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The Dialectical Tensions in the Funding Infrastructure of Cyberinfrastructure

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Abstract. This article focuses on funding for cyberinfrastructure and *how* funding affects the cyberinfrastructure foundation laid, *who* completes the work, and *what* the outcomes of the funding are. By following qualitative procedures and thematic analysis, we identify five dialectical tensions across three difference levels of institutions, individuals, and ideologies in the funding infrastructure of cyberinfrastructure. Through an organizational communication lens, we define funding infrastructure as the communication arrangements of institutions, individuals, and ideologies that must be coordinated in order for cyberinfrastructure to be brought into existence. These communication arrangements include salient motivations of and financial compensations for individuals who engage in them. They also comprise explicit policies about funding, as well as implicit ideologies about science embedded in funding, as held by institutions involved in these communication arrangements.

Key words: cyberinfrastructure, dialectical tensions, funding infrastructure, organizational communication

1. Introduction

Cyberinfrastructure (CI) is a term proposed by Atkins et al. (2003) to describe an "infrastructure based upon distributed computer, information, and communication technology" (p. 5). Broadly speaking, the technological components of CI are largely about the hardware, software, algorithms, computing systems, data storage systems, advanced instruments, data repositories, and visualization environments that enable large-scale research (Atkins et al. 2003; Stewart 2007). Of course, the technical systems are the focus of CI, but the potential to impact science, the desire to be the forerunners, and the high cost of such technical systems are the reasons many institutions and stakeholders are pooling their investments in it.

The notion of infrastructure in the sciences has become more than simply the "tubes and wires" (Ribes and 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.

As a socio-technical system (Hughes 1989; Jirotka and Goguen 1994; Ure et al. 2009), CI also consists of communications, institutions, personnel, and people (Atkins et al. 2003; Stewart 2007), what David (2004) calls the 'soft' foundations of cyberinfrastructure. Kee et al. (2010) argue that the socio-technical system of CI can be further framed by virtual processes and organizational results. In Latour's (2005) terminology, both humans and technology have 'agency' to influence organizational structure and outcomes.

The recognition of the social and organizational dimensions of CI is well explicated by Lee et al. (2006). They introduce the concept of the 'human infrastructure' of cyberinfrastructure in the computer supported cooperative work (CSCW) literature 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). 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 of people and technology that is effective only when it 'interacts'.

In order for the human infrastructure to coordinate and give rise to CI, an argument for funding needs to be made for its development. Abrahamson (1996) develops the argument that management fashions are about the "appearance of rationality and progress" (p. 259), and that such norms of rationality and progress create a market for rhetorics that champion these techniques. Managerial 'rhetorics' are used because exact causal relationships on the effects of practices are difficult to isolate. Managers are required to develop a rhetoric, a way of talking about what they do and what effect their program will have, that is convincing to a group of clearly defined stakeholders. CI rhetoric is primarily visionary, and the discourse is about its incredible potential for the future, as can be seen in the persuasive Atkins Report (2003).

Despite the financial and rhetorical enthusiasm for its development, Edwards et al. (2009) observe, "Infrastructure today seems both an all-encompassing solution and an omnipresent problem, indispensable yet unsatisfactory, always already there yet always an unfinished work in progress" (p. 365). We take this observation about infrastructure as a guide to explore tensions expressed in these authors' statement. To pursue this, we look at and identify the dialectical tensions in cyberinfrastructure, specifically in its funding infrastructure.

Given the establishment of a U.S. governmental office dedicated to CI development (Seidel et al. 2009) and the steady investments in this area (Edwards et al. 2009), a research opportunity emerged for an investigation of the funding infrastructure behind this development. We identify five sets of seemingly opposing forces on three levels of institutions, individuals, and ideologies. Instead of interpreting these tensions as negative forces that should be dissolved, a dialectical frame (Gibbs 2009; Tracy 2004) posits that these forces exist in relation to each other and co-sustain the actors and arrangements that give rise to CI. To offer two physical metaphors, the arc of a bridge whose opposing forces give it strength and the hollow body of an acoustic guitar whose frame holds it apart are both examples of parts that give strength to the structure.

