicated from a network perspective (Rice, 1993).

Innovation adoption has been studied from the perspective of innovation attributes (Rogers, 2003) and perceptions of these attributes (Moore & Benbasat, 1991). The assumption of these perspectives is that the objective characteristics and how people perceive them are good predictors of technology adoption behaviors. In addition to this classic view, the notion of rationality (Browning, 1992) was briefly discussed by Fulk and colleagues (1990) in the social influence model. They argue that in the context of technology use, rationality is an important consideration because "sense-making may well be created *after* the occurrence of the behavior. In this case, it is to interpret the behavior retrospectively rather than to direct the choice prospectively" (p. 123, emphasis original). This argument extends the predictive model to consider a retrospective model as useful and valid.

The argument Fulk and colleagues (1990) put forth was influenced by Weick's (1979) notion of retrospective sense-making, in that people often create goals and intentions to justify and explain past actions. Fulk and colleagues state, "The inferred goals are sensible and rational in the current interpretations, whether or not they were at the time of the behavior occurred" (p. 123). The implication is that behaviors and choices are subjectively and retrospectively rational, justifiable, and sensible. By accepting this view, research can capture the post-adoption sense-making to complement active pre-adoption perceptions. Furthermore, in order for the explanation to be accepted as rational to others, especially when a change is involved, one needs "a socially acceptable rationale that defines both past resistance and current acceptance as appropriate" (Fulk et al., 1990, p. 124). In other words, rationalization needs to be situated within a large social-organizational-cultural-political context. This argument makes a case for why the macro structures layer is important in the fuller conceptualization of cyberinfrastructure as discussed earlier. Leonardi, Jackson, and Diwan maintain that rationalization reflects what is considered natural, normal, and proper in a professional community. It is with an argument for the role of rationalities in context that this dissertation turns to perspectives in organizational communication.

ORGANIZATIONAL COMMUNICATION PERSPECTIVES ON INNOVATION

Two perspectives in organizational communication are especially useful for a qualitative investigation of rationality behind cyberinfrastructure adoption. They are the Lists and Stories framework (Browning, 1992) and Technologies-In-Practice perspective (Ballard & Seibold, 2003; Orlikowski, 2000). The Lists and Stories framework is particularly enlightening because it shows the two realms of logic and experience as a complete explanation of organizational life. The Technologies-In-Practice perspective, also known as the practice lens, is informative because it directs research attention to a broader conceptualization of workplace technologies in situated practices. These two theoretical perspectives are further reviewed below.

Lists and Stories Framework

Browning's (1992) framework of *lists* and *stories* as organizational communication is valuable for extending traditional innovation adoption literature from a sense-making perspective. According to Browning, two forms of rationality operate in every group or organization: technical rationality and narrative rationality. Technical rationality is scientific, formulaic, public, and instructive. Lists usually represent the "standards, accountability, certainty, and reportability" (p. 281) in an organization. Lists consist of techniques, a set of specific steps, produced by "experts who designate steps and strategies that apply to parochial topics, such as software" (p. 283). Technical rationalities, as sense-making mechanisms based on standards techniques and accountable steps, are useful for explaining the logic behind cyberinfrastructure adoption because it involves technical specifications and reportable details. The notion of technical rationalities is useful in that it emphasizes the logic in adopters' rationalization of adoption.

On the other hand, narrative rationality is romantic, humorous, conflicted, tragic, and most of all, dramatic (Browning, 1992). According to Browning, "stories are communications about personal experience told in everyday discourse" (p. 285). Stories are forms of knowledge and history, and they contain multiple voices. Furthermore, narrative is a sense-making response to complexity (Browning & Boudes, 2005). Narrative rationalities are appropriate for revealing the intuitions behind cyberinfrastructure adoption. Similar to Browning's (1992) notion of narrative and technical rationalities, Jameson (2001) maintains that narration and logical reasoning represent the state-of-the-arts and the state-of-the-sciences, respectively. Browning's distinctions of *lists* and *stories* also parallel the *mechanistic* and *organic* perspectives in organizational communication (Putnam, 1982) and the philosophical and literary dichotomy of *Apollo* and *Dionysus* in ancient Greek mythology.

Narrative approaches to management and organizational theory have rapidly expanded in recent years (Rhodes & Brown, 2005). Narratives are considered communication mechanisms that create and maintain organizational cultures (Weick & Browning, 1986). The values embedded in organizational cultures can be uncovered through analyzing pervasive narratives that members share (Meyer, 1995), including story telling in mentoring and organizational learning (Bokeno & Gantt, 2000). This argument is important for cyberinfrastructure adoption that results from learning from veterans who are existing adopters. Narratives allow organizational members to face existing and new situations that are not bounded by existing lists of rules and policies (Barge & Martin, 2002). This point is significant for adopters who are approaching cyberinfrastructure as an independently new decision. Eisenberg (2001) argues that every dimension of environmental influences in an organization or community is constituted by *lists* and *stories*.

The relevance of Browning's (1992) theory to the study of innovation adoption and implementation has to do with the interplay between these two forms of rationality. Browning contends, "Stories fill the breaks in technical rationality. Narrative rationality fills the loose coupling between intentions and outcomes" (p. 292). In other words, a cyberinfrastructure project may begin with technical intentions but end with narrative outcomes, and vice-versa. Furthermore, within the organizational adoption/diffusion process perspective, it may begin with an instrumental agenda by end with a creative routinization, or the reverse (Johnson & Rice, 1987). Star (1999) states that many aspects of infrastructure appear as:

> lists of numbers and technical specifications, or as hidden mechanisms subtending those processes more familiar to social scientists. It takes some digging to unearth the dramas inherent in system design creating, to restore narrative to what appears to be dead lists. (p. 377)

Therefore, considering both lists and stories is critical to discover a richer understanding of cyberinfrastructure adoption.

As pointed out earlier, cyberinfrastructure is a participatory innovation co-developed by domain scientists and computational technologists. The adoption decision and development process may begin with technical rationalities when the two groups jointly submit a grant proposal and begin a project. However, during the development process, narrative rationalities may emerge out of disciplinary-specific practices, funding agencies political priorities, and theoretical and methodological orientations of competing scientists (Kee, 2008). Therefore, the understanding of the communication process surrounding cyberinfrastructure adoption is incomplete if we examine only the lists and technical rationality or only the stories and narrative rationality.

Both technical and narrative rationalities co-initiate and co-sustain cyberinfrastructure adoption during the development stage. The narrative-practice view is equally as important as the technical-hypothetical view. This theoretical distinction between the technical-hypothetical and the narrative-practice views mirror Ballard and Seibold's (2003; 2004a, 2004b) distinction of the 'construal' and 'enactment' of organizational phenomena, which is rooted in the Technologies-In-Practice perspective discussed next.

Technologies-In-Practice Perspective

Communication research has traditionally employed a narrow conceptualization of technology as an information and communication tool (Ballard & Seibold, 2003, 2004b). As the majority of communication research has focused on the study of information and communication technologies (Ballard & Seibold, 2003, 2004b; Fulk & Steinfield, 1990; Rice & Gattiker, 2001), this narrow conceptualization is perhaps inevitable. However, building on the work of Orlikowski (2000), Ballard and Seibold (2003) argue to adopt the ‘technologies-in-practice’ (p. 404) perspective in organizational communication research.

This perspective is useful for several reasons. First, it brings our attention to the structure created by routine and recurrent uses of technologies in the workplace. Second, it expands the narrow focus on information technology to include a “specific machine, technique, appliance, device or gadget” (Orlikowski, 2000, p. 408), as well as “all physical machines and time-related social technologies (like the assembly line) created by humans to assist task completion” (Ballard & Seibold, 2004a, p. 10). This argument adds to Perrow’s (1967) foundational conceptualization of technology as the regularized conversion of inputs to outputs, so that task process is also technology. Third, the technologies-in-practice perspective brings us to the ‘everyday situated activities’ (Orlikowski, 2000, p. 408), and the situatedness reveals the aspects of the technologies relevant to users in actual implementation. Finally, people’s willingness to use a technology is often the result of social influence/social information moderated by their direct interactions with the technology (Leonardi, 2009b). Therefore, it is important to take on a ‘technologies-in-practice’ perspective to study innovation adoption. This perspective is closely aligned with the sociotechnical perspective (Coakes & Coakes, 2009; Zimmerman, 2007) of cyberinfrastructure discussed earlier.

Ballard and Seibold's (2003) call to employ a technologies-in-practice perspective is important to this dissertation study. This perspective fully encompasses the complexity of cyberinfrastructure, to include the general information and communication tools, specialized scientific and niche research technologies, macro cultures, and micro behaviors embedded in the routine operation. Technologies are not just tools, but as Orlikowski & Iacono (2001, p. 122) maintain:

> the ensemble or 'web' of equipment, techniques, applications, and people that define a social context, including the history of commitments in making up that web, the infrastructure that supports its development and use, and the social relations and processes that make up the terrain in which people use it.

This perspective makes a case for why cyberinfrastructure is an appropriate topic to expand traditional innovation adoption research (in the field of organizational communication that has a tendency to focus on ICTs adoption) to consider all the 'technologies-in-practice'. By taking this perspective, the present dissertation joins organizational communication with the fields of human-computer interaction and computer-supported cooperative work via the case of cyberinfrastructure. Furthermore, this perspective brings research attention to the 'everyday situated activities' during the adoption, development, and implementation processes, which is closest to the micro interaction layer discussed earlier. In addition, the 'everyday situation activities' focus can reveal the disruptive nature of cyberinfrastructure in how it interrupts existing models of scientific work, and how this interruption impacts adoption decisions.

In her study of the Illinois Digital Library Project (i.e. digital library as an information infrastructure), Star (1999) documented that there was a puzzle of "human irrationality" (p. 386). There was an observation that people were routinized and rigid in their ability to change, and they would rather "walk across campus to get a copy of something" (p. 386) than to "punch a couple of buttons" (p. 386) in front of a computer terminal in their office. At the point of first observation, this does not make rational sense. However, Star argues that the conclusion of human irrationality as the explanation is only logical if we employ the 'user-meets-terminal' model and are primarily concerned with understanding the behavior from the traditional perspective of looking at production tasks related to “keystrokes and functionality” (p. 386). Instead, Star (1999) argues to look at:

> the process of assemblage, the delicate, complex weaving together of desktop resources, organizational routines, running memory of complicated task queues (only a couple of which really concern the terminal or system), and all manner of articulation work performed invisibly by the user (pp. 386-387).

She concludes that “only by describing *both* the production task and the hidden tasks of articulation, together and recursively, can we come up with a good analysis of why some systems work and others do not” (p. 387). Although not explicitly stated, Star’s argument resonates with the technologies-in-practice perspective articulated by Orlikowski (2000) and Ballard and Seibold (2003). Furthermore, Star points out the importance to studying ‘rationality’ in innovation adoption and implementation, and position also articulated by Rice and Schneider (2005).

CONCLUSION/IMPLICATIONS

This literature review discussed three bodies of literature. First, the historical emergence of cyberinfrastructure was presented. More importantly, the construct of cyberinfrastructure was re-categorized into four layers: information and communication layer, scientific and research layer, macro structures layer, and micro interactions layer. This re-categorization is useful because the influences of the information and communication layer, the macro structures layer, and the micro interactions layer are critical in understanding the way CI’s nature influence its adoption and implementation for Research Question 1 (RQ1, listed below). Then this re-categorization highlights the scientific and research layer (what scientists use mainly for specialized and research purposes) as the core of cyberinfrastructure under investigation for Research Question 2 (RQ2, listed below). Second, Rogers’ (2003) classic innovation attributes were discussed along with other theoretical perspectives, including Technology Acceptance Model, Social Influence Model, and ICT Succession Theory. These attributes and adoption factors include relative advantage/perceived usefulness, perceived compatibility, perceived complexity/simplicity, observability/communicability, trialability, and social influence/communication network. These factors provide the background for examining cyberinfrastructure adoption and how cyberinfrastructure may mirror or differ from other innovations studied in the past. Third, two organizational communication perspectives were discussed and their relevance explained in how the constructs of lists and stories may influence the rationalization of CI adoption and how participants interact with CI in practice on a regular basis. More specifically, the role of rationality in context was emphasized. Rationality could be understood in the two forms of technical rationality (i.e. lists) and narrative rationality (i.e. stories). The notion of context was explicated with the notion of technology-in-practice and the situatedness in which technologies are embedded.

RESEARCH OBJECTIVES

Given the coupling of cyberinfrastructure emergence as a powerful platform for the early 21st century science with the availability of two organizational communication perspectives, I propose to investigate two research questions about the adoption of cyberinfrastructure. Broadly, the proposed dissertation addresses the following two research questions: RQ1: How does cyberinfrastructure's nature influence its adoption process in early 21st century U.S.? RQ2: What are the rationalities that drive cyberinfrastructure adoption in early 21st century U.S.? RQ1 addresses the technologies-in-practice beyond ICTs and the interplay between the macroscopic structures, rules, and resources of cyberinfrastructure and the microscopic thoughts, experiences, and behaviors of adopters. Findings from RQ1 will provide a picture of the prominent and salient challenging conditions for cyberinfrastructure adoption. RQ2 addresses the justification, sense-making, and explanations for adoption decisions. In other words, answers to RQ2 reveal the driving conditions for cyberinfrastructure adoption despite challenging conditions. Then, the findings for these two research questions will be used to develop a preliminary theoretical model for the general issues of early cyberinfrastructure adoption in the early 21st century U.S. Table 1 below shows the two research questions and how the theoretical constructs reviewed are relevant.

CHAPTER THREE: METHODOLOGY

As stated earlier, the purpose of this dissertation project is to apply existing innovation adoption theories to the complex innovation of cyberinfrastructure that is participatory/bespoke, meta/complex, disruptive/revolutionary, and community/network in nature. While there exist a wealth of literature on predictors of innovation adoption (as modestly reviewed in Chapter 3), because cyberinfrastructure is an emerging innovation, my research purpose is exploratory instead of confirmatory. Furthermore, the focus of the dissertation is on the notion of 'rationality', which emphasizes retrospective sense-making and justification. Given the exploratory and retrospective assumptions of this dissertation, a qualitative approach guided by grounded theory is appropriate (Patton, 1990; Sørnes, Stephens, Browning, & Sætre, 2005). Throughout the data collection and analysis, I keep in mind the approach embraced by Star (1999) as she states, "In each case, I brought an ethnographic sensibility to the data collection and analysis: an idea that people make meanings based on their circumstances, and that these meanings would be inscribed into their judgments about the built information environment" (p. 383). The 'built information environment' in this dissertation is cyberinfrastructure.

GROUNDED THEORY

This dissertation employs grounded theory (Corbin & Strauss, 1990; Glaser & Strauss, 1967; Strauss & Corbin, 1998) in qualitative data collection and analysis. Grounded theory and qualitative methods have been employed to study industry consortiums (Browning & Beyer, 1998; Browning, Beyer, & Shetler, 1995; Browning & Shetler, 2000) and emerging information and communication technologies (Browning, Sætre, Stephens, & Sørnes, 2004; Sørnes, Stephens, Sætre, & Browning, 2004). According to Corbin and Strauss (1990), grounded theory describes and explains a social phenomenon and offers some degree of predictability under specific conditions. Furthermore, “grounded theory seeks not only to uncover relevant conditions, but also determine how the actors respond to changing conditions and to the consequences of their actions” (p. 5). Corbin and Strauss also explain the following procedures to guide qualitative investigations. In the spirit of Glaser and Strauss’ (1967) recommendation to weave literature and data, I juxtapose the Corbin and Strauss’ methodological procedure with my own data collection experience in the discussion below:

1. ***Data Collection and Analysis Are Interrelated Processes.*** In other words, analysis begins immediately after the first piece of data is collected. This dissertation project began with a pilot study in November 2007. Initially, I was mainly interested in understanding the adoption and implementation of cyberinfrastructure. Shortly after the first interview, I realized that adoption and implementation are also related to the grassroots emergence within a wide range of disciplines and co-developments between domain scientists and computational technologists during the entire process of adoption and implementation. Furthermore, I also recognized that implementation takes place at multiple levels. It can be microscopic deployment of cyberinfrastructure resources, as in distributed collaborations among teams of collocated and dispersed scientists (Olson et al., 2008). It can also be macroscopic implementation of national and international grid infrastructures (Bird et al., 2009) that create a complex virtual organization (Foster et al., 2001) that contains a range of distributed collaborations. Therefore, I added the topics of distributed collaboration and virtual organization in subsequent interviews.

2. ***Concepts Are the Basic Units of Analysis.*** Individual thoughts, opinions, experiences, incidents, specific applications, tools, technologies, etc., are all considered raw data. Each item reveals how concepts manifest in different forms across a range of contexts and situations. While the details could be interesting, a study guided by

grounded theory looks for concepts, grounded in raw data, as the basic units of analysis. For example, during my data collection and initial analysis, when specific applications were mentioned, and they all appeared to be used for visually representing data and the results of the analyses, the concept of ‘visualization tools’ emerged.

3. ***Categories Must Be Developed and Related.*** Once the concepts have been identified as described in (2), the concepts converge to form the next level of underlying concept, referred to as a category. In other words, the conceptualization of similar concepts yields a category. For example, when the concepts of visualization tools and simulation tools appeared to run on supercomputers with high-performance computing capability, the category of “high-performance computing applications” emerged to represent both visualization and simulation tools. Furthermore, categories also relate to each other. For instance, because visualization and simulation tools are often used to process large data sets, they can only be processed by a supercomputer. Therefore, high performance applications and supercomputers are then related to each other. In fact, they represent the relationship between the niche hardware and the specialized software used by domain scientists who use cyberinfrastructure, referred as the ‘scientific and research layer’ earlier. Similar to how concepts can be converged to form categories, categories can be converged and form ‘clusters’ (Browning, 1978).

4. ***Sampling in Grounded Theory Proceeds on Theoretical Grounds.*** A researcher guided by grounded theory may begin an investigation with some idea of a phenomenon of interest. Based on the existing background knowledge about the phenomenon of interest, appropriate individuals, groups, organizations, and communities can be selected for data collection. In this dissertation, the domain scientists, computational technologists, and administrators at the University of Texas at Austin/Texas Advanced Computing Center (UT/TACC) were identified as the appropriate individuals and

organizations with which to explore cyberinfrastructure adoption. It was appropriate because TACC supports about 200 million dollars a year in externally-funded research at UT, and Ranger at TACC was the most powerful supercomputer for open science research in the world as of March 2008 (Boisseau, 2008). Once I was in contact with potential interviewees, sampling was then directed towards thoughts, opinions, experiences, and incidents related to cyberinfrastructure adoption and the conditions that facilitate, interrupt, or prevent adoption and implementation. After analysis of the first few interviews, the term 'adoption' developed more specific and complex meanings. For example, adoption may be driven by the need to process large-scale data that is impossible to process using commercial desktop computers (i.e., technical rationality). Adoption can also result in a struggle with understanding computational science in order to stay in adoption (i.e., narrative rationality).

Then the sampling begins to focus on identifying as many variations in rationalities as possible, especially different types of technical and narrative rationalities behind adoption decisions and how they are interrelated. The sampling can also focus on intensity, looking for the conditions that generate more or less intensity of different types of rationalities behind cyberinfrastructure adoption. Corbin and Strauss (1990, p. 9) explain:

> It is by theoretical sampling that representativeness and consistency are achieved. In grounded theory, representativeness of concepts, not of persons, is crucial. The aim is ultimately to build a theoretical explanation by specifying phenomena in terms of conditions that give rise to them, how they are expressed through action/interaction, the consequences that result from them, and variations of these qualifiers

5. ***Analysis Makes Use of Constant Comparisons.*** This is when data and concepts are being constantly compared and contrasted for similarities and differences. Constant comparisons are important because this process helps a researcher achieve

greater precision and consistency. Precision refers to the grouping of cases with similar qualities. When constant comparisons lead to sub-division of an original concept into two distinct concepts, the resulting distinct concepts are said to have greater precision. Consistency refers to always grouping a similar case with other similar cases. For example, the software in cyberinfrastructure was initially considered a concept, as suggested by the definition put forth by Atkins and colleagues (2003). However, during data collection and data analysis, sub-division of the concept ‘software’ occurred. By constant comparisons, it became clear that scientists adopt and implement commercial software applications, such as email and instant messaging, in their cyberinfrastructure-enabled distributed work. These applications can be conceptualized as information and communication technologies (ICTs) scientists use concurrently for non-research purposes. Furthermore, they also use data management software and analysis applications specific to process their data for research, often powered by high-performance computing systems and supercomputers. In that case, these applications could be conceptualized as high-performance computing (HPC) applications for specialized usage.

6. ***Patterns and Variations Must Be Accounted For.*** While analyzing the data, a variation of an original pattern suggests the existence of exceptions. When a different pattern is noted, it calls for an investigation of the condition that may have caused the new occurrence. For example, while bioinformatics scientists are open to putting their data online and sharing with a community of researchers, chemists are not as open. This difference calls for an examination of underlying conditions. The field of bioinformatics was born around the same time the Internet was being adopted by scientists. Putting data online for bioinformatics scientists became a natural practice due to their young disciplinary history and Internet-compatible culture. Chemistry has a longer history, and its disciplinary culture existed before the invention of the Internet. Therefore, putting data

online is not a cultural practice for chemists. In understanding cyberinfrastructure adoption among scientists, this variation points out that CI’s disruptive nature does not affect bioinformatics as much (in terms of data sharing) because of the field’s short history. However, it does affect chemistry because some chemists are resistant to adopting the CI work model that differs from their pre-existing work model.

7. ***Process Must Be Built into the Theory.*** In grounded theory, the process can include progressive stages, phases, or steps. The process can also be non-progressive, as “changes in response to prevailing conditions” (Corbin & Strauss, 1990, p. 10). In this dissertation, I break down the cyberinfrastructure process into five overlapping stages: emergence, development, adoption, deployment, and implementation. Sætre and Browning (2004) argue that emergence refers to “something that is genuinely new, not simply perceived as new” (p. 100). Cyberinfrastructure emergence refers to the period of time when grassroots projects (such as the Trillium consortium discussed earlier) led to the birth of the term ‘cyberinfrastructure’ proposed by Atkins et al. (2003). Emergence came to fruition when NSF established the Office of Cyberinfrastructure. Development refers to the designs, production, and efforts that go into building the hardware and software, and facilitating the norms and practices embedded in cyberinfrastructure operation. Adoption refers to the decision to invest in a collection of tools and resources tied to high-performance computing systems in order to do large-scale science. Adoption could be marked by the first official grant proposal to begin a cyberinfrastructure project and/or a formal commitment to transition into using high-performance computing applications to process scientific data. Adoption also involves co-developing the tools with computational technologists. Therefore, as stated in the Introduction, adoption in this dissertation is conceptualized as intertwined with development, use, appropriation, implementation, and diffusion. In other words, adoption overlaps with deployment.

Deployment refers to the micro usage of cyberinfrastructure resources for collaboration with a team of collocated and dispersed scientists. Deployment at this level provides feedback to the development stage and sustains the adoption stage. Once deployment is relatively stable (along with development and adoption), macro implementation at the scale of virtual organization around a national or international grid infrastructure appears. This macro implementation represents a collection of micro deployments. Although I use different terms to label these stages, they are progressive yet recursive; they are interrelated at any given point in time. The entire process is a complex system. In addition, as mentioned in the Introduction, this project examines adoption as it takes place during the innovation development process, when "actors ranging from individual entrepreneurs and collaborative users through governmental agencies and corporations attempt to identify needs and/or problems, conduct research on the ways to solve these problems, develop the innovation, and commercialize or otherwise promote it" (Rice, 2009, p. 491). The focus on the innovation development process will further narrow the dissertation to a focal process although embedded in complexity.

8. ***Writing Theoretical Memos Is an Integral Part of Doing Grounded Theory.*** Theoretical memos are not simply about ideas. They involve formulation and revision of theory throughout the entire research process. Writing memos should begin as early as the first coding session and should continue until the research project concludes. In this project, theoretical memos involve notes from preliminary analyses, discussions with colleagues and professors, insights from literature and conferences, and continuing reflections. The four pairs of qualities discussed in the Introduction and the five stages of cyberinfrastructure process described in (7) are a result of memo writing. Both conclusions are ideas still under revision.

9. ***Hypotheses about Relationships Among Categories Should Be Developed and***

Verified as Much as Possible During the Research Process. The relationships developed among the categories should be taken back to the field and verified and/or revised during the research process. In order to fulfill this criterion, I have shared my preliminary analysis on cyberinfrastructure development with a small, select group of past interview participants. During the next stage of post-dissertation analysis, I will continue to do the same. Another strategy is to use the findings from the study as prompts to collect new data with additional interview participants as an extension of this dissertation. In other words, in the next round of interviews, I will share brief findings from the existing data set with new interview participants and ask them to respond to the findings. Besides collecting more data, this is a method of verifying the relationships and validity of the findings.

10. ***A Grounded Theorist Need Not Work Alone.*** Discussion with fellow researchers in the same area often helps reduce the tendency of individual bias: "Discussions with other researchers often lead to new insights and increased theoretical sensitivity as well" (Corbin & Strass, 1990, p. 11). I have done this by presenting the preliminary analysis mentioned in (9) at a cyberinfrastructure research workshop at the 2008 Computer Supported Cooperative Work conference, the annual meeting of the Society for the Social Studies of Science in 2009, and the annual iConference in 2010. Furthermore, one can also practice collaborative analysis (Strauss, 1987) with several researchers as a team that shares occasional or ongoing discussions.

11. ***Broader Structural Conditions Must Be Analyzed, However Microscopic the Research.*** Structural conditions can be economic conditions, cultural values, political trends, social movements, and so on. They are also referred to as the 'Conditional Matrix' (Corbin & Strauss, 1988, pp. 135-138; Strauss & Corbin, 1989). Once identified, an attempt should be made to link the structural conditions with the actions and

consequences observed. In this study, there are three structural conditions identified during preliminary analysis, including disciplinary history/culture, funding agencies' political priorities, and the theoretical/methodological orientations of early adopters (Kee, 2008). These conditions are built into the installed base of cyberinfrastructure before later adopters arrive. Furthermore, the participatory/bespoke, meta/complex, disruptive/revolutionary, and community/network nature of cyberinfrastructure are also important conditions to include in understanding its adoption.

CODING

According to Corbin and Strauss (1990), there are three types of coding for grounded theory research: open, axial, and selective. In this section, I will briefly explain the three types of coding for my data analysis, based on Corbin and Strauss' work.

1. ***Open Coding.*** Open coding is the analytic fracturing and systematic interpretation of raw data. Thoughts, actions, events, incidents, etc in raw data are compared with each other for similarities and differences and then given conceptual labels. Similar concepts collapse to form categories and subcategories. As described earlier for the research procedures guided by grounded theory, concepts and categories guide the next episode of data collection. Because a researcher is informed and guided by preliminary concepts and categories, he or she is able to ask generative and comparative questions with the next interview or during the next observation. Asking generative questions (e.g., What is a rationality for adopting cyberinfrastructure and how does this rationality manifest itself?) helps a researcher recognize the empirical implications/theoretical sensitivities. Asking comparative questions (e.g., How does this rationality differ from other types of rationality that scientists used to explain their adoption decisions? How does a rationality provided by a domain scientist compare to/differ from the rationality provided by a computational technologist, administrator, NSF officer, etc?) helps to give each category

specificity. Then the properties and dimensions of each concept derived for rationalities are analyzed, and additional field work adds specification to the concepts obtained.