As a preview, in Section 2, we provide the article's theoretical grounding in organizational communication, the key analytical lens of dialectical tension, and a communication definition of funding infrastructure based on the constitutive nature of communication for organizations. We briefly explain, in Section 3, our data collection and data analysis. Section 4 provides an overview of the National Science Foundation, the Office of Cyberinfrastructure, and its flagship project, the TeraGrid project. In Section 5, we share our key findings of the five dialectical tensions. In Section 6, we provide one reinterpretation of the seemingly opposing forces across various levels. In Section 7, we conclude by offering a trio of implications from the study.

2. Theoretical grounding in organizational communication

2.1. Dialectical tensions in organizational research

Recent organizational studies of CI projects have examined the issues of 'tensions'. For example, through a qualitative study of the Linked Environments for Atmospheric Discovery (LEAD), Lawrence (2006) argues that the solutions to tensions in large-scale CI projects are not in building more sophisticated technologies, but rather in attending to social and organizational challenges. An exemplary article in information systems is Ribes and Finholt's (2009) ethnographic studies of LEAD, Geosciences Network (GEON), Water and Environmental Research Systems (WATERS), and Long Term Ecological Research (LTER). They identify nine tensions in CI development by creating a matrix based on three concerns (aligning end goals, motivating contribution, and designing for use) across three scales of infrastructure (institutionalizing, organizing work, and enacting technology).

The tensions that Ribes and Finholt (2009) identify reveal the larger tension between the short-term and the long-term vistas. They propose to focus on the 'long now', which is a perspective on CI development that formulates a way of working in the present that links it to the future. The goal is to integrate "multiple concerns, and matters of organization and technology, into the single frame of action that participants encounter on a regular basis" (p. 391). When 'regular encounters' (what are you doing now?) of participants are in contact with technology development (how do we prepare for a future?), the 'long now' keeps participants working in a 'shadow of the future'. In the cooperation literature, a 'shadow of the future' means that participants' day-to-day activities are conducted with an awareness that their long-term relationship makes a difference (Cohen et al. 2001). We borrow this language to describe the way today's CI development is executed with an awareness that its long-term sustainability matters.

Building on the existing interest in 'tensions' in cyberinfrastructure in the literature of CSCW and information systems, the present study enters into this conversation using the concept of dialectical tension from the field of organizational communication. A dialectical tension is defined as the "copresence of two relational forces that are interdependent, but mutually negating" (Fairhurst 2001, p. 420). Two aspects of dialectical tension are relevant to this study. First, the study of dialectical tension "centers on contradictions or the ways that oppositional forces create situations that are 'both-and' or 'either-or'" (Putnam 2004, p. 40). An actant (either human or organizational) experiences being pushed or pulled by simultaneous forces. In accounting for this in our study, each dialectical tension is identified in statements with 'both-and' or 'either-or' to characterize the relationships. Second, dialectical tensions exist in interdependence (Putnam 2004). We only know them by the connection we have with opposing forces. The tension unifies the two seemingly opposing forces. When a dialectical tension is identified, it also reveals an inherent connection between the two forces.

2.2. Funding infrastructure as a communication arrangement

Besides being a socio-technical system, CI is a community based on a network of social and political relationships comprised of actors who communicate both directly and virtually (Ribes and Finholt 2008). Furthermore, Ribes and Finholt (2009) contend that the concepts and language from the social sciences have been well-received by CI participants and well-integrated into CI projects. Building on Lee et al.'s (2006) conceptualization of the human infrastructure, we apply an organizational communication lens to define the funding infrastructure of CI.

Different theoretical approaches have been used to study the social dimensions of organizations (Jirotka et al. 1992). Organizational communication is employed because "communication theory can be used to explain the production of social structures, psychological states, member categories, knowledge, and so forth rather than being conceptualized as simply one phenomenon among these others in organizations" (Deetz 2001, p. 5). Rather than focusing on 'communication' within an 'organization', this lens showcases the idea that the communication *is* the organization (Hawes 1974). The communicative constitution of organizations (Mumby and Stohl 1996; Putnam and Nicotera 2009) is particularly applicable for studying CI and its funding infrastructure because, like constitution theory, the analysis focuses on how organization is built up over time by commitments across institutions and people.

By taking the constitutive assumption of communication as organizations and structures, we define 'funding infrastructure' as *the communication arrangements of institutions, individuals, and ideologies that must be coordinated in order for cyberinfrastructure to be brought into existence. These communication arrangements include salient motivations of and financial compensations for individuals who engage in them. They also comprise explicit policies about funding, as well as implicit ideologies about science embedded in funding, as held by institutions involved in these communication arrangements.* Table 1 briefly summarizes the five dialectical tensions that we will detail in Section 5. Table 2 shows the examples (discussed throughout the article) of the four key elements in the communication definition of funding infrastructure.

3. Data collection and data analysis

3.1. Data collection

From November 2007 to August 2009, we conducted 68 interviews with 65 participants (8 in 2007, 41 in 2008, and 16 in 2009). As most of the interviews were conducted during 2008, the analysis primarily reflects the development during this period. Sixty-one participants were from 17 U.S. states, and four were from three other countries (the U.K., Germany, and Australia). Interviews range from 15 min to 2 h and 16 min, averaging about an hour each. Sixteen participants were interviewed in person and 49 over the phone. All the interviews were audio recorded except for two, due to technical difficulty and a participant's

Table 1. Tensions identified on institutional, individual, and ideological levels in the funding infrastructure of cyberinfrastructure.

Institutional Level	
Tension 1	Funding *either* science *or* technology.
Tension 2	Juggling priorities of *both* NSF *and* local states, home universities, and federal agencies.
Individual Level	
Tension 3	Providing *either* unrewarded service to cyberinfrastructure community *or* building an individual tenure case.
Tension 4	Spending time *both* on virtual organizations *and* at a local supercomputer center.
Ideological Level	
Tension 5	Building cyberinfrastructure *either* for one's theory/methodology *or* a competitor's theory/methodology.

Table 2. Examples of key elements in the communication definition of funding infrastructure.

Salient Motivations	• A scientist's unrewarded service to cyberinfrastructure community. • A scientist's belief in the vision of cyberinfrastructure
Financial Compensation	• A scientist's tenure promotion. • A technologist's pay arrangement. • The funding a supercomputer center receives from its home university/sponsor, local state, and/or federal agencies.
Explicit Policies	• An institution's mission statement. • NSF's proposal evaluation criteria. • A funder's policy on data, findings, etc.
Implicit Ideologies	• The slogans of a supercomputer center and its home sponsor. • The theoretical and/or methodological orientation of a group of scientists.

request. However, notes were taken immediately after these two interviews. Total transcripts amount to approximately 485,000 words.

We sampled participants based on specialized knowledge about CI, so snowball recruitment (Johnson 1990; Sætre et al. 2007) was chosen as the appropriate recruitment strategy. Participants' primary professional roles were diverse, including domain scientists who used CI to conduct science (16), computational technologists who built CI (14), a range of administrative directors and program managers at supercomputer centers and national research laboratories across the country (20), NSF program officers who helped allocate funding to CI projects (3), and social scientists and policy analysts who studied and participated in CI projects (12).

This data set is unique is two ways. First, there have been studies based on specific CI projects, for examples, LEAD (Lawrence 2006), LTER (Karasti et al. 2006), and TeraGrid (Lawrence and Zimmerman 2007; Wilkins-Diehr et al. 2008; Zimmerman et al. 2008). The present data set moves away from project-level analyses and instead tries to answer a broader question across projects and to examine the entire national venture of CI development. Second, many existing studies are based on interviewing and observing domain scientists, technologists, and project administrators. This study includes NSF officers, who offer a national perspective, and social scientists, who have a high degree of reflexivity and knowledge about CI projects.