2. ***Axial Coding.*** Axial coding is a process in which "categories are related to their subcategories, and the relationships tested against data" (Corbin & Strauss, 1990, p. 13). This is an ongoing process, and a researcher continues to develop and revise the identified categories. Furthermore, a researcher pays attention to how conditions, contexts, strategies (action/interaction), and consequences influence the relationships between subcategories and their super-category. For example, once an adoption rationality was identified, I paid attention to determining the conditions that gave rise to the rationality, the context in which it was formulated, the actions/interactions that demonstrate it, and its consequences. The goal is to identify relationships tying concepts with conditions, contexts, strategies, and consequences. A researcher will also look for variations of the patterns or exceptions to the rules. Once identified, the relationship will be revised with greater specificity until no variations and exceptions can be found in the data. Therefore outliers lead to new, provisional, conditional relationships. The goal is to make a theory conceptually denser, the linkages among concepts more specific. A researcher may conclude, "Under these conditions, action takes this form, whereas under these other conditions, it takes another" (p. 14).

3. ***Selective Coding.*** Selective coding often occurs during later stages of an investigation, and this is when all categories converge to reveal a 'core' (or root) category. The core category is the focal phenomenon of interest in a study. One strategy to integrate categories is diagramming. In a diagram, the other categories will appear in relationships to the core category as conditions, contexts, strategies, and consequences. A strong theory with great explanatory power usually has categories and subcategories with high conceptual density. Poorly developed categories will be identified during selective

coding. Then a weak theory can be strengthened by additional data and revisions of initial concepts, categories, and relationships. In this dissertation, I present tables instead of diagrams to show a grounded theory of cyberinfrastructure adoption during the innovation development process by pioneering scientists.

In addition to explaining the core phenomenon within the context in which data was collected, a grounded theory possesses a certain degree of generalizability: “The more abstract the concepts, especially the core category, the wider the theory's applicability” (p. 15). However, a grounded theory also states the conditions under which the core phenomenon was discovered in the particular data set. In addition, “no theory that deals with social psychological phenomena is actually reproducible in the sense that new situations can be found whose conditions exactly match those of the original study, although major conditions may be similar” (p. 15). Therefore, a grounded theorist is cautious when generalizing the findings to new situations.

SNOWBALL RECRUITMENT

Recruitment of interview participants mainly relied on snowball sampling technique (Biernacki & Waldorf, 1981). Snowball sampling is a non-probability sampling technique that depends on a present participant’s referrals of the next participant(s). Babbie (2001) explains that snowball refers to “the process of accumulation as each located subject suggests other subjects” (p. 180). He further states that this recruitment technique is appropriate for participants who belong to a special community that is difficult to locate, such as homeless individuals, undocumented immigrants, etc.

The requirement of difficulty to locate subjects presents a critique to my current research approach to date because my research participants are not difficult to locate. In fact, many of them have public information on the Web. However, there are still two important reasons for using snowball recruitment technique. First, cyberinfrastructure is a highly specialized area. This dissertation sampled participants based on their specialized knowledge of the topic, so snowball recruitment was appropriate (Johnson, 1990; Sætre, Sørnes, Browning, & Stephens, 2007). Second, many of my participants are busy individuals and high profile professionals. Access to them is difficult and limited. However, they are likely to be willing to participate if they learn that a trusted friend or a respected colleague has referred me to them. The credibility of a friend/colleague, as well as the relationships a potential participant had with an existing participant, contributed to successful recruitment in many instances.

PERSUASION FOR RECRUITMENT

Cyberinfrastructure is a national development, and this dissertation is a national study. It is not possible to travel to various sites and conduct face-to-face interviews with every willing participant. In order to capture a diversity of perspectives, I chose the phone interview method (for 51 interviews, about 73% of total) as the most suitable way to conduct interviews with long-distance participants. In addition to the 51 phones interviews, I was able to conduct 19 face-to-face interviews (about 27% of total) with participants at UT/TACC and at the Supercomputing 2008 conference. Phone interviews are different from face-to-face interviews. A face-to-face interview involves rich nonverbal cues for feedback and observation to create immediacy and build trust between a participant and the researcher. In a phone interview, the only nonverbal cue available for immediacy and trust is voice (or paralanguage or vocalics). In an interview that involves uncertainty and ambiguity between two strangers and a task that requires immediacy and trust for disclosure, the interview process needs to be strategically designed.

Since this dissertation employs an unconventional mix of phone interviews and face-to-face interviews with dispersed and high-profile professionals, it is important to discuss how a combination of media was used in purposeful sequence with related strategies for recruitment. This section provides a preliminary model for future studies of similar nature. Invitation is persuasion. The goal of an invitation is for a potential participant to respond, agree, and commit to an interview appointment. Here are the strategies I employed:

1. ***Persuasion by Association.*** At the end of each interview (sometimes during the interview or in a follow-up email), I asked the participant to recommend new contacts I could invite to expand the project. Most of the time, they would generate a list and give me a few names. Two participants offered to send out a recruitment message through listservs they were on, and a few actually took the initiative to contact their colleagues directly and copied me in an email. Two participants introduced me to their colleagues at the Supercomputing 2008 conference. When a participant used his or her name in conjunction with my recruitment message, that association increased their colleagues' likelihood of being persuaded to participate.

Second, for each new contact on the list that participants generated, I sent him/her an email, copied the recommender on the correspondence, and mentioned the recommender in the body of the email. Once again, I did that to establish an association with the recommender. Often a new contact would reply and copy the recommender to indicate a response. In addition, naming and copying the recommender in an email also verified the legitimacy of the study. Since many people often receive spam or unsolicited emails, an email copied to a trusted and credible colleague increased positive responses.

2. ***Persuasion by Specificity.*** In the invitation, I specified exactly what the topic was about (e.g., cyberinfrastructure adoption and implementation) and the process (i.e., I will call them to conduct a phone interview). In that case, the potential participant knew what he or she was committing to when accepting the invitation. I also provided specific time

blocks that I was available. Therefore, a new contact could look at his/her schedule and pick a time immediately. Specificity made their decision to respond efficient, thus increasing the likelihood of their participation.

3. ***Persuasion by Trust.*** Trust in this case is a participant's assurance that the researcher will not misuse the information to damage his/her career and/or reputation. Trust can be established by association (i.e., referral) as discussed earlier. Trust can also be established by the researcher's institutional affiliation and personal information. I included a link to my professional homepage in my email signature as a way to give potential participants another way to find out about my qualifications as a researcher, in case he or she had doubts or questions about the legitimacy of the study. Quite a few participants made references to my university and homepage, and I believe the access to these types of information allowed them to look me up, thus increasing trust and encouraging them to participate.

4. ***Persuasion by Inducing Kindness/Goodwill.*** Many participants agreed to participate because they did it out of kindness and goodwill. Stating my graduate student status in the invitation sometimes induced people's willingness to help. All my participants had been students themselves at one time, and many had been graduate students. My student status increased their likelihood to respond out of kindness and goodwill.

Second, one participant who voluntarily contacted his colleague said in an email, "I thought he [Kerk] might benefit from the opportunity to speak with one of the people setting the direction of cyberinfrastructure development on a national scale." Another participant specifically stated goodwill and good karma in an email he voluntarily sent to his colleagues, "I encourage you to contact Kerk and participate in his study. It's both good karma and in our own selfish best interests. It's not often that happens - we ought to take advantage of that!”

5. ***Persuasion by a Sense of Opportunity.*** The reverse of the previous strategy (kindness/goodwill) could also hold true. When a research project is conducted by a graduate student and not a full-fledged professor, a new contact may not assign much value to the invitation. I explained in the email that my project was on an important topic and that I had interviewed a wide range of stakeholders across the U.S. This strategy gave a new contact a sense of opportunity of being a part of an important national study. A sense of opportunity motivated some to respond. Furthermore, as quoted to illustrate goodwill and good karma in (4), the same participant saw the study as an opportunity for the entire cyberinfrastructure community. He also stated in the same email, “As a group of people who are producing cyberinfrastructure, we deal everyday with the challenges of getting more people to adopt cyberinfrastructure. I think one of the best things we can do, over the long run, to facilitate adoption is to participate in studies such as the one Kerk is engaged in.”

6. ***Persuasion by Personalization.*** One’s identity is important. I did a Google search on every new contact before sending him/her an email invitation. In the invitation email, addressed appropriately with their titles, I emphasized an angle of the project that related the most to them (i.e., depending on whether they were domain scientists, computational technologists, administrators, NSF officers, etc). If the recommender had mentioned that a new contact would be a good informant for a particular reason, I also mentioned the reason he or she was recommended.

Second, I provided my availability converted to their time zones. For example, I typed (PST, your time zone), signaling to them that I was aware of their locations. In addition, I would always respond to their replies as soon as possible. Speed of reply indicates the seriousness with which I regarded a potential interview participant. The faster my reply, the more I showed him/her my seriousness. With these efforts, the invitation email was personalized, and personalization made a new contact feel unique and special. This increased the likelihood that he/she would respond.

7. ***Persuasion by Flexibility.*** In every email, I usually included about two weeks of availability (following the Principle of Specificity discussed earlier). However, I made sure that my availability was wide and accommodating. I would get up and conduct interviews at 6 AM central time (which is 7 AM in the east coast) and 9 PM central time (which is 7 PM on the west coast). When a participant needed to reschedule or failed to pick up the phone for the first appointment, I continued to offer a flexible schedule for rescheduling. A few times participants completely ignored my availability and replied with dates/times that I had not specified. In that case, I did what I could to rearrange my own schedule to match theirs. This effort to accommodate participants was a result of my realization that if I did not remain flexible, some interviews would not take place.

8. ***Persuasion by Sequence.*** Using a foot in the door and Cialdini’s (2009) principle of consistency, I recognized that persuasion is a sequence and not a single act. The first invitation email was to get a new contact to respond and agree to be interviewed. The reminder email prior to the phone call was to persuade a new contact to allow audio recording. I did not want to request audio recording in the first email because digital documentation may make some new contacts uncomfortable before trust has been established. After several email exchanges, and when I sensed that trust has been established, I extended the audio recording request, but I made it optional. Among the 70 interviews conducted, there was only one instance when a participant requested not to be audio recorded.

Interview Procedure

As mentioned earlier, phone interviews limited the number of nonverbal cues a researcher could employ to create immediacy and establish trust. The interview process involved an intentional sequence with appropriate improvisations. The general structure was as follows:

1. ***Clarify Initial Uncertainty.*** After the beginning greeting, I did not give a brief overview of the study. I did not find that necessary because I usually engaged in a series of emails that explained the purpose prior to the phone call. By the time we talked on the phone, participants already had a general idea of what the interview consisted. Instead, I started the conversation by giving the participant an opportunity to ask any questions about the interview. I would usually say, "Before we begin, do you have any questions about the interview today?" If they wanted an overview, I would then provide one. If they wanted to know how the interview would be used, I would then address that issue. Giving participants an opportunity to ask clarifying questions in the beginning gave them a sense of control over the interview. A frequent question participants asked is how the interviews will be used. I explained that the interviews will be used for a dissertation project in organizational communication. Another question that came up was who funded or sponsored this project. I then explained that this project was not funded by any external sources but by the doctoral student and researcher himself.
2. ***Build Trust.*** In order to build trust further and to indicate that I did not have a hidden agenda, I would say, "Can I have your permission to put you on speakerphone and turn on the audio recorder?" This signaled to the participant that they would be informed of every step to be taken during the interview. This gave them a sense of control, and it also increased trust.

3. ***Document Consent.*** Since consent is an important part of today's research protocol, I made sure that verbal consent was documented during the interview with the question in (2), in addition to the signed consent form. Once the audio recorder was turned on, I would continue, "(Name of the participant), you are now on speakerphone and the audio recorder is running, can you hear me alright?" Their response indicated that they were aware of being audio recorded and that they were agreeing to it. In addition to verbal consent, I also keep a copy of all email exchanges as additional evidence of consent to participate.
4. ***Warm Up with a Biography.*** Since this was the first synchronous phone interaction between two strangers, the warm-up exercise was for the participant to provide his/her biography. A biography was a good warm-up topic for three reasons. First, it was a topic the participant knew a lot about, so it was an easy topic with which to start. It relaxed the participant in the beginning. Second, in the process of telling me about his or herself, trust emerged (or was strengthened from prior emails) because a relationship had started (or continued) between the participant and the researcher. Third, human beings have the need to be known. Allowing a participant to share his or her biography in his/her own way fulfilled this need to be known. I also wanted to let participants know that I was interested in them personally before the interview, so my strategy at this point was to state, "I did a Google search on you, and I found out that you did (this, this, and that). However, I would like to begin the interview with you sharing about who you are, what you do, and how you came to be where you are today." In other words, I was interested in their versions of their own biographies, not just what I had found online.

As noted above in (6) in the previous section, it is important prior to the phone interviews to Google and do some background research on the participants. Stephens (2007) proposes, “Using mass media as a precursor ICT increases the effectiveness and efficiency of information, status, and learning tasks” (p. 498). The essence of this proposition is that proactive use of mass media for information (prior to an actual communication episode) is an effective covert strategy to increase the effectiveness and efficiency of a communication episode. Appropriate and complementary proactive use of mass media for information increases the likelihood for success by providing prior information and making one more knowledgeable for the actual communication episode. My interview approach followed the wisdom of Stephens’ proposition.

Some participants took a bit of time sharing their biographies. That was useful for three reasons. First, the more they talked about themselves, the more trust was established because they told me about themselves and they felt known. Second, the length of their biographies primed them to share just as much about cyberinfrastructure in the remaining time. The use of biography was a priming strategy. Third, many caught themselves taking a lot of time talking about themselves (i.e., one took 20 minutes out of a 60 minutes interview), and they felt bad, as if their biographies wasted my interview time. When they felt that way, they often offered more information and became more open about cyberinfrastructure during the remaining interview time. Some even offered to extend the interview time further if their schedules allowed. Biographies as a warm-up prompt were not only effective as a strategy to start the interview, to build trust, to prime the participant for more sharing, and to set the stage for more disclosure, biographies also provided information for improvisation and customization as described next.

5. ***Customize Pre-Scripted Questions.*** I had pre-scripted interview questions (see Appendix A) about the adoption, deployment (i.e., distributed collaboration), implementation (i.e., virtual organization), definition (i.e., explanation, metaphors, and analogies), history, and future vision of cyberinfrastructure. The notion of the future is theoretically captured by Boje's (forthcoming) notion of 'antenarrative' (i.e., a bet on its future patterns). However, not every question applied to every participant. With their biographies in mind, I was able to improvise, customize, and personalize the interviews based on their unique backgrounds and experiences with cyberinfrastructure. When time was limited (for example, a couple of interview participants had only about 20 minutes each), I was able to select which questions to prioritize, drop, and pursue. Furthermore, customizing pre-scripted questions based on biographies allowed me to show my attentiveness to the conversation and to discover what was salient in their consciousness about their identity at work at the moment. If time allowed, I later pursued less pertinent issues. Having heard their biographies also prevented me from asking uninformed questions due to a lack of knowledge of a participant's background.

6. ***Free Flow Narrative for Surprises.*** An important strength of qualitative interviews is the potential for serendipity. A highly structured interview may be efficient, but it may miss interesting insights. In grounded theory, an investigation is guided by pre-scripted questions that also allow rooms for improvisation, adaptation, and deviation during data collection. In order to increase the likelihood of serendipity, I built in an opportunity for free flowing narrative. This

is when I say, “We have covered a lot of issues in this interview. Before we wrap up, were there questions or issues you thought might come up during the interview, that didn’t?” This question usually prompted participants to talk about what they thought might be relevant (if they had given some thought to the interview beforehand) or to answer their own questions about the interviews. There were often interesting insights that otherwise would have been left out by a pre-scripted protocol. For example, two participants talked about tensions and conflicts between groups of scientists in the process of CI development only after I started wrapping up the interviews. These tensions and conflicts then became a salient theme discussed in Chapter 4.

7. ***Give in Return.*** Before concluding the interviews, I thanked the participants for their time and insights. Furthermore, I also offered to share my research findings when the dissertation project is complete, giving my anticipated graduation in 2010. Because I offered to give something back in return, participants often felt appreciated for their efforts. This promise of reciprocation in 2010 although a couple of years in the future at the time the interviews were conducted (in 2007 and 2008), helped further strengthen the trust that was established beginning with the first email invitation and culminating in the interview.

SEMI-STRUCTURED INTERVIEW

Appendix A provides the pre-scripted interview guide. As noted in (4) above, during the actual interviews, I often improvised and followed a semi-structured template in order to make the interview conversational and not limit the directions some interview participants wanted to take. I branched off and asked questions about what was salient at the moment, and I returned to the interview guide when the participant was ready to move on to another topic.

Taking a semi-structured interview approach to study innovation adoption is appropriate in order to explore rich and unanticipated results. The successful employment of this approach by Everett Rogers was documented by Dearing and Meyer (2006). They tell a story of Rogers' participation in a team project on diffusion and adoption:

> Accordingly, we took great care to develop and validate measures and instruments. Our methods of data-collection included structured personal interviews… we spent considerable time making sure that the interviewers understood the structured interview protocol, and would ask the questions in the same way… When Ev joined us at the site and we began interviews… Ev was not following the [interview] protocol. He didn't even seem to be looking at the structured set of questions and prompts! It would have been easy to pull a junior team member aside and correct them. But this was Ev Rogers. Later, poring over the transcripts, we felt deflated. His questioning was so different from everyone else's that we resigned ourselves to having to limit the number of organizations in our analysis, excluding the interviews in which Ev had participated. (p. 39)

According to Dearing and Meyer, this disappointment came from their initial orientation to structured interviews in order to solicit confirmatory responses to validate prior speculations. They continue the story with a twist:

> Then an interesting thing happened. Once we got beyond the odd questioning approach that Ev had followed, we noticed that the number of transcript pages for his interviews were larger than for the rest of us. Analyzing the responses he had generated from interviewees, we were amazed. Ev was eliciting far richer, more detailed responses than the rest of us. The protocol was more tightly focused on our priori concepts of interests, but Ev was learning more, including some fascinating, unanticipated results… Later, after reflection, we concluded that Ev's friendly and sincere style of engaging interviewees in dialogue had produced greater and richer data than had our planned approach, which had been less dialogue and more of a confirmatory question. (pp. 39-40)

Although far from being a master interviewer like Everett Rogers, I was inspired by his story. Therefore, interviews for this project were collected with the spirit to follow Rogers' approach as documented by Dearing and Meyer.

DATA COLLECTION

I conducted interviews over a period of 32 months, from November 2007 to June 2010. The data set includes 70 interviews with 66 participants from across 17 U.S. states and three other countries. The interviews were spread across four years with 10 participants in 2007, 42 in 2008, 16 in 2009, and two in 2010. Because most of the interviews were conducted in 2008, the analysis primarily reflects the development during this period. The shortest interview was 15 minutes and the longest was 2 hours and 16 minutes. The interviews averaged approximately one hour each and were conducted in person with 19 of the participants and over the phone with the remaining 51 participants. All the interviews were audio recorded except for two, due to technical difficulty and following one participant's request. However, notes were taken immediately after these two interviews. Furthermore, I attended several events locally organized by the Texas Advanced Computing Center in 2007, 2008, 2009, and 2010, and attended the Supercomputing 2008 conference in Austin. Additionally, I attended lectures on cyberinfrastructure and e-science held at the Queensland University of Technology in July 2009, 'Society for Social Studies of Science' annual conference in Washington DC in October 2009, the National Communication Association annual conference in Chicago in November 2009.

The 66 interview participants came from Texas (12), Illinois (11), California (10), Michigan (5), Indiana (4), Massachusetts (3), Arizona (2), Colorado (2), Louisiana (2), Washington (2), DC (1), Maryland (1), New York (1), Virginia (1), Ohio (1), Pennsylvania (1), Delaware (1), as well as Australia (2), Germany (1), and the UK (1). The geographic affiliations refer to the primary locations of the participants at the time of the interviews. Participants include 52 males and 14 females. Participants' primary professional roles were diverse, including domain scientists who used CI to conduct science (15), computational technologists who built CI (12), a range of administrative directors and program managers at supercomputer centers and national research laboratories across the country (21), NSF program officers who helped allocate funding to CI projects (4), social scientists and policy analysts who studied and participated in CI projects (12), and experts from commercial industry (2).

It is important to note that these roles are the primary roles of the participants at the time of the interviews. However, many wear multiple hats and have multiple backgrounds and disciplinary expertise. Some technologists are professors of computer science and they engage in research. However, they are labeled as technologists in this dissertation because they are involved in the technological aspects of CI projects. Also, two of the participants were NSF directors before the interviews, and one became an NSF director shortly after the interview. They were categorized as not in the NSF categories due to the timeline of the interviews, but their insights about the influence of NSF were apparent during the interview. Additionally, two participants left academic computing and joined the commercial computing shortly before the interviews. Although they were categorized as experts from commercial industry, they were very familiar with cyberinfrastructure in academic and scientific computing.

When geographic origins do not match the physical locations when the interviews were conducted, participants were placed in the locations they were speaking from. This is obvious for a few interviews conducted at the Supercomputer Conference in Austin, Texas. Furthermore, one interview was conducted on a plane from Los Angeles to Kuala Lumpur. This participant is an American chemical engineer who received his Ph.D. from the University of Delaware in the 1980s. He was traveling to Kuala Lumpur because he works for Shell in Malaysia. During the interview, he talked about his experience remotely using supercomputing resources at Illinois during the time of his dissertation research, providing a historical background to the topic. Although his geographic affiliation at the time of the interview is Malaysia, he is assigned to the state of Delaware because he made no reference to cyberinfrastructure in Malaysia except about his experience while in Delaware. Another mix in the demography of the participants is dual countries; one of the two participants from Australia is also an American. However, he talks about cyberinfrastructure development in Australia during the interview. Therefore, his interview was put in the category of Australia.

CHAPTER FOUR: CHALLENGING CONDITIONS FOR CYBERINFRASTRUCTURE ADOPTION

The grand vision of cyberinfrastructure is to enable large-scale research using aggregated computational resources and combined datasets through the Internet, high-performance networks, and local machines and to be able to mine publicly-funded datasets accumulated over time. When this grand vision is achieved, there will be increased productivity and breakthrough discoveries in research (note: this foreground will be explored in more details in Chapter Five: Driving Rationalities for Cyberinfrastructure Adoption). However, like most innovations, an ambitious endeavor such as cyberinfrastructure adoption often encounters challenging conditions in the general environment. A leading computer science professor in Indiana who has extensive experience organizing conferences and special issues of journals on cyberinfrastructure shares, "If you like informal evidence that I've collected over the last 2 to 3 years… with cyberinfrastructure, technology is around 20% of the problem. 80% of the problem is organizational, social, political or institutional" (14 February 2008). Although the analysis results in this chapter do not amount to an exact 20/80 split as he reflected, in line with sociotechnical approaches, the findings reveal a range of challenging conditions that are technological, organizational, social, political, and institutional in nature.

Research Question 1 asks, "How does cyberinfrastructure's nature influence its adoption process in the early 21st century U.S.?" CI's nature in this question refers to the four pairs of unique qualities (i.e., participatory/bespoke, meta/complex, disruptive/revolutionary, and community/network) discussed in the Introduction of this dissertation. From the interview data four areas of challenging conditions for cyberinfrastructure adoption emerged to reveal how CI's nature influence its adoption process, resulting in: a lack of trialability/observability (due to the participatory/bespoke nature), a lack of simplicity (due to the meta/complex characteristic), a lack of perceived compatibility (due to the disruptive/revolutionary quality), and a lack of full control (due to the community/network property). Table 1 below briefly summarizes the key findings in response to RQ2. The rest of the chapter provides interview excerpts to elaborate on these key findings.

Table 1. Challenging Conditions for Cyberinfrastructure Adoption

A. Participatory/Bespoke Innovation
1. Specialization-Synergy Gap
   a. Scientists: Limited Ability to Envision New Tools
      - Don't Know What is Possible
      - Don't Fully Know Their Needs Yet

   b. Technologists: Limited Knowledge of Domain Science
      - Don't Know Enough Science
      - Don't Have the Motivation to Learn Domain Science
2. Science Investment-Technology Quality Gap
   a. Science Funders: Limited Funding for Technological Development
      - Limited Direct and Unstable Funding for Software Development
      - Mostly Short-Term Funding for Science (and CI) Projects

   b. Technological Developments: Time Consuming, Unstable Software
      - Open Source Platform Lacks Turnkey Solutions
      - Rushed and Unstable Software Development
      - Unstable Software Gets in the Way of Serious Research
      - A Generation of Scientists is Lost

Outcome: Lack of Trialability/Observability

B. Meta/Complex Innovation
1. Scientist-Developers: Facing a High Learning Curve
   a. Need to Know Hardware Details
   b. Need to Become Master Programmers
   c. Need to Downscale the Science
2. Users of Existing Tools: Facing Low Usability
   a. Low Usability with Multiple Screens
   b. Differing/Competing Approaches to Science
   c. Long-Term Availability/Sustainability Concerns

Outcome: Lack of Simplicity

Table 1 (continued)

C. Revolutionary/Disruptive Innovation
  1. Technological Resources: Networks of Systems and Arrangements
    a. Material Systems
      - Local Personal Computers
      - Lagging Software environments
      - Expensive Data Storage
    b. Organizational Arrangements
      - Laboratory Workflows
      - University Traditions
      - Entrenched Interests
  2. Social Rules: A Mix of Motivations and Norms
    a. Professional Motivations of Research Teams
      - Graduate Students Need to be Trained as “Scientists”
      - Post-Docs Need to Publish “Science” to Get Jobs
    b. Publication Cultures of Traditional Academia
      - Lead/Single Authorship is Favored in Many Disciplines
      - Unconventional Findings are Sometimes Difficult to Get Published

  Outcome: Lack of Perceived Compatibility

D. Community/Network Innovation
  1. Seasoned Users vs. New Users
  2. Power Users vs. Small Users

  Outcome: Lack of Full Control

PARTICIPATORY/BESPOKE NATURE

According to Rogers (2003), *trialability* is “the degree to which an innovation may be experimented with on a limited basis” (p. 258). Rogers points out that trialability is an important factor because when a potential adopter tries out an innovation, he or she gives meaning to it in the process of figuring out how it works. In the initial cases of CI adoption, trialability was largely missing, especially for those pioneering adopters; Rogers would categorize these as “innovators”, or the first 2.5 percent of adopters in the overall scientific community. This group adopts cyberinfrastructure at the conceptual level and gives it meaning when they submit a grant proposal (often jointly with technologists). Once funded, they work with technologists to co-produce CI tools that do not yet exist. During the co-production process (Bødker, Kensing, & Simonsen, 2004), they continue to give meaning to it as they get deeper into the development. In other words, pioneering scientists adopt cyberinfrastructure as a possibility, not as a fully developed tool in the physical sense. This participatory characteristic of cyberinfrastructure complicates the traditional notion of trialability and makes it a unique case for studying innovation adoption. However, user-generated innovation is not a new phenomenon. Von Hippel (2005) maintains that users tend to develop functionally novel innovations, and in the case of scientific instruments, about 80% of the innovations were user-innovated. He argues that lead users have needs that foreshadow general demand in the marketplace, and they also expect to obtain high benefit from a solution to their needs ("necessity is the mother of invention").