3.2. Data analysis

Grounded theory (Corbin and Strauss 1990; Strauss and Corbin 1998) provided direction for our qualitative analysis that evolved throughout the entire data collection process. However, a general qualitative procedure (McCracken 1988) and a specific thematic analysis (Owen 1984) were performed on the data for this article. First, the important data were sorted out from the unimportant data.

Second, slices of data were examined for logical relationships and contradictions. Third, transcripts were re-read to confirm or disconfirm emerging relationships and scanned for the general properties. Fourth, general themes were identified and the themes were sorted in a hierarchical fashion, while discarding those that proved irrelevant in the organization. Finally, the emergent themes were reviewed and synthesized into overarching themes. Thematic analysis was based on three criteria of recurrence, repetition, and forcefulness.

Our interviews were originally conducted to investigate the organizational communication (Browning 1992) during cyberinfrastructure adoption, distributed collaboration, and virtual organizing. However, a semi-structured approach (Wengraf 2001) allowed for a serendipitous discovery. Based on qualitative analyses, five tensions related to funding, funders, grant, money, salary, pay, etc. emerged organically based on data with the following word counts: Tension 1 (4,976 words), Tension 2 (5,247 words), Tension 3 (7,041 words), Tension 4 (4,341 words), and Tension 5 (4,490 words). These tensions are paired 'clusters' (Browning 1978) that converged to form the funding infrastructure of cyberinfrastructure on three levels: institutional (Tensions 1–2), individual (Tensions 3–4), and ideological (Tension 5). In writing this article, we modeled our writing style after Browning and Beyer's (1998) example, which follows Glaser and Strauss's (1967) recommendation of weaving data with literature to validate emerging theory.

4. A brief description of the National Science Foundation, the Office of Cyberinfrastructure, and the TeraGrid Project

The National Science Foundation (NSF) is the governmental branch established by Congress in 1950 to oversee the scientific activities in the U.S. by reviewing and selectively funding grant applications. The NSF's mission, according to its websites, is "to promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense." The NSF administered an annual budget of about $6.1 billion in 2008, $6.5 billion in 2009, and $7.045 billion for 2010 (NSF 2010). It allocates funding through 18 different accounts, including Directorate for Biological Sciences, Directorate for Geosciences, Directorate for Mathematical & Physical Sciences, Directorate for Social, Behavioral & Economic Sciences, Office of Polar Programs, and Education and Human Resources, just to name a few. The NSF is one of the most powerful forces behind scientific research in the U.S. A technologist, who is also a professor of computer science, from Indiana bluntly states, "NSF puts funding into certain areas. That's the way things will go" (14 February 2008). This is true with CI development to support the sciences.

As a result of grassroots CI projects and their increasing impacts on scientific discovery in recent years, the NSF established the Office of Cyberinfrastructure (OCI) in 2005 to coordinate 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 a budget of about $185 million in 2008, $200 million in 2009, and $219 million for 2010 (NSF 2010). The mission statements of both NSF and OCI represent the notion of *explicit policies* of our communication definition of funding infrastructure.

NSF's flagship CI project is the TeraGrid (TG), which Zimmerman and colleagues (Zimmerman 2007; Zimmerman and Finholt 2006, 2007, 2008; Zimmerman et al. 2008) have extensively documented. TG 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 and Finholt 2007, p. 241) needed to conduct large-scale research. TG began in 2001 and Zimmerman and Finholt (2008) provide a detailed account of its historical development. The idea behind TG was to create partnerships to provide combined resources and services to scientists through tools and environments they were already using (Catlett et al. 2006).

Today, TG is a consortium based on 11 partner sites, including National Center for Supercomputing Applications (NCSA), San Diego Supercomputer Center (SDSC), University of Chicago/Argonne National Laboratory (ANL), Pittsburgh Supercomputing Center (PSC), 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). TG 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 this is a technological platform with wide applications, thus justifying the investments in it.