In cyberinfrastructure co-production, a scientist presents a scientific problem and a technologist explores ways to create a tool to help investigate it. A CI project manager in Indiana explains, "We [technologists] have to understand enough of their [scientists'] problem to be able to understand ourselves where computers can help. And then do the best we can to explain that to them [scientists] and give them options" (25 January 2008). This is a critical process that this project manager repeated during the same interview, "I can't do my work unless the domain scientist is willing to take the time to explain necessary things to me. The domain scientists can't do their work unless I can build them the right tools" (25 January 2008). Therefore, cyberinfrastructure co-production is often driven by a problem within a particular scientific context and domain. Furthermore, because the research is also primarily defined by the scientist, the tool produced is based on the approach (i.e., theory, measurements, methodology, etc.) employed by him or her. Hence, cyberinfrastructure is described as a bespoke innovation in the Introduction.

The co-production process also impacts cyberinfrastructure adoption due to its lack of observability. Rogers (2003) defines *observability* as “the degree to which the results of an innovation are visible to others” (p. 258). He explains, “Some ideas are easily observed and communicated to other people, whereas other innovations are difficult to observe or to describe to others” (p. 258). In the case of cyberinfrastructure, it is a multi-dimensional innovation shared by a community of users through high-performance networks. It is a difficult innovation to explain. Furthermore, Rogers maintains that equipment (i.e., computer hardware) tends to be adopted faster than programs (i.e., computer software) do because equipment is usually more visible and observable than programs are. In the case of cyberinfrastructure, neither the hardware nor the software is highly visible or easily observable to users in the traditional sense. A key component of cyberinfrastructure hardware includes big supercomputers enclosed within air-conditioned rooms and housed within supercomputer centers. Users will only see these supercomputers when they take special tours. Cyberinfrastructure software is under development in co-production; therefore, it is not widely spread within scientific communities as a final and polished product that can be put to use immediately.

As cyberinfrastructure is a participatory/bespoke innovation, two major gaps exist for cyberinfrastructure adoption and implementation during the co-production process. They are the specialization-synergy gap and the science investment-technology quality gap. Simard and Rice (2007) documented practices gaps as barriers to the diffusion of innovations. The two gaps identified in this dissertation further compound the lack of trialability and observability. This discussion begins with the specialization-synergy gap.

Specialization-Synergy Gap

There is a critical gap between participating in the co-production process as specialists and the need to achieve synergy under the time constraint of a funded project.

In this dissertation, this organizational gap is referred to as the specialization-synergy gap. As CI is a participatory innovation, the first part of this gap involves specialists building CI tools. CI tool development is driven by a scientific problem pursued by domain scientists (as users of the tool). Therefore, the development process requires the participation of specialized scientific experts in the domain. On the other hand, a CI tool is a piece of technology that cannot be bought off-the-shelf commercially. Its production requires specialized technologists who are skilled at high-performance, distributed, and parallel computing techniques and knowledge. One often has to focus on a very narrowly defined area of knowledge in order to become a specialist in domain science, computing techniques, etc.

The second part of the gap is the need for synergy because CI is a bespoke innovation custom-made for specific scientific problems. Synergy can be defined as the process or mechanism that enables collaborative advantages (Roz, Elisa, & Rebecca, 2001) among diverse specialists and participants. In order to achieve synergy among specialists, there needs to be a common language, shared understanding of basic concepts, motivation to learn, and the ability to see the outcome, all of which is impossible without synergy. However, it takes time for these four elements to fully develop before true synergy can positively impact CI co-production. As these elements cannot fully develop when projects are funded for on a limited time basis, such as a three-year or five-year term, the development of CI tools is compromised. The analysis continues with examples offered by scientists and technologists who have experienced the specialization-synergy gap.

Scientists. A Scientist's ability to envision what is possible for a CI tool is limited by his/her ability to see the outcome, and this is impossible without synergy. More specifically, it is difficult for them to recognize and articulate their needs. These needs are different from those of computational power, massive storage, multi-scale integration, and multi-disciplinary collaboration, which were discussed in Chapter 4. These are new needs yet to be clearly defined for new CI. Because pioneering scientists are in the stage of prototyping tools, co-production becomes an experimental process in which scientists try to determine what is even possible. In other words, co-production can be interpreted as setting an agenda for cyberinfrastructure and science, involving the work to "define what cyberinfrastructure should be" (see interview quote below). A pioneering cyberinfrastructure adopter and a water resources engineering professor at Illinois shares her co-production experience working with a leading supercomputer center in the country, "I've been… trying to figure out what they are,… working with [the center] to try to understand the cyberinfrastructure needs … We're… prototyping and developing what might be possible,…to define what cyberinfrastructure should be and to prototype early cyberinfrastructure" (22 April 2008).

Pioneering co-production is time-consuming because the exploratory process requires working closely together often in face-to-face interactions. A big part of this limitation experienced by scientists could be the result of not knowing enough about computational science to envision the potential. Therefore, the co-production is an exploratory process "trying to sort of make a match" between the needs to be discovered and the tools to be developed, similar to the activities during the 'matching' stage in the diffusion process. A social scientist in Michigan observes, "It is time-consuming… They [technologists and scientists] really work closely… face-to-face to try to… make a match in a way between their [scientists'] needs, needs that they don't really know they have yet… so that they can do different things with their science (24 March 2008). This quote implies that scientists often do not enter into co-production with a clear design, product, and outcome in mind; they explore and figure out the tool with technologists in a time-consuming process.

These excerpts reveal that scientists often experience difficulties in envisioning new CI tools for their science. This difficulty comes from not fully knowing what is possible for their science, and not fully knowing their needs yet. Therefore, CI tools remain in the prototype stage, and co-production is very time intensive. Technologists also experience challenges in specialization-synergy gap.

Technologists. While scientists are constrained by their ability to articulate clear needs and envision what is possible, technologists appear to be limited by their knowledge of domain science and their lack of motivation to acquire it quickly. It is understandable that most technologists (as specialists in computer science and computational techniques) do not often speak the language and understand the basic concepts of science. However, not having enough scientific knowledge can lead to developing tools that do not match the scientific problems to be investigated. Furthermore, acquiring the necessary language and concepts for synergistic communication and participating in ongoing communication both take a lot of time. A technologist in Indiana explains, “We speak different languages. It’s very easy for the [technologists] to do something that turns out to be nonsensical because we don’t understand the science… The domain scientists get frustrated… because [they] don’t necessarily understand the complexity involved in it” (25 January 2008).

The challenge of having technologists who are unfamiliar with the science is that the co-production process often requires repetition of cycles and revisiting the design. As technologists acquire scientific knowledge in the process, they often need to re-work some early recommendations and/or parts previously built. The result is a delay and slow progress in CI projects. Moreover, the learning process can be impaired or hampered if technologists are not personally interested in or motivated by the field of science because their participation in the co-production process is short-term and they do not actually work under their scientist counterparts. A geochemist in New York reflects on her experience, “You had to go back many times… they said – Oh, if this is that way, then we cannot do it here…. They were not really that motivated and that enthusiastic about learning it. It was just part of the work” (23 January 2009).

These quotes about the technologists explain that they often do not possess either the language or the concepts of the science they are building tools to address. It becomes more challenging if technologists are not personally motivated to learn the science. Because their participation is often on a short-term basis and many of them do not work long-term and full-time for the scientists and/or in the field of science they temporarily serve, the specialization-synergy gap is likely to persist.

Due to the early stage of cyberinfrastructure prototyping, co-production is very time-consuming because of the specialization-synergy gap demonstrated. Because CI adoption implies co-producing and prototyping CI tools with technologists, adoption can negatively impact a scientist’s research productivity. In order to stay with CI adoption, pioneering adopters have to have a strong conviction in the future and vision of cyberinfrastructure, as articulated in the Atkins report[4] cited in Chapter 2 (about the emergence of cyberinfrastructure). A water resources engineering professor in Illinois reveals:

> I’ve had a lot of exposure to all the different aspects of cyberinfrastructure… Just a little bit about my perceptions about where cyberinfrastructure is at in terms of the question you asked of ‘how does it help you research?’ I don’t know that it really has helped my research. Right now, cyberinfrastructure slows down my

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[4] Atkins, D. E., Droegemeier, K. K., Feldman, S. I., Garcia-Molina, H., Klein, M. L., Messerschmitt, D. G., et al. (2003). *Revolutionizing science and engineering through cyberinfrastructure: Report of the National Science Foundation blue-ribbon advisory panel on cyberinfrastructure*. Washington, DC: National Science Foundation. Retrieved December 19, 2006 from http://www.communitytechnology.org/nsf_ci_report/.

> research because we’re not there yet, at the point of the Atkins vision…. You’ve got to be willing to take a hit on your research to do that, because you believe that the research will be better when you’re done. But it’s a very time-consuming process and it’s not something that makes my research better – makes my researcher easier, put it that way. It makes it better in the end, but it is not helping me get it done faster. That vision isn’t there yet. (22 April 2008)

The specialization-synergy gap is a critical challenge for cyberinfrastructure adoption because it compromises the CI tools developed to explore important scientific problems and grand challenges. It also has a detrimental impact on the research productivity of the pioneering adopters.

Science Investment-Technology Quality Gap

The second gap, the science investment-technology quality gap, involves funding patterns and software developments in co-production. As cyberinfrastructure is a participatory/bespoke innovation, successful adoption is often impeded by a gap between science funding and software development. This often leads to negative impacts for this generation of scientists who are ushering in the cyberinfrastructure vision.

Science Funders. The first part of the gap, science investment, represents a funding condition under which cyberinfrastructure has emerged. However, the investment pattern to fund science also represents two important challenging conditions for CI adoption. The first challenge is that there is not a dedicated public funding source for long-term and sustainable software development to support cyberinfrastructure development. Funders, such as NSF, are set up to fund science, and not technology. A technologist from Indiana laments, “NSF funds research. Sustainable software is not research. You can’t keep doing it, that’s the problem. You can do it for a few years. I doubt if you can do it for 20 or 30 years” (14 February 2008). Because there is not a ‘National Technology Foundation’, software development for cyberinfrastructure is often compromised.

The second challenge is that there is limited long-term outlook for most science (and e-science) projects funded by agencies such as NSF. The technologist quote above continues, “Governments tend not to pour money into areas more than five or at most 10 years… Often NSF will fund the initial steps, but not the long-term sustainability” (14 February 2008). Due to these two challenging conditions, the lack of direct and stable funding for software development and the lack of long-term funding for projects, cyberinfrastructure development, adoption, and implementation based on short-term funding for science creates a challenge for quality tools.

In the short-term and science-oriented funding environment, software development for CI is often assumed to be free and/or a part of a science project that does not require direct financial support. A senior administrator who retired from a major university in California shares, “The instability of the software is due to… [people who] make funding decisions just don’t think of software as something requiring a big long-term ongoing investment. It’s nice to think of it as somehow being free… [it] gets created and maintains itself” (7 February 2008). This is an inherent challenge when cyberinfrastructure is a bespoke innovation based on specific scientific problems to be funded by federal agencies.

NSF funds projects that rely on open source platforms and CI adopters often turn to open source software as the primary preference for software development under these funding conditions. The rationale is that the software will be created as part of the process of science and that the scientific community will maintain it as a public good. As a project manager in California explains, “Most of the organizations the NSF is involved with are using open source. [It] is more a part of cyberinfrastructure than Windows technology… They appear to be less expensive because you don’t have to pay for the software licensing" (14 December 2007). However, relying on open source software development also encounters challenges that will be discussed next.

Technological Developments. The first challenge in the area of software development for cyberinfrastructure is the dependence on open source platforms. While these are free and the open source philosophy also sits well with academics, it does not have many pre-determined and standard solutions to known problems (i.e., turnkey solutions) to speed development. This disadvantage poses a challenge to timely technological development. The project manager in California quoted earlier continues, "Our project didn't come in on time because instead of using…open source software, we should have migrated to Windows technology. We would have had more turnkey solutions that… the existing team could have produced software more quickly" (14 December 2007). In the same interview he continues to explain that using open source software also requires more programmers due to the same limitation of a lack of turnkey solutions. While the open source approach has its inherent benefits, including pooling a wide range of ideas, knowledge, and expertise (von Hippel, 2005) and organizing beyond traditional boundaries (Shirky, 2009), the organic and emergent nature of an open source approach cannot always guarantee effective outcomes under critical time pressure.

The second challenge under the current funding condition is that software development is both rushed and unstable. As previously discussed, there is no long-term funding for software development. Funded scientists and technologists have to reapply for funding in order to sustain a cyberinfrastructure project. To secure the next round of funding, sometimes there is a need to rush through the development process. A technologist and a professor of computer science in Louisiana states, "There's so much to do and there's a tendency to rush the job, try and get systems into place, try to get scientists using them… before they're really ready to be used because of the pressure to have continued funding" (27 February 2008). This excerpt is illuminating in terms of many time-related constructs in organizational communication literature discussed in the next paragraph.

Work *pace* is accelerated faster than usual in the context of time *scarcity* in order to cope with the pressure to renew funding. Ballard and Seibold (2004a) characterize pace as "tempo or rate of activity" (p. 6) and scarcity as limitation of time in work situations where "too many inputs within a given unit of time or by not enough time to complete a task" (p. 7). In the case of cyberinfrastructure, there are too many inputs within a given unit of time and there is not enough time to complete tasks. However, if the implementation is not rushed to meet funding deadlines and funding stops, CI adoption and development may come to an impasse. The outcomes of pace are often evaluated as *punctual* and *delayed* (Ballard & Seibold, 2003, 2004a, 2004b) against funders' allocation cycles. According to Ballard and Seibold (2006), *punctuality* refers to the "exacting nature of timing and deadlines" (p. 321) where as *delay* means "working behind schedule" (p. 321). As a result, funders' allocation cycles become the source of *entrainment* (Ballard, 2008) for how scientists organize their work, leading to a sense of *urgency*, defined as "persons' preoccupation with deadlines and task completion" (Ballard & Seibold, 2004a, p. 7). The pressure to rush through the co-production process in order to secure the next round of funding can compromise the quality of the technology produced and the adoption process.

The third challenge that results from the funding conditions is that software development can hinder scientific investigation since the tools are neither robust nor fully developed when applied. In other words, the science that was originally funded can be compromised when the tools that were supposed to enable the research investigation are actually experimental tools being prototyped in the process of serious research.

Therefore, both technological development and the scientific research will be compromised. A technologist at a commercial software company in Washington shares a compelling argument that illuminates this problem:

> We saw too many projects in the past that – where experimenting with technology at the expense of helping scientists do science. So cyberinfrastructure should be… services and technologies and computing-related infrastructure that just work… That, to me, is the critical factor of a success…. It shouldn't get in the way [of science]…. Cyberinfrastructure really has to not get in the way... [Cyberinfrastructure projects] have tried to come up with new ideas while being applied during [e-science]… Those new ways should not be part of a science-related project or a new scientist-created project. Those should be on their own. Only when they prove themselves, then we can apply them to e-science… The same way that the industry will not use experimental methods in order to do critical business tasks, in the same way, we shouldn't be using experimental methods to do critical to science tasks. (18 March 2008)

This excerpt reveals the unfortunate outcomes of many cyberinfrastructure co-production efforts. Since scientists adopt cyberinfrastructure at the conceptual level before the tools exist, efforts to bring forth cyberinfrastructure compromises the science the technology was supposed to serve. A technologist in Texas laments, "[The] generation [of scientists] that brought it in and really started – basically they put their research agenda on hold to figure out how it could be done to define this field. That generation was lost because the science was not done" (20 November 2007). This is a direct outcome of cyberinfrastructure being a participatory and bespoke innovation. Scientists have to be active participants of the development of the CI tools they have adopted conceptually.

The science investment-technology quality gap is the result of CI development being dependent on short-term funding for science and the CI tools being developed in the middle of a serious research project.

The co-production process often involves exploration of what is possible, an attempt to match an emerging need with technological development, learning of the science, iterative cycles, finding solutions of open source software developments, and working on a limited short-term budget for science, and producing unstable tools that face the possibility of no sustaining NSF funding or community support. The participatory nature of cyberinfrastructure hampers adoption. The specialization-synergy gap and the science investment-technology quality gap complicate the process. In addition, because co-producing tools is not engaging directly in doing discovery science, it is considered a service that does not count much towards a scientist's career in traditional academia. A senior social scientist in California shares:

> Domain scientists so frequently complain that time they spend helping build cyberinfrastructure, or working on cyberinfrastructure, is service work. It's unrecognized and it will certainly not get them tenured… [They] have very, very good institutional reasons for not doing it. (14 April 2008)

In this sense, tenure and promotion is like the pressure of quarterly dividends and stock values on corporations, which forces them into short-term visions. The time investment to work with technologists, supercomputer centers, and other organizations in co-creating the future of cyberinfrastructure is what Birnholtz (2006) calls 'infrastructural contribution', and unfortunately, it is regarded as unrewarded service in traditional academia.

Overall, the adoption of cyberinfrastructure as a participatory/bespoke innovation has several challenges. The first is that it lacks trialability and observability. A potential adopter does not get a chance to 'observe' it or 'try it out' to give meaning to it before formal and/or long-term adoption. They 'observe' it and 'try it out' during serious research and the process of co-production after conceptual adoption of and formal commitment to cyberinfrastructure. However, the process is compromised by the specialization-synergy gap and the science investment-technology quality gap. Both gaps compromise the science being served at the expense of the technology being produced, and scientists’ careers and research agendas are negatively impacted. This naturally leads to the next challenge, which is a lack of simplicity.

META/COMPLEXITY NATURE

Cyberinfrastructure is a meta/complex innovation because it involves multiple layers of hardware, software, and processes. Not all scientists interested in adopting cyberinfrastructure engage in co-production with technologists, as previously described. There are two other groups of adopters: scientists who develop their own CI tools and scientists who use existing tools developed by pioneering adopters. For scientists who develop their own CI tools, they also must possess advanced knowledge and skills for a range of hardware and software related to supercomputing in addition to the computer, software, and scientific instruments in their own labs. A technologist in Indiana explains, “You need to be a software developer… have domain knowledge… know how to take advantage of the middleware… that actually implements the middleware part of the cyberinfrastructure. It’s pulling together knowledge from a lot of different areas” (25 January 2008). For scientists who use existing tools, they must understand the tools developed, the datasets collected, and the measurements used by the creators, as well as the scientific instruments employed.

Scientist-Developers

The first group of scientists, those who developed their own CI tools, are referred to as ‘scientist-developers’ in this dissertation. The notion of a scientist-developer has an emphasis on the role of a developer like a technologist. However, they are developers of their own tools. They can be faculty scientists, post-docs, or graduate students working on CI projects. The faculty scientists often were trained by advisors who did computationally intensive research, like those discussed in Chapter 4. The graduate students and post-docs acquire the knowledge and skills necessary for developing CI tools by attending training workshops. Sometimes they consult with technologists at supercomputer centers if they have access to them. In this section, the analysis reveals the challenges scientist-developers encounter in the adoption and development process as cyberinfrastructure is a meta/complex innovation.

The practice of self-developing CI tools has several limitations for faculty scientists. Ideally, faculty scientists would receive big grants to co-produce CI tools with technologists, as discussed earlier. Frequently in reality, their graduate students are the actual scientist-developers due to the limited funding faculty scientists receive. Furthermore, these are graduate funding and learning opportunities for graduate students. A chemical engineering professor from Massachusetts shares, “The correct way [is to] have the government pay chemists to hire computer programmers to work with them... But the current size of the NSF grants [is] too small… [So] we’re using our chemistry graduate students to write the software” (7 February 2008).

In order for these graduate students to do this work, faculty scientists often send their graduate students for training to increase their computational science knowledge and skills. Most scientists themselves do not participate in this training. A CI project manager in California shares, “We had a special conference that we convened once a year… to train end-users… We mostly got grad students… We got maybe one or two actual researchers from our community here in the States that were professors” (14 December 2007). This further shows that graduate students are often the hands-on scientist-developers of CI tools for projects. This project manager also explains that faculty scientists from out of the country participated because they wanted to learn skills and techniques related to the open source software being developed in the U.S. so that they could build on the American effort when they returned to their home countries. Since cyberinfrastructure tools are open source, attending the training conference in the U.S. can be the cheapest way to gain technology for their science back home.

Hardware Details. Cyberinfrastructure is challenged by the first limitation scientist-developers encounter: the need to be knowledgeable about supercomputer hardware details. In order to become a competent scientist-developer, a scientist (or usually a graduate student) has to acquire the advanced knowledge and skills of a professional CI computational technologist. The first skill is the hardware, and a scientist-developer has to understand the technical specifications of the hardware down to the "nitty gritty". A center administrator in Pennsylvania shares, "It's vital … for any code to work right… [you] need to understand the nitty gritty down to a very deep level, ….[you need to] work very closely down to the most intimate details of the hardware" (21 April 2008). This quote shows that a scientist-developer needs to be as knowledgeable about the hardware as a technologist, down to the finest level of detail.

Master Programmer. The second challenge a scientist-developer encounters is that they also have to become highly skilled at the software aspects of high-performance computing. Not only does a scientist-developer have to know how to write programming codes, he or she has to become a "black belt" or master programmer. In order to utilize the vivid details in the interview data, a few block quotes are provided to illustrate the meta/complex nature of cyberinfrastructure during CI adoption and development. An administrator at Indiana shares:

> So to use a supercomputer from a UNIX shell, you've got to know MPI, you've realistically today got to know C, you've got to know… about computer architecture. They are the fastest supercomputers on Earth for a reason. They're built with the newest, most advanced components so in general, they have the least polished interfaces. They're just harder to program. There's no getting around that… If you wanted to be able to use one of these things, it is a reasonable expectation that you are going to be a black belt [MPI] programmer. (16 January 2008)

Message Passing Interface (MPI) is a standard for writing parallel programs on supercomputers, including mastering processor-to-processor communication routines, monitoring collective operations performed by groups of processors, defining and using high-level processor connection topologies and user-specified derived data types for message creation. Clearly, to become a "black belt" MPI programmer as a scientist-developer is a challenging task. This is on top of understanding the hardware or "computer architecture" as previously discussed, programming language C, etc. These elements make cyberinfrastructure a meta/complex innovation.

The analysis continues to build on the finding that the ability to fully optimize cyberinfrastructure resources requires a very high level of programming skills (the "black belt" skills). Computing programming on a commercial personal computer is a difficult skill to master. It is an even more difficult on a supercomputer. Due to the complexity of supercomputing systems, the difficulty is exponential. If the programming algorithm is not written efficiently by a master programmer, the speed and performance can go down. A big challenge is for scientist-developers to think at the computational scale to program for cyberinfrastructure. A center administrator in Texas explains what is required to program on supercomputing or high-performance computing systems:

> Well, using high-performance computing systems is much more complex than using an individual workstation… You've got to rethink your application. You have to come up with a parallel algorithm that leverages the concurrent power of all the processors that you want to use and it does it efficiently – which is also very difficult. Even if you have a parallel algorithm, it's challenging to implement it efficiently… When it becomes inefficient is if you aren't fully utilizing the memory that comes with all those processors so you do something not very smart, like every processor contains the entire problem in it. Well, then you're not really leveraging all that memory. If your performance doesn't scale, it begins to turn over and that can actually happen. Your speed up can actually start going down if you write a parallel code, but you write it inefficient so there's lots of communications going on. Communications are not computations, so you're performance can actually go down if you write it particularly badly. (2 January 2008)

For scientist-developers to become familiar with the hardware aspects of supercomputers and to become master programmers for parallel computing for their science, they really have to play two roles or take on a dual identity effectively. They have to remain fully knowledgeable of their own field, which is very difficult given the rapid advancements in science. In addition, they have to take on the second identity of becoming a computational technologist as they acquire the knowledge and skills needed to program efficiently and effectively for their own science. Otherwise, when a programming code is badly written, not only can the performance suffer, but valuable resources will be wasted. This center administrator continues:

> The real barrier is learning enough about high-performance computing in addition to the field that they're in – biology or astronomy or chemistry or whatever – is learning enough about high-performance computing to be effective with it, such that it really does provide an advantage for your research. It's not too challenging to write a parallel code that stinks, but you don't get any real research advantage if it's not speeding up your research or solving bigger problems. So you have to write it well to use multiple compute nodes at once… If they aren't efficient and effective, they're kind of wasting a valuable resource. (2 January 2008)

Sometimes Downscale the Science. Given the complex and meta nature of innovation, an unintended outcome sometimes arises for scientist-developers: the need to downgrade their own science. As previously suggested, some faculty scientists depend on their graduate students to program and maintain the CI tools required for their science. However, as illustrated thus far, the skills required to become a master, efficient, and effective programmer for cyberinfrastructure are very difficult to acquire and develop. In order to still be able to keep and maintain their own codes without depending on technologists, some scientists are willing to compromise their science in order to continue using their graduate students for their programming needs. A physicist in Louisiana shares, "Typically, the fluid dynamists have no expertise in… parallel computing… But they're often willing to do work on problems that are less sophisticated computationally… downgrade the science they do [so] their own grad students …[can] maintain… the software" (18 February 2008). In doing so, faculty scientists can continue to use their graduate students to develop CI tools in house. Cyberinfrastructure adoption is a balancing act. Cyberinfrastructure adoption requires a high degree of computational knowledge and programming skill in addition to knowing about the hardware, computational process, and cyberinfrastructure components. However, in order to stay in the game, one compromise some scientists are willing to make is to scale down their scientific agenda.

Scientist-developers (or self-developers) face three challenges in adopting the meta/complex cyberinfrastructure through developing their own tools. First, they have to know the nitty gritty details of CI hardware. Second, they need to become highly skilled in computational science as master programmers. Third, they sometimes scale down their science agenda because they assign their graduate students to develop and maintain the CI tools. Given these challenges faced by scientist-developers, cyberinfrastructure adoption is hampered.

Partly due to a high degree of temporal flexibility, defined as "the degree of rigidity in time structuring and task completion plans" (Ballard & Seibold, 2004a, p. 5), in how academics choose to perform work, scientists are able to expand their work from simply doing discovery research to time-intensive co-production and self-development of CI tools. However, this expansion also leads to an increased workload and perhaps internal/external expectations because there is not a clearly defined boundary on how they should structure their time for work. For those who are not able to attend to such a demand on their time, some simply adopted existing CI tools built by the pioneering scientists who came before them.

Adopters of Existing Tools

In addition to the scientist-technologists who co-produce and self-develop CI tools, an important and growing group of adopters are the scientists who simply use existing tools. A physicist in Indiana states, “Not all scientists want to be technologists or technology developers” (14 February 2008). Science Gateways are existing CI tools these scientists can simply adopt. According to TeraGrid’s website,

> A Science Gateway is a community-developed set of tools, applications, and data that is integrated via a portal or a suite of applications, usually in a graphical user interface, that is further customized to meet the needs of a targeted community.

Due to a graphical user interface, Science Gateways adopters do not have to face the challenges of scientist-developers.

Using pre-existing tools makes cyberinfrastructure adoption easier for scientists who are not computationally savvy. However, in order for Science Gateways to exist, there will always be a need for a group of scientists willing to work with technologists to produce new tools. Therefore, while Science Gateways increases the simplicity for cyberinfrastructure adoption, there will also be a need for scientists to be computational experts or to work with technologists in co-production. An administrator from Indiana talks about how a Science Gateway can increase CI adoption, “People who are discipline science experts [can] use computing at scale without first having to become computational experts… [But] there’s another group of scientists some place that is made up of computational experts who are making these Gateways” (16 January 2008). Although existing CI tools exist, adoption of them is not without challenges.

Low Usability. The first challenge for adoption of existing tools is low usability. Science Gateways are tools developed by pioneering scientists. Their tools often become public goods due to the open source nature of the tools. According to Olson (1971), a public good is “any good… [that] if any person in a group consumes it, it cannot feasibly be withheld from the others in that group" (p. 14). In other words, everyone can contribute and benefit from open source tools. Yet many of the tools lack usability, which can negatively impact cyberinfrastructure adoption. The cyberinfrastructure vision is to build a system that allows a community of scientists to share data with each other. However, the interface with low usability is difficult for scientists to adopt and use because the tools were built within a particular project. A cyberinfrastructure project manager in California talks about a CI tool that NSF was trying to get researchers to use to put data into the system, and he recounts how the navigation required multiple screens, "A user had to drill down and navigate multiple screens – might have to click through maybe 5 to 10 screens to get to the screen they wanted to get to… There's more work that needs to be done" (14 December 2007). Since this observation was reported in 2007, improvement in this area might have been achieved in 2010.

Furthermore, the design of a CI tool reflects the preference and/or workflow of the original scientists (and/or technologists). The outcome is a tool that is complicated for other scientists to adopt. The interface and design may not make sense for scientists with no experience with the particular domain. This can severely impact the adoption and spread of existing tools. In the same interview, the project manager in California also comments, "The system was complicated. It had a complicated database schema for somebody who works in that domain as scientific researcher. It would make no sense to somebody who's never worked in that area" (14 December 2007). As this interview was one of the very first conducted for this project, the usability of this tool might be better almost three years later.

Differing Approaches. The second challenge adopters of existing tools face is implied by an observation of researchers' differing and sometimes competing approaches to science. Thus, the notion of norm compatibility in scientific groups is invoked.

Existing tools are often built for a scientific problem based on particular approaches to science, described earlier as a participatory/bespoke innovation. In science, there are often competing theories, methods, and measurements for approaching a scientific problem (Fuchs, 1991, 1992). Sometimes the competition between groups who hold differing approaches plays out in the development of CI tools. Two block quotes are chosen to demonstrate this dynamic in rich details. A center administrator at Illinois shares a revealing story:

> We've been in disputes with people essentially having two different… methodologies to approach a problem. They would come to the cyberinfrastructure folks and say – 'We're glad to be on the project and of course you're going to include my methodology in the way the software works and exclude my competitor over there'. (23 January 2008)

A social scientist in Michigan also observes that CI tools are not neutral technologies, but products of competition between groups of scientists. She shares:

> A number of sites [were]… developing competing software… [Then] NSF essentially intervening and saying – You can't afford to be spending your money developing two potential pathways for developing the software and you need to end one of them… People… had to fight it out. It's whoever was the noisiest person, won… The noisiest people are the ones that have the most prominence in the community and who are more assertive. (17 March 2008)

These two quotes reveal an important challenge in adoption of existing CI tools. It is inevitable that pioneering scientists built their particular scientific approaches (i.e., theories, measurements, methods, etc.) into early tools. However, this implies that other scientists who hold similar approaches can more easily adopt these CI tools. This could be seen as the 'structuring' stage in the organizational diffusion process. Potential adopters who hold different approaches must either engage in the co-production/self-development of tools or they cannot adopt cyberinfrastructure until computationally savvy scientists with the same scientific approach make new tools they can use.

Long-Term Availability/Sustainability Concerns. The third challenge adopters of existing tools face is the uncertain long-term availability/sustainability. As previously established, CI projects are funded on a short-term basis, and there is limited or no long-term funding specifically for software development on these projects. Because scientists are aware of this pattern of NSF and other science funders, they hesitate to adopt a tool for fear that they may become dependent on it and that then the funding for continuing development might stop or the developing scientist might leave. A physicist in Louisiana shares, “I was trying to understand why the fluid dynamics groups are reluctant to embrace our cyberinfrastructure that we’re trying to develop for them. They said – Well, how do we know that it’s going to be available in two years?” (18 February 2008). Scientists are careful about their cyberinfrastructure adoption decision, even in the case of adopting an existing tool built by pioneering scientists and technologists. The key concern is long-term availability/sustainability if they become dependent on it, thus reducing its long-term relative advantages.

Similar to adopters in co-production and self-developing software, scientists who simply adopt existing tools face three challenges as a result of the meta/complex natures of cyberinfrastructure. First, existing tools often have low usability. Second, existing tools are built based on particular approaches to science. Potential adopters with differing and/or competing approaches cannot easily adopt these tools. Finally, because cyberinfrastructure projects are funded on short-term grants, their long-term availability/sustainability is uncertain. A retired senior administrator from California shares, “There is the feeling that cyberinfrastructure is not ready for prime time, would be one way of putting it – the software isn’t fully stable and it isn’t fully featured and it’s hard to use” (7 February 2008).

The challenges that stem from complexity are compounded by the meta nature of cyberinfrastructure. Because there are many components to cyberinfrastructure, they need to work seamlessly if scientists are to derive benefits from their adoption. However, as different components may be developed independently, the meta cyberinfrastructure may not be optimal when pieces do not fully integrate well together. A physicist in Indiana talks about these components, “They may not actually interoperate with each other so that you can use one piece of technology or software at one site and one at another…You can’t use one piece of software that satisfies all the requirements” (14 February 2008). He was talking about using one piece of software to satisfy the needs of all or most scientists for their big-scale projects.

The first two pairs cyberinfrastructure characteristics discussed so far are the participatory/bespoke natures (which leads to a lack of trialability/observability and the time-consuming co-production that compromises science) and the meta/complex characteristics (due to its layers of hardware, software, processes, etc.). Short-term funding and a lack of direct funding for software development also impact the long-term sustainability of existing tools in prototyping stages. The common thread in these two major challenges is adopters’ conflicted experiences with the wish to adopt cyberinfrastructure on one hand, and the time-related concerns (i.e., time to co-produce, time to master programming and related skills, long-term availability/sustainability of existing tools if they adopt) on the other. These challenging conditions demonstrate an irony in innovation adoption: “early adopters of a technology receive less of a benefit than later adopters do” (Lievrouw, 2006, p. 251). This is especially true when those who adopt early help remove these conditions for those who join the movement later. However, “[m]ost scientists [are] reluctant to invest more than a very small amount of time to learn to use new technologies unless the benefits [are] substantial and related directly to their research” (Lee & Bietz, 2009, p. 3). Time and related matters (Ballard, 2007; Ballard, 2008; Ballard & Seibold, 2003) appear to be a critical issue in the adoption and development of cyberinfrastructure. The analysis continues with the challenges due to the next two pairs of cyberinfrastructure characteristics: disruptive/revolutionary and community/network.

REVOLUTIONARY/DISRUPTIVE NATURE

Rogers (2003) defines *perceived compatibility* as “the degree to which an innovation is perceived as consistent with the existing values, past experiences, and needs of potential adopters” (p. 240). Rogers points out that the contexts through which compatibility is evaluated include social values and cultural beliefs, information and ideas presently held by potential adopters, and the needs and situations that could be addressed by the innovation considered. The notion of ‘needs’ was previously examined in Chapter 4 as a separate construct because it stood out as a forceful theme from the data and as a multi-dimensional theme that deserved a detailed elaboration.

The notions of ‘existing values’ and ‘past experiences’ are key in the discussion of this chapter as they represent the sociotechnical environment (Coakes & Coakes, 2009; Girard & Stark, 2007; Zimmerman, 2007) in which scientists work. The sociotechnical perspective emphasizes how the social arrangements and the technological systems are intertwined to create an environment for work (Coakes & Coakes, 2009). Loosely put, existing values are related to the mix of professional motivations of the research teams on which scientists depend and the publication cultures to which traditional academic scientists belong. These motivations and cultures reflect the ‘rules’ of most scientific communities. Past experiences are tied to the material systems and organizational arrangements that make up scientists’ technological networks. These systems and arrangements reveal the ‘resources’ most scientists draw from in the process of CI adoption and implementation. Girard and Stark (2007) maintain, "Socio-technologies of assembly are not simply settings, they are setups" (p. 152). Collectively, cyberinfrastructure as a disruptive/revolutionary innovation is perceived to be incompatible with the sociotechnical setups in the early 21st century U.S. The third sub-section of this chapter will further elaborate on this perceived incompatibility.

Technological Resources

Material Systems. The first challenge is a transition from personal computing to supercomputing. All scientists already have personal computers (i.e., commercial desktop and/or laptop computers that can be bought off-the-shelf as separate units) in their laboratories. From a historical perspective, this disruption is similar to the transition from using university mainframes to personal computers. These are often connected to scientific instruments for data collection/processing, which scientists are accustomed to running as local machines that process mostly single computing jobs. Cyberinfrastructure adoption is disruptive to this common setup because working beyond local machines with remote supercomputers is drastically different from doing science at the scale of desktop computing locally. A center administrator in Ohio shares, "Go[ing] from a desktop to using a supercomputer,… transition[ing] to a computer that is running a different operating system or requires a scripting language, or the concept of a queue exists…Small inexperienced users can be challenged sometimes" (28 January 2008).

There are several important distinctions between desktop/personal computing and supercomputing. Supercomputing requires *computational thinking*, the ability to organize computations in distributed and parallel fashions, along with the concept of *queue* when multiple jobs from different locations are being submitted and processed at the same time by one or a network of supercomputers. Moreover, the *operating system* and *scripting language* are different between a personal computer and a supercomputer adding to the argument that most scientists and/or new users would benefit from some technical support by technologists. This can be in the form of co-production or training, as previously discussed. The essence for the first point for material systems is that the computing environment for cyberinfrastructure adopters is drastically different from the personal computing world.

The second challenge is a technological incompatibility within the framework of cyberinfrastructure internally as an innovation. As previously defined in Chapter 2, the technological components of cyberinfrastructure are more than simply supercomputers. However, CI adoption is compromised by the lagging software development. A center administrator in Texas shares, “We have continued to develop new chips and new supercomputers. And the software is not keeping up” (10 January 2008). At a subsequent interview, this administrator continues, “They can run on 4, 8, 12 [processors] – when you get to 256 [processors], it might be a challenge. You get to 1024 [processors] and suddenly it grinds to a halt because there are so many little hiccups in the code” (12 March 2008). Supercomputing resources cannot be fully utilized without the matching software environment, which is under-developed relative to the hardware. This internal incompatibility impedes cyberinfrastructure adoption.

The third challenge with material systems highlights an issue with long-term data storage in the context of internal cyberinfrastructure incompatibility. Cyberinfrastructure requires long-term documentation of data, which can be maintained on a free, open source, wiki platform. However, long-term archival storage of actual data is problematic. Data storage is expensive. Paying for long-term data storage and making long-term storage space for data is a major concern; yet without it, cyberinfrastructure is incomplete. A chemist in Massachusetts and a former NSF program officer shares, “You have to be able to document the history of the data… Wiki… sort of springs to mind…

[Then] data storage… is very expensive and long-term storage of the data moving from medium to medium is well challenged" (20 February 2008).

Data storage is a critical challenge to be resolved if the cyberinfrastructure vision of long-term, cumulative, and massive data-storage for unprecedented science is to be achieved. A possible entity to maintain long-term data is journal publishers, as they maintain the long-term archival of research publications out of these datasets. A chemical engineering professor from a university in Massachusetts shares one side of the challenge he encountered, "I tried with one journal and that journal decided that it would be too expensive. They didn't want to invest the money. They didn't see that they would sell any more subscriptions because they had this electronic data" (7 February 2008).

While publishers might be interested in providing long-term data storage if they could copyright the data, this would discourage scientists from submitting their research (along with the data) for publications as the data is all open source. The chemical engineering professor from Massachusetts continues with the other side of the challenge, "The journals will definitely want to do it if they can keep the copyright on the data… [But] to get the copyright on it… would probably stop a lot of people from submitting it" (7 February 2008). Furthermore, data from research publicly funded by the government is difficult to be copyrighted. If cyberinfrastructure does not lead to more publications, then adoption defeats the purpose of a vision of breakthrough discovery in science.

In the area of material systems, there are three challenges related to perceived incompatibility. They are in the area of computing environment, software development, and data storage. The next section continues to elaborate on the technical environment in the area of organizational arrangement.

Organizational Arrangements. The first challenge of organizational arrangement is in the area of scientific workflows. Cyberinfrastructure is disruptive to existing workflows. A professor of physiology in Illinois shares, “[High-end] computing is pushing us in the direction of organizing our scientific work quite differently” (4 February 2009). In order to effectively and efficiently adopt cyberinfrastructure, a scientist needs to restructure and/or give up an active workflow in their laboratories. Although the current workflow for some scientists may be awkward, the organizational arrangement works for them. Scientists, like most people in general, often resist change. A geochemist in New York talks about an awkward workflow in details:

> A lot of people in our community use machines where the data comes out … either into some sort of analytical software or actually printed out [on] paper still. And people go back and type it into Excel spreadsheets. Then they type them into a new data table for their publication. So it’s this awkward workflow… And changing that behavior or their practices, that I think is another aspect [of challenge]… [To adopt] big cyberinfrastructure, you have to be able to plug into that… these individual researchers with [their] own working environment and working procedures… And that becomes… a stumbling block.... Because I think that’s a huge… cultural change to achieve. Basically chang[ing] personal working practices – that they’re behind their own [closed] doors with that – Nobody touch the way that I’m working. If they have to publish something, they will go along with rules set out by a publisher. But what I’m doing in my lab is up to me. Influencing people there [in their own workspace] is much more difficult. (23 January 2009)

Some scientists are still working with a mix of paper and digital technologies in managing data. This observation verifies the argument that people use different technologies concurrently and sequentially to perform work (Stephens, 2007; Stephens et al., 2008). It also exemplifies the broadened notion of ‘technologies’ to include non-ICTs (Ballard & Seibold, 2004b). Furthermore, although the manual workflow may appear awkward to an outsider, it works for these scientists. Scientists are likely to want to maintain their existing workflows in the laboratories, which are maintained behind closed doors of their labs. Unless the publishers impose a new rule, scientists likely will not welcome intervention or interruption by outsiders, especially with the adoption of a disruptive cyberinfrastructure.

The second challenge in the area of organizational arrangement is the technological infrastructure of the institutions at which scientists work. In order for scientists at a range of institutions to adopt cyberinfrastructure, the current computing capacity at these institutions is critical for supporting the adoption and implementation process. Many small institutions may not have the computing infrastructure in place to support such an ambitious endeavor. An NSF program officer shares, "[At] the next level of institutions, the challenges have really been… if you sit and you talk to a handful of Chief Information Officers on campuses, do they have the capacity, do they have the capability in place?" (17 March 2008).

Small, resource-limited universities also experience resistance to this distributed computing model. There are decision makers who are content to keep their campus off the cyberinfrastructure model. If these smaller institutions are in the same state with institutions who have more computing resources, they may not feel comfortable collaborating with bigger institutions. A technologist in a national lab in Illinois shares:

> And a lot of these guys are very content on keeping their campuses off the Grid, uninteracting with others, not pooling resources. I think that's the really important thing– I may pick on a university that doesn't deserve it – University of Louisiana Monroe can go out and buy a P575 frame from IBM, drop a half million dollars on that, drop another quarter million dollars on housing it, and then drop $75K on an administrator to run it. And the $200K and $75K are recurring costs. It would have been a lot more efficient for them to hand LSU [Louisiana State University] a check for half a million to a million dollars and [say] – We'd prefer you guys to run this, and pool resources. Instead,… [they] wind up insecure, never really making use of all the resources out there, not taking advantage of experts. (18 November 2008)

This quote demonstrates that small institutions can resist cyberinfrastructure adoption rationalizing like an individual human. Universities can be assumed to have feelings, emotions, and even pride and egos in the context of CI adoption. They can decide to remain local and not move to the cyberinfrastructure model at this point.

On the other hand, big and resourceful universities favor a local computing model on their own campus instead of a distributed, aggregated computing model offered through CI. This tendency stems from the historical tradition and desired reputation of certain universities. As a disruptive and revolutionary innovation, cyberinfrastructure imposes a threat to some universities, requiring them to give up the historical tradition of having their own (super)computing centers on campus. A policy analyst based in DC shares, “[Universities] need to have a stake in the ground [so] that they can say they’ve got their own center…There’s a lot of history with the universities and the universities don’t change easily. It’s like an ocean liner” (8 February 2008). The analogy of an ocean liner is powerful. It suggests that CI adoption may be difficult with big universities with a steady forward momentum. Cyberinfrastructure adoption is not simply an individual decision at the level of the scientists, but rather it is a decision for their institutions as well. This observation is parallel to Rogers’ (2003) point about multiple levels of adoption. Changes do not come easily with big universities that are permeated in existing history and tradition. Cyberinfrastructure vision includes not only collaboration of distributed scientists, but of a range of universities, big and small, and their scientific communities, state governments, etc.

The third challenge in terms of organizational arrangement is that people and institutions have entrenched interests in existing technological infrastructure. This observation is similar to the notion of ‘path dependence’ in innovation/technology diffusion and evolution. When cyberinfrastructure presents new workflows and new ways to relate to computing resources, people who are heavily invested in existing arrangements naturally resist. A technologist and professor of computer science in Texas shares, “There’re too many entrenched interests in the current technology. It’s going to take a long time… People have investments in technology that’s obsolete. They’re very powerful. They have great influence with legislatures and regulatory agencies… to protect their positions" (27 March 2008). When cyberinfrastructure appears as a threat to their existing investments, people naturally respond by doing whatever they can do to resist and/or delay its adoption.

Laboratory workflows, university traditions, and entrenched interests make up the organizational arrangements that represent the second area of cyberinfrastructure incompatibility with existing technological resources. Combined with the incompatibility in material systems (local personal computing, lagging software environment, and expensive data storage), cyberinfrastructure adoption and implementation is challenged because of a mismatch with existing technological resources and setups. The analysis continues with cyberinfrastructure's incompatibility with the social environment.

Social Rules

The second category of the macro challenges to cyberinfrastructure adoption and implementation is the set of 'rules' that are already in place. This observation can be understood as a compatibility as well as structuring issue. These rules are reflected in the professional motivations of research teams on which scientists rely and the publication cultures of traditional academia. Cyberinfrastructure adoption and implementation is perceived to be incompatible with these rules. Lee and Bietz (2009) state in a position paper, "Community norms, while functioning to advance science, also serve to enact barriers to the adoption of potentially useful collaborative technologies" (p. 3). In this dissertation, the notion of norms is examined at both the levels of research teams and of scientific community. The analysis begins with the professional motivations of members of the research team.

Professional Motivations of Research Teams. Research teams make up the first layer of the social environment in which scientists work. Most, if not all, scientists depend on a research team of graduate students and post-docs to carry out the front line of work in their research programs. In fact, it is almost impossible for a scientist to carry out a serious research program single-handedly. A technologist and a professor of computer science in Louisiana shares, “In academia, most of the real work is done by post-docs and students” (27 February 2008). A social scientist in California concurs and shares this thought, “[Data are] known intimately only by the graduate students and the post-docs of these PIs. They are often so busy chasing down grants, managing multiple projects. They don’t… roll up their sleeves and get dirty with the data” (5 March 2008). PIs are principal investigators of CI projects. They are often faculty scientists who fund and supervise graduate students and post-docs in their labs. These excerpts add to the argument that graduate students and post-docs play a key role in cyberinfrastructure adoption, development, and implementation. However, research teams also present a major challenge because of the short-term commitments and misaligned motivations of graduate students and post-docs who make up these research teams.

The first challenge of incompatible professional motivation stems from the graduate students’ needs to be trained as scientists, not technologists. As previously established, graduate students play a critical role in CI adoption. However, the reliance on graduate students for cyberinfrastructure adoption and implementation is problematic in two ways. First, their support and involvement are short-term. A technologist and a professor of computer science in Louisiana shares, “Students, by the time they get to do any research, will only have a couple of years [left] working on a project” (27 February 2008). This short-term involvement can lead to a lack of long-term continuity for cyberinfrastructure development. Second, their work in software development does not directly help them with their future careers in science. Similar to an early argument that NSF often does not fund cyberinfrastructure tool development directly because it is not ‘science’, and prototyping CI tools is not considered discovery research and does not count towards a scientist’s tenure promotion case, development activities do not make graduate students look like ‘scientists’ to their academic colleagues. This can negatively affect their competitiveness for jobs in the sciences and traditional academia.

Performing technological development for science does not contribute directly to the scientific career of, and therefore professional motivation of, graduate students in the sciences. A chemical engineering professor in Massachusetts shares, “[We are] hoping that somehow they’ll [the graduate students will] get credit for it [writing software for CI projects] in their careers. I don’t know if that’s going to work out. That’s an unfortunate aspect” (7 February 2008). It appears that faculty scientists are aware of the mismatch between the activities that graduate students engage in (i.e., software development) and their future career prospect (i.e., a research faculty position in traditional academia). However, there are not many options to make cyberinfrastructure work if they do not depend on their graduate students for software development. This particular mismatch does not fully motivate graduate students in the process of cyberinfrastructure adoption and implementation.

The second group experiences similar incompatibility are post-docs on research teams. Similar to the situation of graduate students, post-docs also represent short-term contribution and a mismatch of professional motivations. A technologist and a professor of computer science in Louisiana shares:

> Post-docs are typically one year, extended to two years. Those guys want to go out and get a faculty position. They need to publish papers. You just have to look at what’s going to motivate them… The physics post-docs… they need to get science results. If the post-doc in astrophysics [is] to get a faculty position, right now, there [are] very few departments that are going to care too much about whether they have a computational science publication in some strange HPDC [High Performance Distributed Computing] conference or something like that. They’re going to be looking for somebody who can publish in [a journal’s abbreviation] about physics. Nope. So working for the moment to … develop

> cyberinfrastructure is a distraction for physics… [So] on a post-doc level, there's not much motivation for helping to develop cyberinfrastructure… to make it successful. (27 February 2008)

The excerpt demonstrates a parallel story between science graduate students and science post-docs.

In fact, the story above is applicable to post-docs and faculty in computational science as well. This technologist and professor of computer science continues talking about the scenario for computer science post-docs, "You can't publish helping somebody in science do something. It's not enough to say – I knew how to put these pieces together for this science problem… [They] need to be able to get papers from it [cyberinfrastructure development]" (27 February 2008). When faculty in the sciences need help with CI development, it is natural to turn to their computer science colleagues (post-docs and/or faculty). But there is also a mismatch with research oriented (as opposed to service-oriented) computer scientists. A CI project manager at Indiana explains, "Computer scientists are trying to do computer science research. So the computer scientists often face a difficult balancing act between building something that's useful to the domain scientists and building something that they can write a paper about" (25 January 2008). This is an important point because there is a need to distinguish between the computational technologists (as discussed in the process of co-production, who are service-oriented and who often work for supercomputer centers) and computer scientists (who are research oriented and who often are faculty, post-docs, and graduate students at universities) involved in CI projects.

There is a bias towards doing science and discovery research, and the publication expectations hold true for post-docs in computational science as well as for those in physical and life sciences. Even when they are involved in the development of cyberinfrastructure tools, computer science post-docs need to think of ways to get research papers out of technological development. They need to publish in computer/computational science journals if they are to get a full-time faculty position. Tool development is not aligned with the professional motivation of these post-docs. This mismatch of motivation presents a challenge to CI adoption in the areas of existing social norms and setups.

The analysis of this data accumulates to show an important theme: in traditional academia, doing discovery science and publishing peer-reviewed articles are key to the careers of graduate students, post-docs, and faculty in science. Funding science, not technology, is high on the priority and mission of funding agencies, such as NSF. The reward system in the scientific community is set up to reward doing science, but cyberinfrastructure requires developing technologies before breakthrough science can be done. There is an overall science-technology gap in cyberinfrastructure adoption. This theme continues in the next section that discusses ‘rules’ of the second layer of social environment.

Publication Cultures of Traditional Academia. The second layer of the social environment in which scientists work is the scientific community. “Community norms revolve around authorship, and allowing one scientist to edit another’s [data] sequence may not be acceptable” (Lee & Bietz, 2009, p. 3). The scientific community is sustained by norms in lead/single-authorship and citation index. Below I focus on the rules of these two specific areas.

In many scientific fields, the cultural rules still favor lead/single-author research. This creates a challenge to CI adoption as a collaborative model of science. While the nature of cyberinfrastructure advocates for the value of sharing data and information, existing rules reward those who get personal recognition from the data and information they produce. A technologist in California explains, “The reward systems for doing a collaborative project are very much in their early stages… So there's a lot of feedback in the system that doesn't encourage, or even discourages, the collaborative work that cyberinfrastructure encourages" (18 February 2009). A professor of water resources engineering in Illinois concurs, "We have a culture that's been very much single investigator… The concept of a virtual organization [via cyberinfrastructure] and the benefits we would get from being more of a community – it's not immediately obvious to people" (22 April 2008). Cyberinfrastructure adoption brings with it a new form of collaborative community. But the essence of this new form of collaborative community is incompatible with existing rules that reward lead/single-authorship. In the same interview, she acknowledges that scientists participate in community activities, such as attending conferences and communicating with colleagues, fostering a sense of community. But they foster a community that also values lead/single-authorship in publications. A technologist at a national lab in Illinois shares, "In communities where the primary mode of communication might still be the single author book – it's a big stick to move toward more collaborative research based on cyberinfrastructure" (13 February 2008).

The second rule in traditional academia is to generate easily citable publications to receive a high citation index score. In order to accomplish this, research findings need to be presented in a traditionally understandable and manageable fashion. Cyberinfrastructure tends to promote unconventional results that may be incompatible with current publication standards. When the findings are too big, too novel, too unreplicable, and requiring code verification, due to the large-scale nature of CI-enabled research, some journals are not willing to publish them. A chemical engineering professor in Massachusetts shares, "If you submit the paper saying I fixed the database for 5,400 molecules, there's a limited number of journals that would publish it… It's so unusual to do something like that… Who's going to cite that he did this" (7 February 2008). There are standards in publications, and the cyberinfrastructure model may not fit the standards very well. If a scientist obtains impressive, revolutionary findings through the use of CI, they must still be publishable and citable in order to receive credit in traditional academia. Obtaining unusual results from CI-enabled research can raise the issue about whether people will get credit appropriately for the science they did when they break away from the traditional model. Otherwise, cyberinfrastructure adoption does not advance a scientist's career and reputation.

The phrase 'publish or perish' is powerful in traditional academia. Every scientific activity is driven by the goal to publish, including cyberinfrastructure adoption. In the analysis thus far, cyberinfrastructure adoption is incompatible with two specific rules of the publication culture of many fields. Cyberinfrastructure does not easily yield lead/single-authored publications with standard findings that can be easily cited by others.

The third characteristic of cyberinfrastructure, being disruptive and revolutionary, presents a range of incompatibilities with the existing sociotechnical environment and setups in which scientists work. Within the realm of technical environments, cyberinfrastructure encounters incompatibilities and challenges with existing material systems and organizational arrangements. The material systems are made up of local personal computers, lagging software environment, and expensive data storage. The incompatible organizational arrangements include laboratory workflows, university traditions, and entrenched interests in existing infrastructures.

In the social environment, cyberinfrastructure is incompatible with the social rules expressed in terms of the professional motivations of research teams and the publication cultures of traditional academia. The graduate students and post-docs are professionally motivated to do discovery science, not tool development. Cyberinfrastructure programming does not directly advance their careers as researchers. At the level of faculty scientists, cyberinfrastructure is incompatible for producing lead/single-authored publications and standard research findings that can be easily cited by other researchers. The technological resources and social rules in the environment create layers of challenges for cyberinfrastructure adoption.

COMMUNITY/NETWORK NATURE

The fourth and last challenge to cyberinfrastructure adoption is a lack of full control due to its community/network nature. Because cyberinfrastructure is a community innovation, no single user can own the entire innovation. From a classic external economics perspective, the utility of an innovation can increase as more people join the system (Rohlfs, 1974). Katz and Shapiro (1986) call this phenomenon network externalities. However, cyberinfrastructure is also a network innovation, where a user does impacts the entire community of users. Therefore, the community/network nature of cyberinfrastructure creates interesting tensions between seasoned versus new users and between power versus small users.

Seasoned Users vs. New Users

The first challenge that stems from the community/network nature of cyberinfrastructure is that users have to be involved in policing the community infrastructure. In other words, users take the notion of ‘governance’ in their own hands, and this relates to the large topic of both offline and online community norms, and perhaps netiquette. A technologist in Illinois shares:

> Every couple of weeks, someone will notice that a new user has gotten on the system and is doing something inappropriate… The users actually notice that themselves. They’ll do a little bit of their own self-policing along those lines. It’s kind of funny. Some of the more seasoned people who’ve been computing with us

> for many years, pick up on things faster than we do occasionally… They'll let us know. They'll see someone doing something that is putting the system in jeopardy or causing a lot of slow down for compile times, or hurting our network performance, and they'll cut and paste the evidence of what they see and send it right to us and say – Would you talk to this user and train them on what they should do? (3 February 2008)

This excerpt makes three important points. First, new users can do things to a part of a cyberinfrastructure community that slows down the performance that would impact the rest of the community. Second, experienced adopters have to take up the responsibility to police the community/network innovation because what someone else does unintentionally can impact their work. Third, seasoned users report problems to technologists and administrators who maintain the community innovation. These points collectively demonstrate a user's need to assert some control over cyberinfrastructure, although he/she knows he/she is sharing a community innovation with many. This observation suggest that the community/network nature leads to more tasks that are not rewarded – or even notice – at the academic level in the traditional reward system.

Power users vs. Small Users

The second challenge from cyberinfrastructure being a community/network innovation is that it requires a constant balance between the needs of power users and those of small users. A center administrator in Ohio shares:

> At the other end of the spectrum, I think the very big users, who have used our machines to scale their problems up to a certain size, can sometimes be frustrated because it is a constant challenge to us to make an adjustment between really big jobs – big science – and lots of little jobs. Trying to find that balance is challenging. (28 January 2008)

This quote makes the important point that power users get frustrated while using cyberinfrastructure because of the many small users. Kraut et al. (1998) argue that social norms have consequence that affect the access to and value of shared resources. Although these users have small computational jobs individually, the small jobs add up and take up computational resources that power users need for one large job.

The community/network nature of cyberinfrastructure created unique tensions between the seasoned users and new users, and between power users and small users. While adoption by more users in general is considered good progress towards wider diffusion, it also brings about challenges for existing users.

SUMMARY OF CHALLENGING CONDITIONS

This chapter explores Research Question 1, which asks, "How does cyberinfrastructure's nature influence its adoption process in the early 21st century U.S.?" The analysis of the interview data led to four areas of challenging conditions for cyberinfrastructure adoption: a lack of trialability/observability (due to the participatory/bespoke nature), a lack of simplicity (due to the meta/complex characteristic), a lack of perceived compatibility (due to the disruptive/revolutionary quality), and a lack of full control (due to the community/network property). The first two challenges reflect the conflicted experiences between scientists' motivation for research productivity and career advancement on one hand, and the time, intellectual, and financial investments needed for successful adoption on the other. The last two challenges reveal the constraints on one's cyberinfrastructure adoption and implementation due to the social, technological, and networked environments in which scientists work.

Star (1999) presents a historical anecdote of the personal computer that is perhaps insightful for and analogous to this study of cyberinfrastructure:

> The example of computers given to inner-city schools and the developing world is an infamous one. The computers may work fine, but the electricity is dirty or lacking. Old floppy disks do not fit new drives, and new disks are expensive. Local phone calls are not always free. New browsers are faster, but more memory

> hungry. And one of those now popular will not support the most popular Web browser for blind people in text-only format. (p. 389)

Although scientific communities are not 'inner-city schools' and the 'developing world' *per se*, Star's quote shows how a technology in its purest sense come into contact with a complex web of social setups and technological environments already in place. She appropriately concludes, "In information infrastructure, every conceivable form of variation in practice, culture, and norm is inscribed at the deepest levels of design" (p. 389). In the case of cyberinfrastructure, these various forms of variation impact its adoption process. If the adoption process is to be accelerated, the design needs to be sensitive to these various forms of practice, culture, and norm beyond simply the technical specifications.

Despite these challenging conditions, as they relate to the four pairs of CI characteristics, during the innovation development process, cyberinfrastructure has been adopted by scientists. The next chapter will explore the driving rationalities that drive cyberinfrastructure adoption in the early 21st century U.S.

CHAPTER FIVE: DRIVING RATIONALITIES FOR CYBERINFRASTRUCTURE ADOPTION

The adoption of cyberinfrastructure is a complex phenomenon involving a range of driving rationalities. It is a complex phenomenon because cyberinfrastructure itself is a complex innovation. By using Rogers' (2003) definition of an innovation (as described in the opening paragraph of this dissertation), cyberinfrastructure can be conceptualized as having three distinct dimensions: it is an object (i.e., a meta-platform of interrelated technologies and processes around a network of supercomputers), it is a practice (i.e., a scientist's transition from simply working with local personal computers in a laboratory with his/her own data to connecting to supercomputers, aggregated datasets, remote instruments, distributed colleagues, etc), and it is an idea (i.e., a shift in discovery science from theoretical and/or experimental methods to simulation, visualization, and modeling techniques on large-scale and multi-scale datasets in digital forms). The three dimensions co-influence each other, and an understanding of CI's adoption process requires triangulating insights from multiple stakeholder groups (i.e., scientists, technologists, administrators, funders, social scientists/policy analysts, and industry experts).

This chapter mainly focuses on answering Research Question 2, "What are the rationalities that drive cyberinfrastructure adoption in early 21st century U.S.?" As stated in the Introduction and in Chapter 3, the notion of adoption is conceptualized as intertwining with development, implementation, use, and diffusion. I draw upon Fulk and colleagues' (1990) argument that rationality represents "sense-making… created *after* the occurrence of the behavior. In this case, it is to interpret the behavior retrospectively rather than to direct the choice prospectively" (p. 123, emphasis original). Furthermore, this project examines adoption as it takes place during the *innovation development process*. In the case of cyberinfrastructure, the innovation development process could be defined as when stakeholders ranging from (individual and collaborative) scientists, technologists, and administrators through governmental agencies and scientific community attempt to “identify needs and/or problems, conduct research on the ways to solve these problems, develop the innovation, and promote it” (Rice, 2009, p. 491). It also involves the agenda-setting, matching, and redefining stages of the organizational adoption process.

Through grounded theory and thematic analysis, three categories of rationalities (in this case, perceptions of needs and attributes, as well as social mechanisms) emerged to explain scientists’ adoption: perceived needs, relative advantages, and shared visions. A close examination shows that these three categories of rationalities also match the three dimensions of cyberinfrastructure discussed. First, the adoption of cyberinfrastructure as a meta-platform of interrelated technologies is driven by the perceived need for computational power, massive storage, multi-scale integration, and distributed collaboration. Second, the adoption of cyberinfrastructure as an organizational/behavioral practice is driven by its relative advantages to produce quantitative and/or qualitative benefits that increase the possibility of major publications and scientific reputations. Third, the adoption of cyberinfrastructure as a new approach to science is driven and maintained by shared visions held by scientists, technologists, professional networks, and scientific communities.

In this chapter, I refer to the first generation of adopters as ‘pioneering adopters’ in the emerging context of cyberinfrastructure. They are pioneers because not only do they adopt the cyberinfrastructure, they co-produce CI tools and co-define CI prototypes in the early 21st century. In other words, they exhibit qualities of ‘innovators’

(Rogers, 2003), ‘lead users’ (von Hippel, 2005), and ‘trend-setters’ (Dell’Era & Verganti, 2010). This distinction needs to be made because the loose language of “early adopters” would be inappropriate as Rogers (2003) defines them: the second group that comes after the ‘innovators’. In places where interview participants loosely use ‘early adopters’ to refer to the first generation of adopters, slight adaptation to ensure language consistency is done to stay aligned with Rogers’ Diffusion of Innovations (DOI) paradigm and the language chosen for this dissertation.

These three facets of cyberinfrastructure are conceptually distinct but practically intertwined in the complex process of cyberinfrastructure adoption. Therefore, the three categories of rationalities (i.e., perceived needs, relative advantages, and shared visions) are also interwoven in an intricate fashion into this analysis. While the analysis presents them as distinct themes and subthemes, their influence is difficult to cleanly tease apart because they interact and simultaneously influence the adoption process. In other words, one dimension/rationality does not make sense in context without the other. For example, the shared visions do not stand alone without perceived needs; relative advantages cannot fully influence adoption without shared visions. Table 2 below briefly summarizes the key themes/subthemes of rationalities behind cyberinfrastructure adoption in the early 21st century U.S. The rest of the chapter unpacks these (sub)themes with representative interview excerpts.

Table 2. Key Driving Rationalities for Cyberinfrastructure Adoption

A. Perceived Needs: Looking Out of Desperation
   1. First-Order Needs: Because There is No Other Way
      a. Computational Power
      b. Massive Storage
   2. Second-Order Needs: Because It is Possible
      a. Multi-Scale Integration
      b. Distributed Collaboration

Table 2 (continued)

B. Relative Advantage: Overcoming Inertia
  1. Quantitative Advantages: Do More in Less Time
    a. Faster Speed
    b. Greater Efficiency
    c. Increase Productivity
  2. Qualitative Advantages: Solving Complex Problems
    a. Bigger Questions
    b. Broader Questions
    c. More Interdisciplinary Questions

C. Shared Visions: Getting in and Staying in for a Meaningful Future
  1. Breakthrough Discovery
    a. A Vision of Engaging in Breakthrough Discovery for Scientists
    b. A Vision of Enabling Breakthrough Discoveries by Technologists
  2. Diffusion Mechanisms
    a. Professional Networks as Social Mechanisms for Diffusion
    b. Community Consensus to Adopt Cyberinfrastructure

PERCEIVED NEEDS: LOOKING OUT OF DESPERATION

A scientist's first rationality behind cyberinfrastructure adoption is the perceived need for their science. Cyberinfrastructure is a meta-platform based on a range of emerging technologies with visualization techniques unfamiliar to most scientists. The desperate conditions usually are more frustrating than the consequences that come with the adoption decision; these desperate conditions include a high-learning curve, low usability, an unstable system, the necessity of sharing resources with a community of unknown users, etc. (these were discussed in Chapter 4). In other words, these scientists believe that there is no other way to conduct their large-scale science without cyberinfrastructure. Those who are optimizing currently available CI resources are scientists working on grand challenges in the sciences that require computational power and large-scale data commercial desktops and personal computers cannot support. These are scientists at the forefront of their fields, tackling problems that require intensive data and supercomputing resources.

These pioneering scientists adopt out of desperation. The background feeling of desperation is critical. A technologist and a professor of computer science in Illinois pointed out that a sense of perceived need can be seen when cyberinfrastructure (both the technological/computing part and the social/collaborative part) is the only way to do science in fields such as high energy physics, “The only way they [scientists] can make progress is by constructing these very large apparatus. The only way they can build them is by building distributed teams” (13 February 2008). A technologist at a research institute in California concurs, “So one group of people who adopt cyberinfrastructure are those people that cannot do their work any other way” **(**18 February 2009**).** When it is the only way, and scientists cannot do their work any other way, cyberinfrastructure adoption is the only option. The notion of “the only way” then becomes the essence of perceived need for pioneering adopters.

Traditionally, or rationally, scientists analyze their scientific data and conduct research in their own labs (spaces over which they have full control), and not in a shared community system with other unknown users. However, the need of pioneering adopters for computing resources exceeds what their personal research labs or the university departments can develop and maintain individually. Therefore, they turn to a nationwide infrastructure funded by federal agencies such as the National Science Foundation. A center administrator in Pennsylvania who has worked with pioneering adopters for over 20 years shares, “[That’s] the only reason that rational people would be interested in a shared HPC system… Why wouldn’t you… do things in the space that you… can control? It’s not rational to… put up with not controlling your own research” (21 April

2008). In other words, the irrational decision to share research resources only makes sense when the perceived need is intense and compelling.

Pioneering adopters also often make a conscious choice to pursue research that requires intensive computing/computational resources that only cyberinfrastructure can provide. Therefore, their chosen research questions lead them to cyberinfrastructure adoption. Furthermore, they usually see themselves as experts in computational science in addition to their home domain disciplines. In other words, pioneering adopters tend to possess a second professional identity as technologists. A professor of physiology at a university in Illinois admits, “I am [also] a computational scientist... It’s what I found my attention and my efforts turning to. It really … was a decision,… it was a decision based on choosing problems to work on that were computational” (4 February 2009). In his language, he calls himself a computational scientist (or computational technologist, the label chosen in this research project to emphasize the role in developing computational tools for science). Although there are full-time technologists who build CI tools, a center administrator in California shares, “You have some very high-end resources and you’re always going to have scientists who have to know how to program… the physics that they want to model in a parallel way” (4 December 2007).

Traditionally a few scientific fields, such as atmospheric physics, particle physics, material science, cosmology, fluid dynamics, etc., make up the majority of the stable group of pioneering cyberinfrastructure adopters. This group is driven by their need for cyberinfrastructure resources and how it enables their large-scale science. Their perceived needs can be categorized into four themes under two levels discussed below.

First-Order Needs

First-order needs are characterized by the statement, “I need cyberinfrastructure because there is no other way.” At this level, first-order needs include the need for computational power and massive storage.

Computational Power. The first type of perceived need cyberinfrastructure meets is that of computational power. For scientists working on large-scale data, it is very difficult or almost impossible to efficiently process, compute, and visually represent data without cyberinfrastructure resources (especially high-performance computing resources). Their need for computational power is related to modeling techniques, such as simulations of macro environmental phenomena and visualizations of micro chemical substances. Although it is not the only use for high computational power, computer modeling on large-scale data makes cyberinfrastructure a perceived need for scientists who depend on this analysis technique.

Commercially available personal computers in their traditional laboratories and departmental offices simply cannot efficiently handle the demand for or the scale of proper analyses. A social scientist in Michigan states, “The leading factor remains the search for computational capacity,… the need to compute ever larger and more complex simulations or models… There are these problems that people need to compute that are beyond the capacity of normal computing environments” (4 February 2008). When the normal computing resources based on commercially available personal computers are insufficient, scientists have to look elsewhere.

Theoretically, if data can be reduced to a much smaller size, computer modeling can be handled by personal computers such as desktops in offices and laptops in laboratories. However, if scientists continue to depend on commercially available personal computers, they have to either scale down their science or take longer to process images. Another social scientist from Michigan concurs with the previous observation adding, “Those who use cyberinfrastructure tend to be… people who do modeling – say environmental or weather… or… complex chemical [models]… [They] rely on it for the computational power… for visualization…. Their desktop computers couldn’t make images without taking forever” (17 March 2008). This would make research time-consuming and inefficient.

The need for computational power is the leading driving rationality for cyberinfrastructure adoption. The observation by the two social scientists from Michigan is further supported by a center administrator in Indiana. He uses TeraGrid as an exemplar for talking about cyberinfrastructure adoption since TeraGrid is the largest cyberinfrastructure project, linking 11 supercomputing resource providers across the country at the time of data collection. He shares, “The largest category of people who use the TeraGrid are people who simply need the largest supercomputers they can get – period…. [They] will go to almost any lengths in order to use the fastest computer they can get to” (16 January 2008). As articulated in this excerpt, the scientists who need computational power are the largest group of adopters of cyberinfrastructure resources. For them, the perceived need for computational power is so high that they would work very hard to overcome any barrier just to get on the next fastest supercomputer. This is motivated by desperation and the perceived need for computational power.

Computational power is a defining element of cyberinfrastructure that makes cyberinfrastructure necessary for complex science. It is what enables scientists with large-scale data to tackle sophisticated problems and grand challenges in science that impact the world. Without it, cutting-edge science can be compromised. A center administrator in Ohio shares, “[If] you want to solve… the most interesting problems today, [which] are complex problems, then that requires that you use what I would call computational science. Computational science relies on the cyberinfrastructure in order to achieve its fullest potential" (28 January 2008). This excerpt cycles back to the argument that cyberinfrastructure and its computational power make up the critical perceived needs that drive the adoption process. Computational power optimizes what is possible with research endeavors at the forefront of science, yet it cannot enable large-scale science without massive storage for data.

Massive Storage. Given that cyberinfrastructure and supercomputers process large-scale data, it follows that cyberinfrastructure also can serve as a repository for massive amounts of data. For some scientists, large-scale data need to be handled in real time as they are captured digitally. Therefore, their computing system needs to be able to move large-scale data from one storage location to another. Neither of these procedures can be easily accomplished on commercially available desktop and personal computers. A social scientist in Michigan shares the following observation about scientists' need for cyberinfrastructure for massive data storage as they use large-scale remote instruments: "They're dependent on data collection from some… equipment that pulls the data in – like a giant telescope… It's coming in too fast or too voluminously for them to… shift data around,…and store… [in a] home or their office computer" (17 March 2008). In these projects, cyberinfrastructure is first used to capture and store data before it is used computationally to analyze the data.

When data handling and storage is long-term, cyberinfrastructure enables cumulative data reuse, which is meaningful to scientific research. However, cumulative data reuse is not common or easily accomplished without cyberinfrastructure resources. An oceanographer and technologist at a research institute in California shares an important example of the Hubble Space Telescope, "Hubble gets cited as this great case of reuse of science results because for any of their observations, on average it gets used three, four, to five times beyond the initial project that it was used for" **(**18 February 2009**)**. In this case, data captured by the Hubble Space Telescope can be reused multiple times beyond the original project because of cyberinfrastructure's massive storage. Therefore, cyberinfrastructure is imperative for science that capitalizes on data reuse for the long-term.

Furthermore, cyberinfrastructure's massive storage allows researchers to aggregate data from multiple sites into a common framework. Because cyberinfrastructure allows the aggregation and reuse of data beyond its initial purpose, robust and sophisticated science is being produced. For scientists who depends on using multiple datasets for research, massive storage becomes a perceived need that drives cyberinfrastructure adoption. The same oceanographer and technologist in California continues with the following detailed example of the National Virtual Observatory:

> The National Virtual Observatory is the first working case,… [the] first known science case, where observations from multiple institutions have been overlaid into a common framework. [By] using interoperable standards and technologies,… greater synergistic science has been produced as a result of that. It's the first great cyberinfrastructure project as far as I'm aware in the sciences… I was involved in some of the earliest conversations of the National Virtual Observatory. It took them five, eight years and several iterations to go from – Here's this idea, let's just do this – to actually have something that was producing useful data. **(**18 February 2009**)**

As illuminated in this quote, with interoperable standards and technologies, data from traditionally separate projects can be integrated to produce synergistic and robust science otherwise not possible. However, the development and implementation of cyberinfrastructure projects also takes time and many cycles of re-development.

Cyberinfrastructure is able to handle and move large-scale data more efficiently as they are being digitally captured. More importantly, when cyberinfrastructure represents a coherent platform that brings together data from multiple institutions that allows scientists to conduct synergistic science based on large-scale, diverse, and long-term data, it presents a perceived need that commercially available personal computers cannot meet.

The computational power and massive storage of cyberinfrastructure make up the first-order needs that drive cyberinfrastructure adoption. Once these needs have been met, second-order needs emerge because there are new possibilities for research given more computational power and bigger storage.

Second-Order Needs

Cyberinfrastructure's computational power and massive data storage capacity form the foundation of second-order needs for multi-scale integration and distributed collaboration. These two needs are considered second-order needs because they become perceived as needs only after first-order computational power and massive storage have been acquired. When the first-order needs have been fulfilled, scientists see that it is also possible to perform multi-scale integration and distributed collaboration. Once the second-order needs have been met and have had a positive impact on science, then scientists regard the second-order needs as absolutely necessary for their science. Because now scientists can process and model large-scale data stored for the long-term, there is an emerging need to work on complex problems that depend on multi-scale data integration and multi-site expert collaboration.

Multi-Scale Integrations. The notion of multi-scale refers to different physical scales and a range of temporal scales. These scales characterize data either when scientists work independently or jointly as they collect data across space and time. Sometimes they gather data on different aspects of a common complex phenomenon; sometimes they collect data from a common site that represents different variables of a complex research problem. With cyberinfrastructure, scientists can combine these data sets and conduct integrative research never before possible. To illustrate integration of data across multiple physical scales, a social scientist in Michigan shares, “In biology,… maybe [you] want to understand phenomena at molecular, cellular, organism level all the way up to the ecological level, all of which have different physical scales… you want to integrate across those different kinds of scales” (4 February 2008). He cites a specific case, the Biomedical Informatics Research Network (BIRN) project run out of the University of California at San Diego, and he describes the project as an attempt to “integrate neuro-anatomical data collected in mice and humans to understand diseases like Parkinson’s and Alzheimer’s and so forth” (4 February 2008) to further illustrate how cyberinfrastructure can integrate across multiple physical scales.

The other layer of multi-scale integration is to bring together datasets across different temporal scales. At the macro level, multi-temporal scales can transpire on a scale of centuries or millennia. At the micro level, the temporal scales can span one day. A graduate student in environmental engineering at a university in Texas shares an example that represents the collaboration of four institutions (University of Illinois at Urbana-Champaign, Texas A&M at Corpus Christi, Texas A&M at College Station, and his unnamed university in Texas) with multi-temporal scale data on a common problem of hypoxia in Corpus Christi Bay. Hypoxia is defined as the depletion of oxygen when it falls under 30% saturation. Hypoxia can kill fish and cause problems to organisms that reside at the bottom of the bay. He shares some rich descriptions articulated in the excerpt below:

> We’re at a point where we’ve got most of our sources’ data available through web services. So the next step is how do we synthesize this data. Because all this information is collected in different ways, people use different instruments,… different uncertainties, and also they collect over different intervals. So, it could be someone goes down and collects oxygen one month a year. Some people do it continuously. Dissolved oxygen changes every day, as this daily cycle, because when there’s light, there’s photosynthesis, so oxygen is produced. And then when

> there’s no light, respiration dominates. So oxygen comes down. So being able to synthesize all that data to actually see that pattern, to find out what’s actually – where hypoxia’s happening and when does it happen, is going to be a major challenge… Because different people are doing the work, at this stage different people are collecting the data…. We work with… [and put data] into this database structure... They [the collaborators] want to know, for instance, if I put more data [from the collaborators with different temporal scales] into this soup of data, how does it affect my predictions? So you could have this visualization sitting in the middle of this cyber-collaboratory and we’ll start feeding data in and it’s still going to change in this bay. (6 November 2007)

The cyber-collaboratory mentioned in this excerpt can be regarded as another term for cyberinfrastructure, except it has an emphasis on the distributed collaboration in addition to the technologies. For this graduate student scientist to synergistically work with diverse data sets, cyberinfrastructure provides an integrative platform for him and his collaborators to perform visualization on diverse data collected at different temporal scales. Although not explicitly stated, science that depends on multi-scale data integration depends on cyberinfrastructure’s computational power and massive storage. Otherwise, complex integration cannot be achieved.

The science enabled by multi-scale data integration represents complex problems with great scientific merit and critical societal implications. If scientists want to pursue such problems, the need for multi-scale integration becomes a perceived need to adopt cyberinfrastructure. Cyberinfrastructure not only integrates multi-scale data for complex science, it brings together multi-site experts for distributed collaborations.

Distributed Collaboration. As digital data are becoming more available and accessible to address complex scientific problems, a natural development is a need for multidisciplinary scientists to collaborate across time and space on big-scale projects. This approach to science is an emerging phenomenon. Complex scientific problems that depend on these data and expertise make cyberinfrastructure a perceived need. As alluded to in the examples of BIRN and hypoxia in the previous section, the desire to tackle these problems then creates the need to support distributed collaborations. A social scientist in Michigan shares, “If they’re taking on these complex,... multi-scale problems, it means the expertise they’re drawing on is not collocated… They need to have ways of richly interacting with those collaborators, and that’s driving the demand for improvements in collaboration technology” (4 February 2008). This suggests that cyberinfrastructure-supported distributed collaborations are rich interactions. They are rich because cyberinfrastructure creates a virtual environment in which the distributed team can interact and collaborate (Schroeder, 2007). In addition, the role of information and communication technologies (ICTs) is alluded to in the overall conceptualization of cyberinfrastructure. Without ICTs, distributed collaborations would be hampered, and cyberinfrastructure implementation would not be complete.

The perceived need for distributed collaboration is becoming recognized as critical for science, thus driving the adoption of cyberinfrastructure. Distributed collaboration is essential to large-scale science for three reasons. First, data, computational resources, and analyses are distributed, making distributed collaboration an inherent need. Second, for large-scale science experiments, there is too much work to be done, and this naturally leads to the need for distributed collaboration. Third, most universities do not have enough collocated expertise to take on complex scientific problems and/or a grand challenge in science. In order to investigate this level of science, distributed collaboration becomes a requirement. A technologist and a professor of computer science in Indiana observes this trend of distributed collaboration as critical to scientific research:

> Their [scientists’] work is now done with everything distributed. Data’s distributed. Analysis is distributed. The people are distributed. Now it used to be distributed, but nowhere near as much… So it is necessary to have something like cyberinfrastructure and implement efficiently such a noble effort. That is actually true both in the small scale… and it’s obvious [and] true for the big science where

> you have an accelerator at CERN [The European Organization for Nuclear Research] in Geneva which supports thousands of physicists across the world [to work] together [in] three or four major experiments… There's just too much to do… The second part of cyberinfrastructure, the distributed teams… if you go into a university, most universities do not have geographical at the same place the expertise to mount a state of the art scientific activity… I would say almost every field needs large teams these days… While I would almost say it's a necessity… I think it's an opportunity that has been taken by some people. Given they've taken it, at least some of them are quite successful. It then becomes almost a requirement. You can't really do research without such things. (14 February 2008)

Based on this excerpt, the perceived needs for distributed collaboration are driven by large-scale distributed data, work, and experts.

Cyberinfrastructure can expand beyond geographical and temporal boundaries and pool expertise and resources otherwise not possible in traditional university settings. The trend of distributed collaboration is not only relevant to collaborations between different institutions, it also can be an approach for an entire field that moves beyond national borders. The observation that distributed collaboration is becoming a requirement, and not just a trend, is also shared by an oceanographer and a technologist in California:

> In oceanography, the biggest factor in adoption of cyberinfrastructure is that oceanographic science has until recently largely been… a personalized, personally directed science. The largest collaborative scientific project might be a collaboration of a ship, or a few ships, with some number of people on board. Most experiments were done at the level of an individual PI [principle investigators] or a small team, and for those kinds of studies, you didn't really need much of any cyber-anything, let alone cyberinfrastructure. More recently, you have collaborations like the development of the International Report on Climate Change, the Climate Change Panel. And those collaborations are thousands of scientists working with all sorts of data sets, including their own, and those of other people, some of whom didn't treat their data sets as related to climate in any way. There's a feedback loop between the science and the technology, the technology permits more collaborative science, and encourages it, and this is pulling more science in that direction, which in turn is creating the need for more collaborative technologies which is essentially cyberinfrastructure… But there are still many oceanographers today who are not

> capable of extrapolating from totally analogous examples to realize that's going to be the way it is in oceanographers five to ten years from now. **(**18 February 2009**)**

This excerpt has a striking parallel with the previous statement. Both are speaking about distributed collaboration of scientists working on large-scale problems. Both excerpts also allude to the observation that distributed collaboration does not begin as a requirement. Because it was taken as an opportunity by some, and they turned out very successful, distributed collaboration rose to the level of a perceived need for large-scale science. In addition, this excerpt makes a bold prediction that cyberinfrastructure will soon be a common practice in oceanography and perhaps in other scientific fields as well.

Due to its computational power and massive data storage, cyberinfrastructure enables multi-scale data integrations and multi-site distributed collaborations that make large-scale science exciting. Collectively, these four needs, computational power, massive storage, multi-scale data integrations, and multi-site distributed collaborations, make up the first category of rationalities for CI adoption.

As discussed in Chapter 2, Rogers (2003) defines a need as "a state of dissatisfaction or frustration that occurs when an individual's desires outweigh the individual's actualities" (p. 172). Perceived need was not discussed in the literature review as a leading factor of technology adoption. In fact, Rogers argues that the sequence of need and awareness-knowledge of a new idea is inconclusive. He suggested that an adopter's sense of need could be the result of awareness-knowledge. However, Hassinger (1959) argues the opposite. Hassinger maintains that the notion of need comes before adoption.

In the case of cyberinfrastructure adoption, the rationality of perceived needs demonstrates both perspectives through the differentiation of first- and second-order needs. Hassinger's argument refers to first-order needs, and Rogers' argument points to second-order needs. This differentiation may be the explanatory factor for disciplinary differences in the diffusion process: Why do scientists in some fields adopt cyberinfrastructure faster than researchers in other fields? Simply put, those who perceived a need for cyberinfrastructure resources as first-order have long been pioneering adopters. Those who did not see a first-order need for it have not adopted. Pioneering adopters became more committed to their adoption when second-order needs developed out of first-order needs after their adoption. However, first-order need for cyberinfrastructure may be growing across scientific fields. This observation turns the discussion to this trend.

The Needs for Cyberinfrastructure is Growing

As alluded to in the last excerpt on oceanography, the landscape of science is changing. As more data and information are becoming digitally converted, captured, and made accessible, scientific fields that traditionally did not see a need for high-performance computing may be entering a new era. Although previous excerpts suggest that the group of scientists who depend on cyberinfrastructure and high-performance computing is relatively small, there are signs that the needs may be growing and spreading. Similar to the diffusion and adoption of personal/desktop computing, supercomputing/high-performance computing (as a central component of cyberinfrastructure for the purpose of this dissertation) is working its way through research in science and engineering. A center administrator at Texas states, “Leading edge researchers in science or engineering… [are] aware of the importance of high-end computing… It’s well on its way to being just as understood that the solution of the number of equations required for any large-scale problem requires computing” (2 January 2008). Although the needs may not be universal yet, the awareness of the importance of cyberinfrastructure and high-performance is there and growing. Moreover, high-performance computing (within cyberinfrastructure) is and/or will be foundational to solving a large number of mathematical equations for scientific research. Therefore, the role of high-performance computing (HPC) in research will be elevated to the level of mathematical equations in research.

The growing needs for cyberinfrastructure resources are also noted by a social scientist in Michigan. Her excerpt below echoes the themes that perceived needs are derived out of no alternatives and that adoption is often associated with frustrating outcomes adopters have to endure. She talks about the contrast between pioneering adopters and future adopters. For pioneering adopters she says, “Current user[s]… had to use [HPC] for their science. It’s like there is no other way... So they’ve got to jump through a lot of hurdles and have been willing to do that” (24 March 2008). For future adopters, she says, “you have a new community of users who don’t yet perceive [the need], but there might [be]… a point at which they can no longer use the tools that they have to look at and analyze their data… [They] just really have to look to some new things because [they] just can’t deal with this massive data that [they] have” (24 March 2008). Her excerpt suggests that a new community of users will emerge when the perceived needs have become necessary beyond the traditional group of pioneering adopters. She also implies that a potential point of frustration for future adopters is the inability to handle massive data for research.

The point of frustration has been recognized and utilized as an adoption strategy by an administrator at a university in Indiana. In his language, he calls it a ‘pain point’. He shares how he uses ‘pain point’ as a chief strategy to promote adoption of advanced cyberinfrastructure by going to the scientists and asking:

> Where do you hit walls? What boundaries do you hit right now? What IT [information technology] related aspects limit your core research capabilities? – When you begin an interaction with a discipline scientist… and ask them what

> their pain points are, and then have them say – I need more processing power. I need more storage. That becomes the starting point for a discussion that can be very, very meaningful. (16 January 2008)

This excerpt relates to the previous point about the frustrating inability to handle massive data for research. When scientists feel frustrated, the need for computational power becomes a pain point. The pain points of not having enough computer processing power or data storage are the two leading perceived needs discussed earlier as the first-order needs.

For scientists who do not experience more computational power and bigger data storage as the only way for them to do science, the persuasive rationality has to be comparatively and relatively more appealing than their current practice. This leads to the second category of rationalities: relative advantage/perceived usefulness.

RELATIVE ADVANTAGE: PERCEIVED USEFULNESS THAT OVERCOMES INERTIA

According to diffusion theory, *perceived relative advantage* refers to “the degree to which an innovation is perceived as being better than the idea it supersedes” (Rogers, 2003, p. 229). Rogers pointed out that this advantage is often conceived as financial profitability, social prestige, and other perceived gains by potential users. Similar to DOI theory, Technology Acceptance Model defines perceived usefulness as “the prospective user’s subjective probability that using a specific application system will increase his or her job performance within an organizational context” (Davis et al., 1989, p. 985). The adoption of cyberinfrastructure as a meta-object, an organizational/behavioral practice, and a new scientific approach can lead to perceived gains in two ways. First, a scientist’s financial profitability comes from his/her research grants and career advancements. Cyberinfrastructure can help construct more persuasive arguments for discovery potentials/intellectual merits in grant proposals to obtain external funding. Cyberinfrastructure can also yield scientific discoveries and peer-reviewed publications that would help with a scientist’s tenure and promotion case. Second, these results increase a scientist’s social prestige and scientific reputation. Receiving external funding, enabling breakthrough discoveries, publishing important science, and being promoted in one’s academic rank are all advantages that increase a scientist’s social prestige in his/her career.

One of the most critical barriers to behavioral innovation adoption is inertia – people tend to keep doing what they were doing before. Behavioral inertia is a powerful factor against adoption when cyberinfrastructure requires time to learn new skills, knowledge to make it work, and funding to develop tools--resources that are scarce in science. A center administrator in Pennsylvania speaks about this at the macro level, “[The] problem is, of course,… inertia. It is that people traditionally just do what they’ve always done and what they understand” (21 April 2008). A social scientist in Michigan states, “I think it really starts with them feeling like this is going to help advance their, the work that they are doing” (24 March 2008). A computer science professor at a university in Illinois who is also a technologist at a national lab states, “People adopt technology on the basis – a mix of self-interest and inertia. I think at first, people need to see some clear advantage – enough advantage to overcome the inherent inertia” (13 February 2008).

The argument advanced is that cyberinfrastructure has to be perceived as beneficial to scientists’ work or better than their current practice in order to appeal to their self-interest, given the costs. In order to appeal to their self-interest and to overcome the inertia, understanding scientists’ core research functions is key. A professor of water resources engineering in Illinois shares her experience talking to potential adopters in the following excerpt, “You talk to them about – We could create a tool that would… work with your data and to get data from all different locations and integrate it and plug it into models… and visualize the results… and publish them" (22 April 2008). She concludes by stating, "They're going to get really excited because that's going to help their core research function" (22 April 2008). Relative advances for core research functions include integrating distributed data, analyzing data via visualization and modeling techniques, publishing the results to share with a community of colleagues. If these core functions can be done easily with cyberinfrastructure, then CI will be perceived as beneficial and advantageous for increasing one's probability of scientific discoveries, producing major publications, and elevating one's scientific reputation in the discipline.

For scientists, the relative advantages and perceived usefulness of cyberinfrastructure are logical (as an example of 'technical rationality'), as a center administrator in Illinois says, "Certainly from the scientists' perspective, it's relatively easy because we can point to examples where the researchers have been able to do their analyses, produce their research results, produce more publications faster, more effectively and [with] better quality" (31 March 2008). A pioneering computational quantum chemist at a university in Massachusetts and a former NSF program officer shares, "People are intrigued by the promise of being able to do their work better, and that's the ultimate motivation" (20 February 2008). The ultimate relative advantage is what cyberinfrastructure can do to help scientists publish. The answers include both quantitative advantages (i.e., speed, efficiency, and productivity) and qualitative advantages (i.e., tackling bigger, broader, and more interdisciplinary questions). When scientists are able to achieve these relative advantages, the natural outcomes would be breakthrough discoveries along with more and better publications that add to a scientist's reputation in the field. The following section unpacks these quantitative and qualitative advantages.

Quantitative Advantages: Do More in Less Time

The first category of relative advantages involves faster speed, greater efficiency, and increased productivity. Taken together, they allow scientists to do more work in less time. Although the three quantitative advantages are discussed separately below, these outcomes are interrelated.

Speed. Science is a competitive race. The faster scientists can do their science, the faster they can accelerate their discoveries and win the race. The assumption is that obtaining a discovery is winning the race, yet there are obstacles along the way. By employing cyberinfrastructure, scientists can gain more resources and overcome obstacles more quickly with the goal of getting to the finish line before others.

In this paragraph, I present a collection of excerpts that illustrate this rationality of speed. A center administrator in Texas shares, “Science is about discovery, and it is a competitive process. You’re pushing the envelope and you’re trying to do new things. So users come here [the supercomputer center] to enhance their scientific capability” (2 January 2008). A technologist working for a leading software company based in Washington shares, “They use it [cyberinfrastructure] in order to assist… in their [science]… [to] do things faster… to accelerate the rate of discovery” (18 March 2008). Although her university has a supercomputer center, a graduate student in civil engineering at a university in Texas talks about her remote access to a supercomputer in Illinois, and she says the motivation is the desire to increase the speed of her research. She shares, “I have been interacting with people at Illinois on this because… they’ve offered to let me use some of their computing power so that I can do more tests…[in]… my numerical model… more quickly…[by] access[ing][their computers remotely]” (27 November 2007).

All these quotes emphasize the relative speed of scientific analyses due to cyberinfrastructure adoption. Speed is related to two interrelated outcomes: efficiency and productivity. When a scientist simply increases the speed of analysis but keeps the amount of data constant, the outcome is greater efficiency. When a scientist keeps the processing time constant but increases the amount of data processed per unit time, increased productivity is obtained. When scientists carefully manipulate both processing time and data amount processed, they can obtain both efficiency and productivity, leading to the outcome of doing more in less time.

Efficiency. In terms of greater efficiency, a technologist and a professor of computer science in Indiana shares, “What cyberinfrastructure does is make discovery more efficient… So I would say cyberinfrastructure is part of the more efficient way of doing things that used to be done by other mechanisms” (14 February 2008). This suggests that cyberinfrastructure is relatively more advantageous in the sense that it helps scientists perform their work in less time, compared to traditional mechanisms, including commercial desktop and personal computers.

As previously established in Chapter 2 and reiterated earlier in this chapter, although cyberinfrastructure is largely a technological system, it also has a social dimension to it. It is technological because it involves computing; it is social because it enables collaboration. An NSF program officer who is also a professor of mechanical engineering in New York states, “Cyberinfrastructure, what it can do is two things. One, it can enable you to process information and data that you need to process for your work efficiently. Two, it can enable you to collaborate and cooperate with others efficiently. In both spheres, there are exciting developments” (28 February 2008). This excerpt shows that cyberinfrastructure increases the efficiency not just for the technical/computing part, but also the social/collaborative part.

Productivity. As previously pointed out, speed can lead to increased productivity. This is an appealing outcome to scientists. A technologist in a software company based in Washington shares, “The scientist is what we call extreme information workers – people with high demands from computing” (18 March 2008). A senior technologist and professor of computer science in Texas adds that a clear benefit of cyberinfrastructure is “sheer productivity for any information based discipline” (27 March 2008). A center administrator in Ohio directly shares, “What draws researchers to using [my center] is the fact that… it is the right place for them to go to get access to robust cyberinfrastructure, but also because … so that they’re more productive in their science” (28 January 2008).

Increased productivity is an important outcome appealing to most scientists. This relative advantage can clearly be illustrated with the following example. An administrator at a university in Indiana shares a story that shows how the relative advantage of increased productivity can overcome the reluctant inertia of a neuroscientist at his university. The details of his story are maintained to illustrate his point. He begins with a background to his mission for increasing cyberinfrastructure adoption:

> I was at one point challenged to increase the use of our supercomputers by people in the medical school. I basically went door to door trying to talk people into making use of our supercomputers. One person who was a neuroscientist basically agreed to meet with me out of politeness and began his meeting with me by saying he was pretty sure that there was nothing that I had that he cared about but he agreed to meet with me in order to be polite. (16 January 2008)

The background of his story shows that a potential adopter may begin with absolutely no interest in adopting cyberinfrastructure. But a dialogue can identify existing limitations and/or barriers in current practice. He continues:

> So I asked him – What limits your research? Where are your pain points? He thought about it for a minute and said – We used the MATLAB Imaging Toolkit to process brain images and we can only do 6 a day. I said – That’s an odd number. Why is it that you can do 6 a day? He said – we have 3 PCs that have MATLAB installed on them and it takes about 8 hours to process an image. We

> start off one set of image processing when we come in in the morning and then we fire up a second set of images at the end of the day. I suppose we could probably [have done] 3 if we had the heart to have some graduate student come in in the middle of the night and start up the third batch, but we really don't do that. So, it's 3 computers times 2 MATLAB jobs a day. (16 January 2008)

This smart administrator then taps into the argument of how cyberinfrastructure can provide relative advantages to help the neuroscientist's work. Here is where he advances his argument with clear rationality of speed, efficiency, and productivity as he continues:

> I said – You know, we have a 50 seat license on the IBM ST supercomputer that we've got, so you can run 50 MATLAB jobs at once. On top of that, the processor speed – the single CPU processor speed on our ST is faster than the single processor speed on the PCs you're using. So you can process 100 images a day on the same duty cycle that you're now processing 6 images a day. He thought that was great… We have found [this rationality] very effective in getting discipline scientists to adopt supercomputers. (16 January 2008)

This is a powerful story because it exemplifies the outcomes of speed, efficiency, and productivity for scientists. When it is clear to scientists that they can increase their productivity exponentially as illustrated in the story above (i.e., from a current productivity of six images per day to a possible productivity of 100 images per day), a scientist's inertia or reluctance to consider adoption can be overcome.

Quantitatively speaking, the relative advantages of cyberinfrastructure adoption are clear: faster speed, greater efficiency, and increased productivity. These are predictable and calculable outcomes that are logical to scientists. Furthermore, cyberinfrastructure also presents relative advantages that increase the quality of science by enabling scientists to tackle bigger, broader, and more interdisciplinary questions about complex scientific problems.

Qualitative Advantages: Solving Complex Problems

A qualitative shift in science depends on the kind of questions scientists ask and the kind of complexity involved in solving the problems they pursue. Cyberinfrastructure allows scientists to ask bigger, broader, and more interdisciplinary questions that were impossible for scientists to tackle before. The adoption of cyberinfrastructure, therefore, leads to qualitative advantages that are perceived as useful and beneficial for the ultimate purpose of investigating grand scientific challenges, having breakthrough discoveries, producing publications, and elevating reputations. Qualitative advantages build on the three quantitative advantages discussed before. A center administrator in Illinois talks about his sense of adoption drivers, "[A] more qualitative change in what they [scientists] can do [or]… a quantitative change of things. But I think both are motivations for people [to adopt]" (23 January 2008). The discussion now focuses on the qualitative advantages.

Bigger Questions. The relative advantage of tackling bigger problem is especially compelling today. An NSF program officer shares, "The amount of data that's universally available now – never been true in the past. Every researcher can access pretty much everything that's happened in [his/her] area and related areas, the entire history" (28 February 2008). Although not every scientist works on a large-scale problem, cyberinfrastructure makes it possible for every field to explore bigger questions. A supercomputer center administrator in Texas shares, "Not all research requires supercomputing. But virtually every research field has very large scale problems that do" (2 January 2008).

When a problem is bigger, it is often assumed to be a better problem. A professor of computer science in Texas shares, "The purpose of a cyberinfrastructure, the physical part of it, is to enable people to do things they couldn't otherwise do. That's all there is to it… Solve a bigger problem or better problem" (27 March 2008). When cyberinfrastructure can process data at a scale and speed not possible before (on a desktop/personal computing model), scientists can now tackle larger problems that were too big to address before.

When a problem is bigger, it is often assumed to be a new problem. A supercomputer center administrator in Illinois shares:

> I think most of the ones [scientists] that I work with have a real interest that there's new science that can be done. I think that that kind of varies between some of them saying – I can do what I'm doing now but 10 times bigger, which is useful. But with more resources, I can get more precise results, more accurate results, I can model a bigger system. (23 January 2008)

Collectively, there is a notion that when scientists work on bigger problems, that leads to good, new science.

The relative qualitative advantage of pursuing bigger questions is simply the result of scale. Scientific techniques for a research problem do not have to change. Cyberinfrastructure simply exponentially scales up any scientific problem. Moreover, when the scale is exponential, the quality can be regarded as better simply because it was not possible previously. A professor of physics and computer science in Indiana shares a personal experience that illustrates how cyberinfrastructure has exponentially made it possible for scientists to work on much bigger scale problems than ever before:

> Let's take the biggest of big science – particle physics. They're just doing the same types of things they did architecturally. What they're doing today is the same as is done 30 or 40 years ago… What's different with cyberinfrastructure? ... When I did particle physics experiments 30 years ago, we had a collaboration of 30 people from 5 institutions. Now it is whatever it is – 200 institutions and 1000 people... But the model has not changed. It's just much better and more sophisticated now. (14 February 2008)

This perspective is important because when a scientific problem is scaled up exponentially, it can lead to new discoveries not possible 30 or 40 years ago. This argument is related to the next point about combining different datasets to ask broader and richer questions.

Broader Questions. The second qualitative advantage is the ability to ask broader questions because cyberinfrastructure allows scientists to combine a range of existing data sets within an established problem in a given discipline. The problem may remain the same, but by combining a range of datasets otherwise not possible without cyberinfrastructure, scientists can explore the same question more thoroughly. The professor of physics and computer science in Indiana quoted above offers another example in which details are maintained for illustration:

> [In the past], astronomers were associated with wavelengths. So the optical astronomers looked at optical data and radio astronomers looked at radio data, infrared astronomers infrared data, etc. Now those data are available on the Internet at each wavelength and you can do multi-wavelength astronomy, linking them together... You’re still looking at the same types of fundamental questions. You’re just doing it in a much richer fashion because you’re joining together half a dozen wavelengths to try to get better answers. The supercomputers, because you can now do realistic 3-D simulations, which was really not possible until we had these TF or hundreds of TF power machines. You’re able to do computations of fundamental problems that you couldn’t do before. (14 February 2008)

This excerpt suggests that the nature of the questions scientists pursue is not drastically different from the past. However, cyberinfrastructure allows scientists to combine existing data sets and make the questions more complex. In addition, before cyberinfrastructure, such broad and sophisticated questions were not possible to tackle. Therefore, cyberinfrastructure again leads to a qualitative change that improves the quality of research.

More Interdisciplinary Questions. The third qualitative advantage is the ability to pursue more interdisciplinary questions. Cross-disciplinary and interdisciplinary questions are multifaceted, and they require bringing together multi-scale data, multi-disciplinary knowledge (theories and models), and multi-site experts (from different fields) related to the same phenomenon. Furthermore, interdisciplinary questions have been out of reach in the past before the implementation of cyberinfrastructure, yet they are now possible, as a supercomputer center administrator in Illinois shares his observation:

> The people who deal with water and flow and rivers and sediment transplant and so on, really have a need to understand more about what's going on in the farm field or how water is percolating through the underground rocks, but those are different disciplines. So they haven't been able to get coordination from those other disciplines in terms of whether their models, what data do they have about various sites, do they have all the information about the surface of the underground and the stream flow all of the same sites so that they can make sense of everything. So they're kind of seeing that by working together [via cyberinfrastructure]. They'll actually be able to tackle those problems which have just been out of reach. (23 January 2008)

Interdisciplinary questions are difficult to tackle because they require scientists to consider multiple aspects single-handedly. With cyberinfrastructure, they are able to access a wider range of multidisciplinary data, knowledge, and experts than they were before, leading to a qualitative advantage.

The scale of computing introduced by cyberinfrastructure makes qualitative shifts that are revolutionary. Scientists are able to pursue interdisciplinary questions because of the scale of computing and the possible access to data, knowledge, and experts in multiple fields. These are the three main resources that drive interdisciplinary research. A professor of physiology at a university in Illinois states, "The fact of using computing has been around for a long time, but the scale of computing is inducing changes that I think are truly revolutionary…It is now possible to become truly… an expert in multiple fields" (4 February 2009). The long term implication is that the adoption of cyberinfrastructure may begin redefining the disciplinary boundaries.

In the competition of science, researchers are always looking for ways to increase their competitive advantage. The ultimate goal is to increase the possibility of solving grand challenges, breakthrough discoveries, highly-cited publications, and elevated reputations. At the same time, scientists are creatures of habit. When there is scarcity of time, knowledge, and funding, scientists are usually reluctant to change their organizational/behavioral practices unless they understand the clear usefulness and relative advantages of cyberinfrastructure. The quantitative advantages cyberinfrastructure provides includes the interrelated outcomes of faster speed, greater efficiency, and increased productivity. They collectively help scientists explore bigger, broader, and more interdisciplinary questions otherwise not possible. This qualitative shift is the result of access to data, knowledge, and experts across time and space in an integrative fashion that was not possible before cyberinfrastructure.

SHARED VISIONS: GETTING IN AND STAYING IN THE POSSIBILITIES

Cyberinfrastructure is not only a meta-platform and an organizational/behavioral practice, it is also a contagious idea. Once caught, this compelling idea can give scientists a vision of a breakthrough discovery, an identity of a revolutionary, and personal meaning to work. However, this idea cannot live long in isolation. It needs to be sustained by a network of participants. Once an idea is shared, scientists who have adopted cyberinfrastructure can help newcomers to get on board. Once the idea has spread through a scientific community over time, a community censuses helps solidify cyberinfrastructure's role in science. In other words, a shared vision is the last piece of the puzzle that ties together a range of technological tools, social mechanisms, multi-scale data, multi-disciplinary knowledge, and distributed experts to form a coherent and powerful cyberinfrastructure rapidly emerging in the U.S. during the early 21st century.

Breakthrough Discovery

The vision of enabling breakthrough discovery is a key mechanism that drives adoption. It is a vision shared by both scientists and technologists involved in the development of cyberinfrastructure. This section will provide details for the vision of breakthrough discovery.

A Vision of Breakthrough Discovery for Scientists. The adoption of cyberinfrastructure involves overcoming different barriers (previously discussed in Chapter 4). In order for scientists to get in and stay in the adoption and implementation of cyberinfrastructure, they need to have a vision of how it can facilitate the impossible. A professor of water resources engineering at a university in Illinois, a pioneer in her field through her involvement in prototyping new cyberinfrastructure tools in modeling the water system, shares the vision keeping her involved in cyberinfrastructure involvement. She begins by explaining the massive scope and complexity of her research for the City of Chicago to manage storm water in order to prevent sewer overflows and water contamination. She explains the source of the problem she is investigating:

> It’s coming from rain that’s falling over this huge area, running through different kinds of infrastructure throughout the city. Think about the sewer system – how big that is. And coming into this treatment system, there’s decisions being made about how to run this giant tunnel and reservoir system. This is just a massive system. (22 April 2008)

Then she talks about the data and computing limitations she faces in her attempt to explore this important research problem. She explains that it is important for her to be able to perform modeling and visualization of the entire city’s water system in real time:

> What I want to be able to do is to look at how you can better manage a system in real time. In order to do that, I need to have real time data streaming in. I need to have the right kind of data… We don’t have the data right now to be able to look at this thing… I need to have the models to be able to work with so that I can try out different solutions and see what their effects might be. I need to have nice visualization systems. (22 April 2008)

This researcher is very clear about her research problem and the data and modeling limitations she is facing. In order to overcome these limitations, she turns to the vision of cyberinfrastructure. This represents the macro, broad, and motivating narrative that promotes CI adoption. Furthermore, her story also alluded to a micro and specific aspect of being able to visualize large and complex data, another aspect of the notion of ‘visions’. As discussed so far in this dissertation, the vision of cyberinfrastructure includes technological tools, social mechanisms, multi-scale data, multi-disciplinary knowledge, and distributed expertise. Although the vision has not fully materialized, she concludes that the vision is what keeps her involved in cyberinfrastructure, “That’s what keeps me at this – the vision of what would be possible for my research if we made all of this work. Otherwise, in order to answer the questions I’m interested in would require about three lifetimes of research” (22 April 2008).

These visionary and pioneering adopters make up an important group of scientists who sustain the initial effort of cyberinfrastructure development. They need to believe so much in the visionary possibility that they are willing to tolerate the pain of initial adoption. Other scientists (i.e., non-adopters) are watching the visionary adopters. If these visionary adopters succeed, they become exemplars of what is possible for their colleagues. When they are rewarded, such as winning a Nobel Prize, their vision becomes even more compelling. A retired and senior leader in the field of computational science in California shares:

> [Visionary adopters] are willing to jump on a new resource, even though they know that it will be painful, even though they know it won’t be stable… When those people get their science done… demonstrate that they can do the things that couldn’t be done before… people in the field will follow… Some people will perhaps do very large scale scientific and data experiments that will lead to a Nobel Prize someday. (7 February 2008)

The vision is not only held by scientists. It also compels technologists and supercomputer center administrators who co-produce cyberinfrastructure.

A Vision of Enabling Breakthrough Discoveries by Technologists. The cyberinfrastructure vision of breakthrough science is shared by both scientists and technologists (and administrators of supercomputer centers). As discussed in Chapter 1, cyberinfrastructure is a participatory innovation that depends on co-production between scientists and technologists. Therefore, technologists are driven by a matching vision. A supercomputer center administrator in Texas shares a compelling vision of how the cyberinfrastructure they develop will help push the competitive edge of researchers in science, engineering, social sciences and humanities and enable ground breaking discoveries otherwise not possible:

> Our vision for what we're going to do is enable breakthrough scientific research, and research overall, not just in science or engineering, but even in social science and potentially, humanities and fine arts downstream… We want to provide, not just the computational power, but the intellectual power for using those computational resources that enable people to do breakthrough research, that enable people in diverse disciplines to push the state of the art in their disciplines... And we want to grow our R&D programs so that we're pushing the state of the art in the systems and software and thereby further helping users push the state of the art in their own applications fields... We want to provide a competitive advantage for our researchers by providing superior technologies for them to conduct ground breaking research on. (2 January 2008)

This vision is not simply rhetoric, but a compelling ideal shared by many others at his center. Although some skeptics may assume that one could simply be repeating the company line and it is simply an act, I observed that technologists at his center appear to be sincerely believing in the meaning of their work. I observed this at events and gatherings outside the formal interview process. Technologists believe they are building technological tools that will enable the next breakthrough discovery. They believe that without the tools they are co-producing, the scientists' visions will be compromised. Therefore, technologists make up a critical part of the grand vision of cyberinfrastructure.

Diffusion Mechanisms

As discussed in Chapter 2, communication networks and social influence play a key role in the diffusion process of an innovation. These mechanisms influence the perceptions of an innovations and its attributes during the adoption process. In this section, I will discuss how professional networks and community consensus play such an influential role.

Professional Networks as Social Mechanism for Diffusion. Professional networks in scientific fields and personal relationships between scientists are critical to the diffusion of cyberinfrastructure. Not only do they help frame the initial perceptions of potential adopters through their conversations about cyberinfrastructure, they provide the opportunities and support for newcomers and new adopters. In other words, pioneering adopters are scientists who are embedded in the same professional networks, who are held in a basic level of trust by their colleagues, and who are interested in collaborating with each other. Therefore, network embeddedness is key. A sociology post-doc at a research center in California shares:

> People that pick up cyberinfrastructure more quickly are people already embedded in big scientific networks where it makes sense… Typically it's someone that's already involved in a series of scientific networks, has other people they know, and wants to work with those people in some kind of way, despite the fact that they are distributed… Scientists who are more embedded in these kinds of networks would be probably the people that pick it up first… It doesn't seem to make much sense to get involved in those kinds of projects if you don't already know some people to begin with… If I don't know anybody, joining a collaboratory doesn't make much sense. (19 February 2009)

This gets at the notion of diffusion networks among near-peers (Rice, 2009; Valente & Davis, 1999). Some visionary users could be the opinion leaders in this case, and newcomers would have to be embedded in their previously established professional networks. Otherwise, they would be beyond the reach of these opinion leaders during regular communication. More importantly, if these newcomers are not already embedded in the social networks (Rice et al., 1990; Rogers, 2003; Valente, 1995; Valente & Davis, 1999) of the opinion leaders, they would not have the scientific reasons or the personal trust to join an existing cyberinfrastructure project or to co-initiate one. Professional networks and network embeddedness then become the critical social mechanisms that help spread cyberinfrastructure vision and practice.

Community Consensus. Once a vision has diffused beyond the initial opinion leaders and their near-peers, it can become a community consensus. The notion of community consensus emphasizes the diffusion of the idea, not the material manifestation. It takes time, but a compelling idea that makes logical sense with compelling perceived needs and clear relative advantages can be contagious. A professor of chemical engineering at a university in Massachusetts talks about the observation of resistance in the past. The resistance was so intense that he describes it as an "argument" at professional meetings involving the audience:

> [In the] combustion kinetics community… for a long time when we started working this [cyberinfrastructure matter], every time we'd go to a meeting, there would be an argument because some people in the audience didn't believe that it was even necessary. That the way that they did things before was just fine. There was no real point [in adopting cyberinfrastructure]. (22 February 2008)

Then about 2004 or 2005, the opinion of the combustion kinetics community began to shift. A community consensus towards cyberinfrastructure began to emerge:

> About 3 or 4 years ago… we changed from every time we had a meeting we had to argue about this [cyberinfrastructure matter], to everybody more or less agreed. It became the majority view that we needed to do this. (22 February 2008)

He further explains that the logic behind this community consensus was the rationality that the research problems that scientists in the community pursued were becoming too large to be single-handedly investigated by individual scientists. Therefore, it was logical for the community to move towards a cyberinfrastructure model that would move their science forward. He explains:

> Now when you go to a meeting, there's consensus in the community that the problems that we're doing are too complicated – that a single researcher can't possibly know all the data that's relevant in understanding his results and also can build a high quality model of what would happen. There's a consensus that we

> need the cyberinfrastructure and tools that we’re building now that there wasn’t before when I started. So there’s that consensus. (22 February 2008)

This excerpt exemplifies the three key categories of rationalities discussed in this chapter.

- First, the notion of perceived need is supported by the community (i.e., “There’s a consensus that we need the cyberinfrastructure and tools that we’re building now that there wasn’t before when I started”).
- Second, it echoes the argument that relative advantages, both quantitative and qualitative, are driving rationalities for a shift (i.e., “…the problems that we’re doing are too complicated – that a single researcher can’t possibly know all the data that’s relevant in understanding his results and also can build a high quality model of what would happen”) to overcome inertia (i.e., “…every time we’d go to a meeting, there would be an argument because some people in the audience didn’t believe that it was even necessary. That the way that they did things before was just fine”) against adoption.
- Third, when the inertia was overcome by the logic of perceived needs and relative advantages, they formed a community consensus around a vision that had reached critical mass (i.e., “It became the majority view that we needed to do this”).

Despite the challenging conditions discussed in Chapter 4, this chapter shows that shared visions include the ability to meet perceived needs and provide relative advantages drive and sustain adoption. The discussion in this chapter mainly focuses on answering RQ2, “What are the rationalities that drive cyberinfrastructure adoption in early 21st century U.S.?” Through grounded theory and thematic analysis, three categories of rationalities emerged to explain scientists’ adoption: perceived needs, relative advantages, and shared visions. A close examination shows that these three categories of rationalities also match the three dimensions of cyberinfrastructure discussed. First, the adoption of cyberinfrastructure as a meta-platform of interrelated technologies is driven by the perceived needs for computational power, massive storage, multi-scale integration, and distributed collaboration. Second, the adoption of cyberinfrastructure as an organizational/behavioral practice is driven by its relative advantages to produce quantitative and/or qualitative benefits that increase the possibility of major publications and scientific reputations. Third, the adoption of cyberinfrastructure as a new approach to science is driven and maintained by shared visions held by scientists, technologists, professional networks, and scientific communities.

The diffusion and adoption of the multi-dimensional innovation of cyberinfrastructure takes time. The rationalities identified in this chapter may be critical conditions that will influence the remaining diffusion process. The next chapter brings findings for the two research questions together in discussions, conclusions, and implications.

CHAPTER SIX: DISCUSSION, CONCLUSION, AND IMPLICATIONS

This dissertation pursues two research questions. First, how does cyberinfrastructure's nature influence its adoption process in the early 21st century U.S.? Second, what are the rationalities that drive cyberinfrastructure adoption in the early 21st century U.S.? This chapter reviews the key findings in answering these two research questions and then links them together to propose a preliminary theoretical framework for early cyberinfrastructure adoption. As noted in Chapter 3, since most of the interviews were conducted in the year 2008, the findings primarily reflect the driving rationalities and challenging conditions most relevant to cyberinfrastructure diffusion during that period of time. Finally, theoretical and practical implications are discussed.

DISCUSSION

Challenging Conditions for Cyberinfrastructure Adoption

Cyberinfrastructure adoption in the innovation development process encounters some barriers and challenges. The first research question asks, “How does cyberinfrastructure's nature influence its adoption process in the early 21st century U.S.?” Based on theoretical memos, preliminary analysis of pilot data for this dissertation, and literature, this dissertation focuses on four pairs of cyberinfrastructure characteristics: participatory/bespoke, meta/complex, disruptive/revolutionary, and community/network. The participatory/bespoke nature complicates the notions of trialability and observability/communicability. The complexity of cyberinfrastructure is compounded by the meta characteristic of cyberinfrastructure, leading to a lack of simplicity. The disruptive/revolutionary nature leads to cyberinfrastructure’s lack of perceived compatibility with the sociotechnological environment in which scientists work. The community characteristic of cyberinfrastructure is heightened by the constraints imposed by not having full control over a networked innovation. Although the driving rationalities are sustaining pioneering scientists in the adoption process, the challenging conditions are often rationalities for not adopting cyberinfrastructure. I will elaborate further on the four pairs of characteristics and associated challenges below.

First, cyberinfrastructure as a participatory/bespoke innovation co-produced by scientists and technologists for a limited funded period leads to a lack of trialability. Not only is adoption required at the conceptual level because tools do not exist at the point of initial adoption (e.g., a commitment to jointly submit a NSF proposal), the adoption process is prolonged because of the co-production process. In addition, because of the participatory/bespoke nature, cyberinfrastructure adoption lacks observability/communicability. What is often observed and communicated in many CI projects is the specialization-synergy gap and the science investment-technology quality gap.

The specialization-synergy gap is the result of co-production between two groups of highly trained specialists. Ideally, efficient and effective co-production requires synergy. However, scientists often lack the ability to fully envision new tools required for their science. Sometimes, they do not fully understand their needs during the process of co-production because they are not fully knowledgeable of what computational science can build for their science. On the other hand, technologists do not possess enough knowledge of the domain sciences for which they are building tools. Furthermore, they may not be motivated to learn much of the domain sciences given that co-production funding periods are short-term.

The science investment-technology quality gap is the outcome of software development under the science funding patterns during the time of data collection. Much of the funding patterns are still true today. There is limited or no stable direct funding for software development. NSF funds science, and software development is not considered science. The gap is further compounded by short-term funding patterns to get science projects started without a long-term sustainable commitment. Under these conditions, software development often depends on an open source platform, which lacks turnkey solutions. Software development is then rushed, and unstable software hinders serious research. As a result, a generation of scientists is lost while bringing in cyberinfrastructure because they put their research agendas on hold to facilitate the development and implementation of CI.

In addition, cyberinfrastructure is a meta/complex innovation that lacks simplicity (or ease of use, usability). It is a platform innovation that includes a range of hardware, software, instruments, storage systems, etc. As previously discussed, cyberinfrastructure is an innovation that involves synergy of specialists in co-production. When individual adopters encounter cyberinfrastructure outside of co-production, the complexity is compounded by the meta characteristic, involving a range of components. There are generally two groups of adopters outside of those in co-production.

First, scientist-developers are those who develop and maintain their own tools, mostly depending on the work of graduate students. This group of scientist-developers faces a steep learning curve, as they need to know the intimate details of hardware and become highly skilled programmers. They need these skills and knowledge to fully take advantage of cyberinfrastructure resources. Some adopt cyberinfrastructure by relying on in-house development at the expense of having to scale down their science.

The second group of adopters outside of co-production are users of existing tools, which are usually prototypes. They often face low usability with interface designs that are not intuitive while facing differing and/or competing scientific approaches built into existing tools. They are also concerned with the uncertain long-term sustainability of existing tools as cyberinfrastructure and the funding patterns evolve.

Third, cyberinfrastructure as a disruptive/revolutionary innovation lacks perceived compatibility with the sociotechnological environments in which scientists work. At the technological level, cyberinfrastructure disrupts the technological resources in place, including networks of material systems and organizational arrangements. The material systems include the familiarity of working with local personal computers, lagging software environments, and expensive data storage. Cyberinfrastructure also wrestles with organizational arrangements, including existing laboratory workflows, university traditions, and entrenched interests in the current technological infrastructure.

At the social level, cyberinfrastructure as a revolutionary innovation is perceived as incompatible with the rules and norms reflected in the professional motivations of research teams and the publication cultures of traditional academia. Graduate students and post-docs on research teams are professionally motivated to conduct and publish science, not developing technologies. Building cyberinfrastructure tools is often not aligned with their research career direction. Many disciplines in traditional academia still favor lead/single-authorships. Unusually large findings are difficult to get published because many journals are not confident that the results can be easily cited by other researchers.

Finally, cyberinfrastructure as a community/network innovation does not allow adopters to exercise full control over the shared technologies for their research. Because cyberinfrastructure is a network innovation, what one user does affects the entire community of users. Seasoned users often police new users and report inappropriate behaviors to center administrators. Power users are sometimes frustrated with the high number of small computational jobs that take up the supercomputing capacity and leave less time for larger jobs.

Driving Rationalities for Adoption

Despite the challenging condition, cyberinfrastructure adoption in the U.S. during the early 21st century is driven by three key rationalities: perceived needs, relative advantages, and shared visions. The driving rationality of perceived needs can be understood at two levels.

The first-order needs include scientists' needs for computational power and massive storage because there is not alternative to manage and process the data required on these large-scale research projects. In other words, there is no other way to do their research except with cyberinfrastructure tools and resources.

The second-order needs stem from the developments created to meet the first-order needs. Cyberinfrastructure brings together distributed computational resources and diverse datasets. Besides simply being able to perform large-scale computations on massive data, scientists are also able to perform multi-scale integration of combined datasets while working collaboratively with colleagues across time and space. When multi-scale integration and distributed collaborations become possible because of first-order needs, they become second-order needs that scientists include when they rationalize their adoption decisions. Perceived need is the primary driving rationality for cyberinfrastructure adoption as a meta-platform.

Moreover, perceived relative advantages play an important role. Similar to the two orders of perceived needs, cyberinfrastructure presents two categories of advantages: quantitative and qualitative. Quantitative relative advantages refer to faster speed, greater efficiency, and increased productivity. With these advantages alone, the adoption of cyberinfrastructure can help scientists do more in less time.

On the other hand, cyberinfrastructure also brings about relative advantages that are qualitative in nature. Scientists ask bigger, broader, and more interdisciplinary questions, integrate multi-scale data, and work collaboratively with colleagues across traditional boundaries. These are practices that are difficult to achieve without the support of cyberinfrastructure resources. In other words, science can tackle problems that are qualitatively complex, leading to discoveries and innovations otherwise not possible. Relative advantages increase cyberinfrastructure adoption as an organizational practice by overcoming behavioral inertia.

In addition to perceived need and relative advantages, another rationality that drove cyberinfrastructure adoption by pioneering scientists was a shared vision. These visions are shared by scientists as users and by technologists as developers through various professional networks and community consensus. Their common interest is successful investigation of grand challenges in science and breakthrough discoveries in research. Scientists envision research projects likely to lead to breakthrough discoveries while technologists see a vision to help develop cyberinfrastructure to support these projects. To a large extent, the Atkins Report is to be credited for this vision, as it has been mentioned by many participants during the interviews. This vision spreads through professional networks and becomes a community consensus that pushes adoption forward. Shared visions drive cyberinfrastructure adoption as a new approach to science.

Initial cyberinfrastructure adoption to date has been driven by perceived needs for more powerful resources. The quantitative and qualitative relative advantages help scientists overcome the inertia of conducting science the way they have always done it in the past. The rapid development of CI and the breakthrough discoveries it enables create shared visions that inspire scientists and technologists to want to get in and stay in this movement for a meaningful future.

A close examination shows that these three categories of rationalities also match the three dimensions of cyberinfrastructure discussed. First, the adoption of cyberinfrastructure as a meta-platform of interrelated technologies is driven by the perceived need for computational power, massive storage, multi-scale integration, and distributed collaboration. Second, the adoption of cyberinfrastructure as an organizational/behavioral practice is driven by its relative advantages to produce quantitative and/or qualitative benefits that increase the possibility of major publications and scientific reputations. Third, the adoption of cyberinfrastructure as a new approach to science is driven and maintained by shared visions held by scientists, technologists, professional networks, and scientific communities. However, these factors positively influencing adoption of CI interact with factors negatively influencing its adoption.

In grounded theory, one goal is to identify the structural conditions (or 'conditional matrix', Corbin & Strauss, 1988, pp. 135-138; Strauss & Corbin, 1989) that underlie a phenomenon of interest. Based on the findings from the interview data and in answer to both research questions, the conditional matrix underlying initial cyberinfrastructure adoption include three primary driving rationalities of perceived needs, relative advantages, and shared visions. As the challenging conditions revealed, cyberinfrastructure adoption can be further accelerated if four additional rationalities/factors are present: trialability/observability, simplicity, compatibility, and control. Collectively and ideally, cyberinfrastructure adoption would be best facilitated by all seven factors. When an area is missing, the adoption process is compromised.

CONCLUSION

What do the findings mean for the big picture of organizational communication and innovation adoption? In this section, I juxtapose constructs from innovation adoption with theories from organizational communication to propose a preliminary theoretical framework of early cyberinfrastructure adoption. Based on Browning's (1992) framework of organizational communication, I argue that cyberinfrastructure adoption lies at the intersection of technical rationalities (i.e., perceived needs, relative advantages, and shared visions) and narrative rationalities (i.e., trialability, observability/communicability, simplicity, perceived compatibility, and full control). This preliminary theoretical framework is presented in Table 3 below. I will elaborate in details in the paragraphs that follow.

Table 3. A Preliminary Theoretical Framework of Early Cyberinfrastructure Adoption

Category	**Technical Rationalities**	**Narrative Rationalities**
Informal Term	Lists (of Logic)	Stories (of Experiences)
Level	Conceptual	Personal
Characteristics	Predictive, Instructive, Technocratic	Interpretive, Contextual, Dynamic
Adoption Themes	Perceived Needs, Relative Advantage/Perceived Usefulness, and Shared Visions	Trialability, Observability/Communicability, Simplicity/Ease of Use, Perceived Compatibility, Full Control
Main Manifestation	'How an innovation should be in organizations'	'How people experience an innovation in a context of existing social norms and material technologies entangled to enable work in a particular way'

Technical Rationalities

Simply put, technical rationalities reason with 'lists' of logic that are predictive, instructive, and technocratic. This category of rationalities suggests that lists of logic guide the way people interact, communicate, and make decisions about innovations at work. The lists include formulas for actions with techniques, steps, and procedures, and they serve as instructive monologues with strategies built on identifiable, predictable, and controllable outcomes. In addition, they represent standards, certainty, accountability, and reportability in organizations that make up what gives legitimacy and authority to technocratic expertise. In other words, 'lists' present the logic people draw from to rationalize decisions and actions in organizations. They are ‘logical’ because they suggest ‘how an innovation should be’ in the persuasion and decision to adopt an innovation.

Technical rationalities represent classic factors of technology adoption, such as *perceived needs* (‘I need cyberinfrastructure because there is no other way to do my science’ and ‘I need it because it is now possible to do this’), *relative advantage* (‘We can do more in less time with cyberinfrastructure’), and the related construct of *perceived usefulness* (‘With cyberinfrastructure, we can now solve complex problems that were not possible in the past’). These arguments converge to form *shared visions* of breakthrough discovery that push the development forward. A commonality among these three driving rationalities is that they do not require a potential adopter to have direct contact or experience with the innovation for the logic to be persuasive and compelling. Perceived needs can be directed by a scientific purpose not yet exist, relative advantage can be calculated hypothetically, and shared visions can be conceived in the mind of an adopter.

Technical rationalities in the case of cyberinfrastructure adoption operate at the conceptual level. Based on lists of logic, scientists can calculate quite precisely and predict the increased productivity that would come from adoption. Because science is a competitive race, scientists always need technologies that help them improve their scientific work and productivity. The need for more advantageous technologies is linked to a sense of usefulness assumed to help scientists get ahead in the discovery of the next breakthrough in science. Technical rationalities create shared visions and inspire (or logically instruct) scientists on the cutting-edge to adopt an innovation lest they fall behind their competitors. Therefore, technical rationalities are hypothetical and visionary, and they are compelling because they conceptually make sense based on lists of logic. They manifest as predictive, instructive, and technocratic.

Narrative Rationalities

On the other hand, narrative rationalities can be understood through the stories of experiences that are interpretive, contextual, and dynamic. Narrative rationalities are the everyday lived experiences of organizational members. These stories are interpretive/emotional (i.e., romantic, humorous, conflicted, tragic, dramatic), contextual (i.e., personal, biographical, historical, retrospective, memory), and dynamic (i.e., multiple voices, evolving, changing). When technical rationalities suggest how things should be and cyberinfrastructure adoption can lead to increased productivity and breakthrough discovery, narrative rationalities reflect the subjective reality and the way scientists talk about their contextual, emotional, and dynamic interpretations of experiences with cyberinfrastructure. They are experiences because they tell ‘how people experience an innovation in a context of existing social norms and material technologies entangled to enable work in a particular way’.

Narrative rationalities capture factors that have been discussed in adoption literature. Most scientists’ experiences with cyberinfrastructure reflect very limited *trialability* (‘We can’t buy CI tools off-the-shelf’) and *observability* (‘We often don’t know what is possible with its potentials’). They also report experiencing a lack of *simplicity* (‘There is a steep learning curve’) and a low degree of *ease of use* (‘CI tools are clunky prototypes out of short-term projects’). Pioneering adopters struggle with cyberinfrastructure because it lacks *compatibility* (‘Cyberinfrastructure disrupts the material systems and the organizational arrangements in place’ and ‘The cyberinfrastructure model is too revolutionary for professional motivations and publication cultures’). Because the networked cyberinfrastructure connects an adopter to a community of users, there is a lack of *control* over this innovation on which one’s research heavily depends (‘Other users can affect my setup or get in my way of doing science’).

A commonality among the rationalities (when the challenges are overcome) above is that they stem from an adopter’s direct experience with an innovation. Trialability and observabilility is achieved only after experimenting with and having seen an innovation (and its results). Simplicity, compatibility, and control can only be determined after having been in contact with an innovation. Even if these conditions are missing in the case of cyberinfrastructure, it appears that pioneering scientists are able to rationalize their decisions to stay in adoption, perhaps based on technical rationalities.

The technocratic vision of cyberinfrastructure is compelling. However, many scientists’ stories reflect that they feel conflicted between the hope to foresee cyberinfrastructure work in the future and the time-investment and risks involved in prototyping cyberinfrastructure in the present. In traditional academia, a scientist’s career largely depends on discovery science and peer-reviewed publications, not (directly) tool development. Because cyberinfrastructure development is often co-produced by scientists and technologists, their struggles can only be understood in the context of their lived experiences. At the personal level, their stories become the rationalities for why some scientists do (or do not) adopt. These stories are dynamic and they change constantly in the rapid world of cyberinfrastructure.

Preliminary Theoretical Framework of Early Cyberinfrastructure Adoption

In grounded theory, Corbin and Strauss (1990) explain, “The aim is ultimately to build a theoretical explanation by specifying phenomena in terms of conditions that give rise to them, how they are expressed through action/interaction, the consequences that result from them, and variations of these qualifiers” (p. 9). A potential contribution of the preliminary theoretical framework of early cyberinfrastructure adoption is the distinction between factors that rely of technical rationalities that operate at the conceptual level (as construed by users), and the factors that stem from narrative rationalities that evolve at the personal level (as enacted by users). In the case of cyberinfrastructure, while trialability, observability, simplicity, compatibility, and control are largely compromised, pioneering scientists remain in adoption. Perhaps the adoption of a multidimensional innovation like cyberinfrastructure during the innovation development process can mainly be prompted and sustained by technical rationalities of perceived needs, relative advantages, and shared visions. As the conditions change in the next phase of the diffusion process, narrative rationalities may become more influential.

Furthermore, driving rationalities can become critical influence in the initial agenda-setting stage – how the general problem is defined/perceived, leading to an initial perception of a potentially suitable innovation solution – this 'sets the agenda' and may be hard to break away from later on, without substantial matching and redefining stages. Although the notion of rationalities are conceptualized as operating at the individual level of analysis, it is important to keep in mind the agenda-setting, matching and redefining organizational-level stages are the initial innovation attributes perceptions at the individual-level stages.

IMPLICATIONS AND FUTURE RESEARCH

Theoretical Implications

First, the innovation adoption literature reviewed in this dissertation suggests a mixed opinion on the role of perceived needs in the process of innovation adoption. Findings from this dissertation, however, show that there might be two types of needs at play in the diffusion process of a multi-dimensional innovation such as cyberinfrastructure. First-order needs appear to precede innovation adoption. There are the kind of needs that drive pioneering adopters to look out of desperation. In this sense, perhaps it reflects a narrative aspect of CI adoption as well. Furthermore, this can lead to an agenda-setting process with cyberinfrastructure. However, second-order needs become perceived a necessity only after initial adoption and/or when the innovation demonstrates that certain new outcomes are possible post adoption. This is similar to the matching process in organizational communication research. This distinction between two orders of perceived needs may be useful for explaining the inconsistency in prior research. There are two stages identified that make these distinctions clear.

Moreover, the notion of perceived needs was considered as a part of the construct of perceived compatibility. Based on the case of cyberinfrastructure, perceived need and perceived compatibility appear to be two distinct constructs. Perceived need operates in the realm of logic, and perceived compatibility evolves on the personal level and reveals an innovation's relationship with sociotechnologies at the environmental level. Perceived needs and perceived compatibility may be distinct when the logic represents visionary possibilities that will disrupt and revolutionize the personal experience and environment, such as in the case of cyberinfrastructure. They two can be aligned when the logic serves to strengthen the foundation of the environment an adopter works in. Therefore, this distinction between perceived needs and perceived compatibility deserves further investigation, perhaps through quantitative validation with a variety of innovations.

Second, the notion of shared visions is not prominent in the existing literature on innovation adoption, although it may be intuitive to assume that a sense of vision and/or a future perspective are important for innovation adoption. This driving rationality is particularly forceful in the case of cyberinfrastructure. The term 'cyberinfrastructure' became official in 2003 with the Blue Ribbons Advisory Report on Cyberinfrastructure submitted by Atkins et al. to the NSF. This report persuasively articulated a compelling vision of cyberinfrastructure for the national scientific community (to be then) funded by the NSF. In other words, the vision of cyberinfrastructure may be an example of what Leonardi (2008) calls a ‘discourse of inevitability’. Since CI adoption also involves development through funded co-production projects, this vision of an inevitable future is shared by scientists and technologies (and arguably center administrators and science funders). As organizations are becoming more grounded in technologies (Leonardi & Jackson, 2009) and technologies are becoming more user-centered (or customizable) and user-driven (von Hippel, 2005), the notion of shared vision among users, developers, and corporations) may become an important mechanism for promoting and sustaining the diffusion of an innovation.

From a visionary standpoint, perhaps cyberinfrastructure adoption, the adoption of a yet-to-be-known innovation in an exploratory manner, can be described by the metaphor of ‘exploration’. The American history is the story of exploration guided by the vision to conquer the unknown territory (Boorstin, 1976, 1993), rooted in the British’s exploration of America and the migration from the east to the west. Since the geographic exploration has been exhausted today, and not everyone can engage in space exploration, cyber-exploration becomes a natural manifestation of the inherent instinct to explore and conquer the unknown. The metaphor of exploration for cyberinfrastructure adoption may have insights and implications for innovation adoption research.

Third, as interactive and networked innovations (Lin, 2003) are increasing in numbers and are becoming more prevalent in our society, the notion of full control over an adopted innovation deserves research attention. Network interactivity (Lin, 2003) has been argued to promote adoption because as the number of users increases, the benefits that everyone can get from adoption also increase (Katz & Shapiro, 1986; Leung & Wei, 2000; Rohlfs, 1974). However, this is particularly true for innovations for which users can draw a clear boundary between the content/activity that belongs to them and the content/activity of others. How would a truly community-oriented innovation, such as cyberinfrastructure, impact adoption when changes by one can impact the workflow of many others? This question deserves future research attention in order to investigate the influence of an adopter's need to exercise full control over an innovation in its adoption process, perhaps in relation to Shirky's (2009) argument of organizing without organizations.

Fourth, while classic factors of trialability, observability/communicability, simplicity, perceived compatibility, etc. appear to be largely compromised, cyberinfrastructure adoption in its early stage is driven and sustained by perceived needs, relative advantages, and shared visions. The missing factors do present barriers for further and more rapid adoption, yet findings suggest that early adoption during innovation development process could be promoted by the three drivers discussed. Perhaps these three factors—along with the four pairs of characteristics—could be theorized as the primary drivers for pioneering adopters for multi-dimensional innovations such as cyberinfrastructure. The driving conditions for perceived needs and shared visions could be further investigated in future studies to understand their influence in the diffusion and adoption of cyberinfrastructure and other similar innovations before these innovations reach critical mass (Markus, 1987).

Fifth, the technologies-in-practice perspective (Ballard & Seibold, 2003), or the practice lens (Orlikowski, 2000), reveals time-related concerns during co-production of cyberinfrastructure development. This perspective, as a particular form of the sociotechnical perspective, highlights "how people, as they interact with a technology in their ongoing practices, enact structures that shape their emergent and situated use of that technology" (Orlikowski, 2000, p. 404). My findings reveal that adoption (and co-production) is time-consuming in the short-term (i.e., a present perspective) and problematic with respect to sustained and long-term funding (i.e., a future perspective). However, today’s investments are guided by a vision for a brighter future (i.e., both present- and future-perspectives). Technology adoption and its co-production process (for participatory/bespoke innovations) provide a unique opportunity to study how members reveal their relationships with time, as expressed in their lived experiences and situatedness between the present/short-term and the future/long-term of technologies for their work and organizations.

The notion of organizational temporality (Ballard, 2008; Ballard & Seibold, 2003, 2004a) is central throughout the findings. The driving conditions for adoption are about speed (i.e., quantitative advantages and perceived needs) and a future orientation (i.e., qualitative advantages and shared visions). The challenging conditions for adoption are about slow pace, delay/punctuality, urgency, time-investment, entrainment, and a present focus on the struggle to make CI work. Because time is a scarce, limited, and exhaustible resource (Ballard & Seibold, 2004b, 2006), perhaps innovation adoption research could further consider time as central to the process of innovation adoption because the influence of time appears to drive and impede adoption simultaneously in the case of cyberinfrastructure in its initial stage. However, when all time-related variables are aligned, diffusion and adoption may be accelerated. Otherwise, regardless of how intense the needs are, how attractive the relative advantages are, and how compelling the shared visions might be, without the alignment of time-related variables, adoption will be severely hampered. When junior scientists are driven by the immediate need to build their tenure cases, they can exhibit what Levinthal and March (1993) call ‘temporal myopia’, including the tendency to avoid “things that might come to be known” (p. 105) and to focus on “short-run survival” (p. 110). One may say that in the face of imminent failure or extinction, this tendency seems very rational.

Sixth, I draw upon Giddens’ (1984) structuration theory to suggest that perhaps innovation adoption can be conceptualized as the outcome of both micro systems (of interactions) and macro structures (of rules and resources). Giddens’ two mechanisms for structuration parallel the ‘micro interaction layer’ and the ‘macro structures layer’ of cyberinfrastructure discussed in the literature review. At the micro level, innovation adoption is a process that involves individual observable interactions/relations among scientists, post-docs, graduate students, technologists, administrators, etc. At the macro level, adoption reflects the fact that rules and resources enable and/or deter scientists from the innovation. By conceiving of adoption as a structuration process involving both micro systems and macro structures, research can systematically identify the communication mechanisms that facilitate the adoption process which takes into consideration the individuals and the cultures in place.

In addition, innovation adoption is a recursive process between macro structures and micro systems. On one hand, the material systems, organizational arrangements, professional motivations, and publication cultures make up the sociotechnical environment in which pioneering adopters consider cyberinfrastructure. This observation shows how the macro structure with rules and resources can constrain adoption. At the same time, large institutions such as NSF and the supercomputer centers are providing the potential for adoption that would not otherwise be there. On the other hand, the micro systems of adoption behaviors by pioneering scientists are creating incremental change in the macro structures, as can be seen in the emerging community consensus.

Seventh, rationalization (of technology adoption) can also be understood as a structuration process. It reflects the network[5] of sociotechnologies at the macro level (as in rules and resources), and it is also sustained by the stories of experiences by individual adopters at the micro level (as in systems of interactions/relations). When the logic for adopting an innovation is not aligned with existing sociotechnologies, the stories provide a rich opportunity to study rationalization. An understanding of rationalization is critical for a better understanding of how an innovation (and/or the visionary logic for its adoption) adapts to and/or becomes integrated into an existing network of sociotechnologies, and in turn, changing the network of sociotechnologies. It is also a rich opportunity for studying technological evolution and users' reinvention of innovations (Rice & Rogers, 1980; Rice & Schneider, 2005).

Theoretically speaking, Feenberg (2010, p. 13) argues, "Technology can no longer be considered as a collection of devices" (p. 13). In other words, technology adoption is not simply about its functions, but what it means to people. Feenberg's quote below further explains this notion:

> [T]he dichotomy of function and meaning is a product of modern technical cultures, which are themselves rooted in the structure of the modern economy. The concept of "function" strips technology bare of social contexts… A fuller picture is conveyed, however, by studying the social role of technical objects and the lifestyles they make possible. That picture places the abstract notion of "function" in its concrete social context. It makes technology's contextual causes and consequences visible rather than obscuring them behind an impoverished functionalism. (p. 14)

The focus of this dissertation on rationality (i.e., how stakeholders make sense of cyberinfrastructure and interpret its meanings) serves to bring the social contexts back to the technology by highlighting the contextual conditions, causes, and consequences

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[5] I use the term 'network' here to also represent and include similar notions of 'web', 'assembly', 'bundle', 'constellation' and/or 'cluster' of entangled social norms, organizational routines, technological systems, and material arrangements to enable work in a particular way.

otherwise assumed irrelevant in a purely functional sense. By focusing on the notion of rationality, adoption further reveals the process of structuration as micro decisions/choices that constitute and reconstitute macro norms of rationality.

Eighth, although one might take on Browning’s (1992) original distinction of technical and narrative rationalities to explain early cyberinfrastructure adoption, I argue that the narrative rationality (i.e. personal stories that are interpretive, contextual, and dynamic) in the case of early cyberinfrastructure adoption suggests a misalignment between the lists of logic (i.e. technical rationalities) (Browning, 1992) and the networks of sociotechnologies (Coakes & Coakes, 2009; Girard & Stark, 2007). Despite the predictive, instructive, and technocratic logic at the conceptual level for cyberinfrastructure adoption, the meta, persistent, and communual sociotechnical environment appears to ‘argue’ against and/or ‘negotiate’ with technical rationalities for adoption. This observation is aligned with Latour’s (2005) actor-network theory and his argument that materials have ‘agency’ and can act and/or have an effect on organizational processes and human outcomes. In other words, the material environment can be understood as having a seat at the table and discussing cyberinfrastructure adoption along with other human actors. Perhaps organizational communication could be expanded by consideration of ‘material rationalities’, especially in the case of innovation adoption.

Perhaps technical rationalities can be understood as different from material rationalities because technical rationalities operate at the conceptual level, and material rationalities show up at the environmental level. For scientists who are not cyberinfrastructure-ready (i.e., they are working at a personal/desktop computing scale, data are not in digital form, research teams unfamiliar with computational science, workflow does not support a distributed model, etc.), adoption means giving up the networks of sociotechnologies on which their science and scientific productivity currently depends. Material rationalities at the environmental level can hold scientists back, although they may be convinced of the perceived needs, the relative advantages/perceived usefulness, and the shared vision of cyberinfrastructure at the conceptual level. In other words, technical and material rationalities can be competing with each other. Narrative rationalities are conflicted when the conceptual lists and environmental networks do not match. Narrative rationalities are full of successes when the technical logic and material sociotechnologies converge and overlap. When the three categories of rationalities (technical, narrative, and material) are aligned with each other, cyberinfrastructure adoption is free of challenge and barrier. When they are not, adoption effort is impeded. However, all three types of rationalities are difficult to align in practice. Perhaps they will converge and diverge at different points in time, or perhaps in a cyclical way.

Ninth, due to a high degree of materiality in today's organizations, compatibility (at the environmental level, with networks of sociotechnologies) becomes an increasingly influential/critical factor for adoption of innovations that are multi-dimensional (i.e., an object, a practice, and an idea) with a range of unconventional characteristics (i.e., participatory/bespoke, meta/complex, disruptive/revolutionary, and community/network). Previous technology adoption studies reported relative advantage and perceived usefulness (at the conceptual level, based on lists of logic) as the most important factor(s). Technologies in the past were mostly isolated innovations (e.g., a VCR, a TV set, a copy machine, a non-networked computer, etc.). Therefore, it was natural for early adoption research to observe adoption as a substitution or replacement. This assumption is true when a new technology is adopted to replace an old technology in its entirety; the new is relatively more advantageous/useful than the old. This substitution assumption is also true when the old/previous technology is relatively isolated/independent, so that it can be easily taken out and replaced by a new technology.

Along the same line, in today’s technologically saturated organizational environment, the substitution assumption may not always hold true because technologies are representative of how organizations and the people in them operate. Traditional substitution assumptions may not hold in a networked environment. In a networked environment, a new technology may be adopted to complement, or can only be adopted by becoming integrated within, an existing network of sociotechnologies. If the new is incompatible with the existing networks, the new cannot be adopted without a cost to prior investments. New technologies that are incompatible with the networks of the sociotechnologies that are already in place wrestle with this base. This base (or installed base) only gives strength to new technologies that fit (Star & Bowker, 2006). Otherwise, adoption of an incompatible technology means replacing the entire base. This is when the notion of entrenched interest can become a barrier to adoption, or, in some cases, a good signal of inappropriateness of the innovation. In sum, this dissertation highlights the increasingly influential role of compatibility with existing sociotechnologies in today’s technology adoption process and questions the traditional substitution assumption. This argument is aligned with what Rice (2009) refers to as the sociological and technological interdependencies of new media.

Tenth, when technologies and associated practices are enacted by members on a daily basis, and the two constitute each other, Leonardi and Jackson (2009) call this the ‘technological grounding’ of an organization. It means the organizational culture is technologically grounded in practice. In the case of cyberinfrastructure, there might be two layers of technological grounding at play, one external in the macro sociotechnical environment, and one internal to a CI project. In this case, the perceived incompatibility discussed in this dissertation can also be framed as an incompatibility between the two layers of (internal and external) technological grounding. This framing could be further examined by future research.

Eleventh, the specialization-synergy gap and the science investment-technology quality gap can be theorized as *dialectics* (Gibbs, 2009; Tracy, 2004). A dialectical tension is conceptualized as the "copresence of two relational forces that are interdependent, but mutually negating" (Fairhurst, 2001, p. 420). More importantly, dialectical tensions exist in interdependence and the tension unifies the two seemingly opposing forces (Putnam, 2004). When a dialectical tension is identified, it also reveals an inherent connection between the two forces. The implication here is that synergy cannot be achieved without specialization and vice versa; scientific enterprise depends on appropriate technologies, and vice versa. These seemingly opposing ends between the gaps are unified by dialectics. Future research can further examine explore creative ways to embrace them.

Twelfth, this dissertation started with four pairs of cyberinfrastructure characteristics derived from preliminary analysis. These four pairs of characteristics (i.e., participatory/bespoke, meta/complex, revolutionary/disruptive, and community/network) have potentials for describing other internet based innovations that bring together a range of social processes and technological components. These four pairs of characteristics may be defining features of cyberinfrastructure (and similar innovations) that deserve future research attention.

Thirteenth, Csíkszentmihályi (2003) applies his concept of "flow" – defined as "the capacity for full engagement in an activity" – to an organizational context. He argues that "Leaders must make it possible for employees to work with joy, to their heart's content, while responding to the needs of society". More recently Reeves and Read

(2009) explores a similar notion of flow that they term “total engagement” with videogames and how this can be translated into the workplace. Given the increasing saturation of technologies in today’s organizations and workplaces, the strategic arrangement of, and continuing alignment with, material rationalities play a key role in creating “flows” for members’ productivity, creativity, and innovation at work. Future research may investigate how the desire to obtain and maintain “flow” influences the adoption process of innovations with some or all four pairs of the characteristics above.

Fourteenth, from an intellectual standpoint, perhaps one of the most important pairs of cyberinfrastructure characteristics is that of revolutionary/disruptive. Although the need for cyberinfrastructure and high-performance computing applications may not be universal across all scientific domains yet, the awareness of its importance is there and growing. Moreover, high-performance computing (within cyberinfrastructure) is and/or will be foundational in solving a large number of mathematical equations for scientific research. Therefore, the role of high-performance computing in research may soon be elevated to the level of mathematical equations in research. If this is true, innovation adoption in this case implies revolutionizing research at the deepest level. Furthermore, academic fields were organized based on specializations and the nature of research questions. A critical contribution of cyberinfrastructure is that it enables interdisciplinary research via access to a wealth of multi-disciplinary data, knowledge, and literature. The emerging phenomenon of cyberinfrastructure may be prompting academics to potentially re-think how they define disciplines.

Practical Implications

First, in order to attend to the specialization-synergy gap, transdisciplinary individuals need to be intentionally introduced into the mix of specialized scientists and technologists. Transdisciplinary individuals refer to scientists who have crossed into becoming a technologist, and vice versa. Specialization in domain science and computational science is critical for cyberinfrastructure development. However, without synergy, the development will be compromised. NSF Office of Cyberinfrastructure and supercomputer centers can consider specific positions for transdisciplinary individuals in order to further stimulate synergy in cyberinfrastructure development.

Second, supercomputer centers can further leverage the domain science knowledge that technologists picked up from past projects for future projects. For example, centers could further develop domain clusters where the same group of technologists will work mainly within the same domain of science and/or with the same community of scientists. In that case, these technologists will be more motivated to learn and retain domain science knowledge for future projects. Continuity with the same community of scientists will also promote tacit knowledge that is gained from directly working in a scientific community.

Third, an effort that would take longer to realize is to target students (graduate and undergraduate) whose career paths are still developing. Domain science students could be proactively recruited by supercomputer centers to help close the specialization-synergy gap. Since centers already provide classes and workshops[6] for domain science students to learn computational science, they can also strategically introduce the idea that students can make a career out of being transdisciplinary individuals in co-production that depends on synergy, instead of planning on becoming research faculty. Students in CI projects are most appropriate for this kind of work because, as the data reveals, most faculty scientists spend most of their time getting grants and funding, and they do not spend as much intimate time with the data as graduate students do. Students' intimate knowledge of the daily operation of science with CI tools should be tapped.

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[6] Continuing training and education is key to bringing and keeping scientists on the technology curve.

Fourth, in order to close the science investment-technology quality gap, science funders ideally would begin taking concrete steps towards providing long-term funding for sustainable cyberinfrastructure development. Software[7] and data are found to be two major challenges in the interviews conducted (mostly in 2008). If science funders cannot play this role, cyberinfrastructure development needs to attract private and commercial interests. In other words, specific steps could/should be taken to gain investment interests from established commercial corporations in the high tech industry, especially those who supply the hardware for building supercomputers.

Fifth, similar to the strategy suggested earlier of targeting students, centers can partner with the business schools at their home institutions (or nearby universities) to intentionally include an ‘entrepreneurial’ component in every computational science class/workshop they deliver. The goal is to introduce and stimulate the idea of entrepreneurship and to help students recognize the potential of the CI tools with which they work for their faculty scientists. Within ethical guidelines, these students could build on the initial effort and develop a start-up/business venture[8] around CI tools. Science and engineering students are often open and willing to try out new business ideas, but they may lack the entrepreneurial knowledge/strategies to begin. Strategic partnership with business schools can lead to long-term funding and sustainable development of CI tools for science apart from traditional science funders.

Sixth, as more CI tools are being developed and promoted within the larger scientific community across domains, science funders and technologists may want to be

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[7] Although interviews suggest that there is limited direct funding for CI software development, it is important to note that there have been sample programs, such as SDCI [Software Development for Cyberinfrastructure] and STCI [Strategic Technology for Cyberinfrastructure] with funding for building general purpose CI. In addition, TeraGrid also funds some CI software development.

[8] It is important to note that CI is about sharing and better utilization of resources. However, industry is about intellectual property and it is not a norm for commercial companies to share technological information. Therefore, from a philosophically standpoint, academically oriented CI tools may have difficulty gaining immediate industry and commercial interests.

sensitive to the ideological differences (i.e. theories, methodologies, intellectual traditions, etc.) held by different camps of scientists. When time, knowledge, and funding are limited, it is very difficult to not make choices. However, long-term implications of short-term choices should be kept in mind to prevent a future that privileges some groups and undermines others. For example, when a specific research methodology is built into a CI tool, the tool becomes a vehicle for the diffusion of the embedded methodology when the technology is being adopted. Methodologies not selected to get built into CI tools lose out in competitiveness when CI diffuses in the scientific community. The material foundation for science is not neutral and may never be completely neutral. However, every possible attempt should be made to promote diversity of intellectual efforts in the competitive enterprise of science.

Seventh, in order to promote adoption at the individual level, a practical strategy is to design messages that emphasize what non-adopters would lose if they don't adopt soon[9]. Framing has a critical impact on the decision- and choice-making process (Tversky & Kahneman, 1981). People tend to be loss-adverse (Tom, Fox, Trepel, & Poldrack, 2007) to many topics although not all, and a frame of loss[10] of non-adoption would likely propel potential adopters to act.

Eighth, the frame of persuasion could/should emphasize the qualitative advantages instead of the quantitative advantages. The quantitative advantages imply a frame of time (based on relative advantage of speed, efficiency, and productivity). A frame of time could be problematic because when potential adopters consider and

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[9] Scientific research and technological capabilities increase in a parallel way, and scientific research is increasingly dependent on technological advances. If a scientist does not increase his/her ability to use a technology, s/he is going to do a decreasing percentage of future science that needs to be done. If s/he is not at least maintaining his/her position and paralleling technological advances, s/he is going to find gaining funding increasing difficult.

[10] This strategy is to be applied with caution and based on situational factors. It is important to note the important role of a positive message that emphasizes the future possibilities of cyberinfrastructure and e-science, of what scientists can do next in e-science with adoption of cyberinfrastructure.

evaluate the potential impacts of adoption and the time investment/productivity loss likely to result, the same frame (of time) could work against efforts to promote adoption. The same frame can heighten their sense of loss aversion in terms of time investment[11] and productivity loss. Instead, Leonardi (in press) argues "perceptions of affordance lead people to change their routines" (p. 1). By emphasizing the qualitative advantages, potential adopters will likely focus on research quality gain, and coupled with the loss due to non-adoption (instead of the loss due to adoption), individual adoption can be further promoted.

Ninth, another communication move is to create strategic ambiguity and keep the shared visions of cyberinfrastructure plastic and flexible. Strategic ambiguity is a practice of organizational communication to minimize clarity and specificity[12] when organizational members face multiple situational requirements and conflicting goals (Eisenberg, 1984). In fact, strategic ambiguity can promote the unification of multiple interests, allowing "different organizational constituents to assert their own interests whilst also enabling collective organizational action" (Jarzabkowski, Sillince, & Shaw, 2010, p. 219). Plasticity allows the shared visions to dynamically evolve and adapt to a diverse range of stakeholders. More specifically, an example would be to (again) emphasize the qualitative advantages of cyberinfrastructure because they are difficult to clearly define across projects. What is considered qualitatively advantageous for one field or project may not translate to another. Therefore, this sense of ambiguity allows

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[11] In order to use high-performance computing resources, a scientist has to invest the time in learning parallel computing. The incentives are that scientists can do bigger and better science downstream, but they have to invest a certain amount of time up front. The key is continuous training and education, so that scientists do not need to set aside massive amount of time to get back on the technology curve.

[12] This strategy is to be exercised with caution and great attention to situational factors because not everyone is willing and able to work with ambiguity. Otherwise, ambiguity can back fire when used inappropriately without sensitivity to situational constraints.

scientists in a diverse range of fields and disciplines to define for themselves what advantages cyberinfrastructure can provide and what cyberinfrastructure means to them.

Tenth, it is important to clarify the target users of cyberinfrastructure development and adoption effort. Cyberinfrastructure currently is considered a rather specialized innovation within a niche community of scientists who depend on computational science techniques for their research. As the vision of cyberinfrastructure continues to push forward, science funders, supercomputer centers, and technologists may need to articulate clearly who their target audience is, as this will impact the technologies they develop. Using Feenberg's (2010) question about the design and production of the bicycle as an example of technology development, he asks, "Was it to be a sportsman's toy or a means of transportation? Design features such as wheel size signified it as one or another type of object while also suiting it to its function" (p. 14). This clarification can help either the adoption effort to target the right audience or the development effort to create perhaps two (or more) parallel efforts for two (or more) different types of users.

Eleventh, given the impeding influence of the larger environment, perhaps science funders and supercomputer centers can creatively partner with universities, journal publishers, and scientific communities to establish new reward systems[13] to support CI adoption in terms of software development and data storage, give credit to pioneering adopters for infrastructural contribution, and encourage new adopters to participate. When scientists focus on short-term and present survival in a competitive environment of

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[13] It is important not to assume that scientists have never faced this challenge before cyberinfrastructure. Building CI tools today is similar to building instruments for science in the past. Scientists in the past had to put their science aside to build telescopes, sensor networks, etc., and these are all parts of the overall scientific process. It would be difficult to change the incentive system to reward somebody for spending time for developing CI because there have been successful cases of scientists building an instrument and producing great science at the same time. The reward system is the same for them. Furthermore, one tends to get rewarded for building a world class instrument although one may not produce as many publications while s/he is building the instrument. Developing a world class CI tool can be regarded as a part of a scientist's overall productivity and impact on the field. Eventually, the tool may lead to more publications in subsequent years by the scientist-developers and other scientists in the community.

science and under the reward system of traditional academia, rapid adoption may be difficult to achieve.

Twelfth, diffusion efforts at this stage can be guided by lessons from network strategies. The next wave of adopters is likely to consist of scientists who are already embedded in certain social networks (Rice et al., 1990; Rogers, 2003; Valente, 1995; Valente & Davis, 1999) of pioneering adopters. More specifically, a citation network analysis (Rice, Borgman, & Reeves, 1988) and/or co-citation network analysis (Perry & Rice, 1998) of conference proceedings (Chen, 1999; Howard, 2002) and/or journal publications[14] (Borgman & Furner, 2002; Small, 1973) can visually reveal the central players in a field. These central players and opinion leaders should be targeted for adoption effort (Valente, 1995; Valente & Davis, 1999) because they will naturally influence those who follow their research and respect their opinions.

More on Future Research

While ideas for future research have been noted in a few places in the implications above, this section discusses four specific areas for future endeavors beyond the original focus on adoption, cyberinfrastructure, and scientific organizations. First, the case of the TeraGrid represents an opportunity to study an inter-organizational consortium with 11 resource providers that cooperate in a competitive environment. In the interviews, participants describe the 11 RPs as experiencing tensions over the need to cooperate in building TeraGrid and the need to compete for the same limited NSF funding. This dynamic is called ‘coopertition,’ a phenomenon documented by

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[14] It is important to note that the citation index associated with CI software does not also reflect its current status in the field. The current community may have moved on from an existing software tool that had been cited a lot in the past. Moreover, a counter-argument to using a CI software tool still adds to the citation index of the tool. If citation index is to be used in some way to gauge a tool’s impact, it is important to account for the changing perception of utility and value of the CI tool in its current state of adoption and implementation.

Zimmerman and Finholt (2008). In the 1990s, Browning and colleagues (Beyer & Browning, 1999; Browning & Beyer, 1998; 1995; Browning & Shetler, 2000) studied a similar tension between cooperation and competition in the Sematech, an inter-organizational consortium in the semi-conductor industry. In the case of Sematech, individual and group contributions eventually became self-amplifying when diverse participants built a moral community and set up a structure that in turn produced other structures (Browning & Shetler, 2000). As the notion of shared visions is compelling in this dissertation, how it operates in the midst of 'coopertition' among supercomputer centers and potentially building a moral community deserve research attention.

Second, the adoption of a health/medical innovation can be framed as infrastructure if it involves the adoption of a set of material technologies and organizational routines and if it also involves interactions from multiple departments within a health care organization (Aydin & Rice, 1992). Furthermore, as hospitals are full of specialists and patient-centered care requires effective synergy, hospitals make up another potential site for investigating the specialization-synergy gap. In addition, the notion of a public health infrastructure (Baker Jr et al., 2004; Gebbie, 1999; Yancey et al., 2007) has also received research interest. It is another example of an infrastructure that involves science, technology, society, and individuals. Future effort could investigate the adoption of innovations with similar nature as cyberinfrastructure in a variety of health/medical context.

Third, the notion of 'infrastructure' is what makes this study of cyberinfrastructure unique. In order to further understand the adoption of infrastructure, a study on green infrastructure (Benedict & McMahon, 2002; Gill, Handley, Ennos, & Pauleit, 2007) could add to the present effort to frame infrastructure as an innovation for adoption. This is particularly appropriate and timely considering the increasing significance of the green energy and environmental sustainability movements around the world. The complexity of green infrastructure, as it involves technical and narrative rationalities coupled with policy and economic constraints, could further theorize infrastructure as a multi-dimensional innovation.

Finally, decision/choice-making and rationalization are processes that require brain activities and cognitive functioning. Past research could not fully include insights from neuroscience because research in this field had not yet reached the necessary level of maturity to merge with social and behavioral science. However, recent research in neuroscience has revealed that the prefrontal cortex is primarily responsible for rational decision-making (Bechara, Tranel, & Damasio, 2000; De Martino, Kumaran, Seymour, & Dolan, 2006; Manes et al., 2002). Given recent advances in the area of cognitive neuroscience (Fellows, 2004) and behavioral neuroscience (Carlson, 2010), perhaps innovation adoption research could begin drawing insights about how the brain works to facilitate decision-making and rationalization. This effort could also add to the emerging area of biological dimensions of human communication (Beatty, McCroskey, & Floyd, 2009) and brainwave monitoring while people are interacting with media and technologies (Reeves & Nass, 2003). Furthermore, neurologist Damasio (2000; Damasio & Sutherland, 1995) has advanced the argument of the ‘emotional brain’ as equally important as the logical brain. Lehrer (2010) further maintains that the computational reasoning of the emotional brain was suppressed in the past because people did not know how to explain that. However, neuroscience may provide insights into how humans reason with emotional information. Thus, an opportunity exists to advance the construct of narrative rationality with neuroscience research.

This dissertation began with a pilot study to examine the adoption of cyberinfrastructure as a technological innovation with various innovation attributes.

Through grounded theory and a qualitative approach, the pilot study expanded into one that explores the interplay among innovation attributes, adopters’ rationalities, and conditional matrix underlying the complex adoption process of cyberinfrastructure as a socio-technical system. In the case of cyberinfrastructure, its diffusion during the innovation development process is the spread of the logical rationalities that promoted the adoption of the material innovation and associated practices despite a set of challenging conditions. The rationalizations during early diffusion cycles are important because they may become the persistent justifications later adopters draw from to accept or reject the innovation in the remaining diffusion process. Although cyberinfrastructure is a relative specialized innovation during the first decade of the 21st century, it can eventually get adopted, implemented, and reinvented in the diffusion process throughout the entire society.

APPENDIX A: INTERVIEW QUESTIONS

1. [Biography] I did a Google search on you, and I found out that you were involved in (this, this, and that). However, I usually begin my interviews with my participants sharing about their backgrounds. So would you like to begin with your version of your story: who are you, what you do, and how you came to be where you are today?
2. [Definition] The central topic of the interview is about cyberinfrastructure (CI). How would you explain the term ‘cyberinfrastructure’ to a lay person? What metaphors or analogies would you use to explain this concept to a family member who does not know anything about CI?
3. [Adoption] What are some of the factors behind CI adoption in the scientific community?
4. [Adoption] What are some barriers to CI adoption?
5. [Development] What are some factors behind CI development?
6. [Deployment/Collaborations] What is the best way to facilitate distributed collaborations among scientists through CI?
7. [Deployment/Collaborations] The development of CI itself can be viewed as a collaboration as well, especially (a) among scientists and technologists and (b) among multiple supercomputer centers across the country and the world. How are these levels of collaboration achieved? How can these levels of collaboration be better organized?
8. [Implementation/Virtual Organizations] What is a ‘virtual organization’ in the context of CI and e-Science?

9. [Implementation/Virtual Organizations] If someone were to set up a large scale virtual organization using cyberinfrastructure for the first time, what advice would you give this person?

10 [Future Vision] Where do you think cyberinfrastructure is going in the next 5 years, and the next 10 years?

11 [Free Flow] Before we wrap up, did this interview unfold the way you thought it would? Were there topics or questions you thought might come up during the interview, that didn't?

12. [Free Flow] What are some of your favorite topics about cyberinfrastructure and e-Science?

13 [Snowball] Based on our conversation today, who would you recommend that I should talk to in order to expand my dissertation?

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