5. Findings: dialectical tensions

5.1. Funding *either* science *or* technology

In the first dialectical tension we examine the balancing act within the NSF with regards to its commitment to funding science or technology. The establishment of OCI presents an interesting shift in NSF's funding environment. Although science and technology are inherently related to each other, the primary purpose of the NSF is to fund scientific/discovery research and not technological/infrastructural development. The technologist from Indiana quoted in Section 4 laments, “NSF funds research. Sustainable software is not research… You can’t keep doing it… You can do it for a few years. I doubt if you can do it for 20 or 30 years” (14 February 2008). His statement represents a tension by implying that it is possible to be off course with funding for only limited periods of time. Since software is integral to cyberinfrastructure, how to pay for software development from a source dedicated to science is problematic.

The tension between either funding science or technology within the NSF funding environment is further amplified by two factors. First, OCI is not set up to directly fund scientific discovery. All proposals to NSF are required to articulate the intellectual merits and broader impacts of the proposed projects. Intellectual merits refer to a proposed project’s significance in advancing knowledge and discovery within its own field or across different fields; broader impacts are the educational, technological, and societal implications of the project’s potential scientific discovery (NSF 2007b). These criteria represent the *explicit policies* in the communication definition of funding infrastructure. Although grossly simplified, the merits of CI projects tend to be technological advancement, not direct scientific discovery. An OCI program officer explains, “Given that we’re not a basic research entity inside NSF… Frankly, we’re not set up well to fund [discovery science] directly. [The excitement is]… more about the [broader] impact of our cyberinfrastructure investments…” (12 May 2008). Therefore, CI projects tend to emphasize one of two NSF proposal evaluation criteria. This situation at OCI amplifies the larger tension between either funding science or technology.

The second amplifying factor is OCI’s commitment to existing high performance computing (HPC). The main focus of HPC projects tends to be building a faster and bigger supercomputing infrastructure. This can be seen in the frequent news that another record-breaking supercomputer for open science research is up and running, most recently at the University of Tennessee through an award of $65 million (ScienceDaily 2009) from NSF OCI (ISGTW 2009). An NSF program officer acknowledges an impression in the research community that OCI mainly funds HPC projects:

> Some would say… the Office of Cyberinfrastructure, it was set up to be about high performance computing and big iron and that’s where all the money goes. That is the domain of not even computer scientists, it’s researchers, but of technologists, of really the implementers, the infrastructure guys (17 March 2008).

Although this NSF program officer is not expressing a personal opinion, the quote reflects an observation of the research community’s opinion.

Why would OCI’s commitment to HPC be a problem? The technological components of cyberinfrastructure are more than simply HPC hardware. CI also includes software, algorithms, advanced instruments, visualization environments, etc. The first problem is that HPC hardware development exceeds users’ demands and software developments. A senior administrator of a supercomputer center in

Illinois states, “the computing power available to the national community is growing faster right now than the demand... The processing power is growing at a faster rate than the community is traditionally aware of and familiar with” (31 March 2008). Therefore, the computing resources available serve a small segment of power users, and wider adoption across the national scientific community is critical if CI investments are to be optimized. Another administrator at a supercomputer center in Texas states, “We have continued to develop new chips and new supercomputers. And the software is not keeping up” (10 January 2008). In a subsequent interview, this administrator in Texas 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). The computing resources development cannot be fully utilized without the matching software, which is under-developed relative to the hardware.

The second problem is the budgetary commitment to HPC development. When most of a set budget is committed to one area of development, other areas of development suffer. A senior social scientist in California, who has been involved in many CI projects explains:

> At the moment, the Office of Cyberinfrastructure … [has] got something like $200 million, most of which is tied up in HPC and continued commitments to HPC, which means that there’s little wiggle room to actually create the sort of research programs that you need in order to create a robust body of knowledge across many disciplines... What this means is the current funding structure… still tends to be a directorate based thing within NSF rather than a true cross-directorate vision... (14 April 2008).

As explained in Section 4, NSF has multiple directorates that fund discovery science, and OCI’s mission is to create an infrastructure that supports all these science-based directorates and units. The commitment to existing HPC projects on a fixed budget constrains OCI’s ability to fund new CI projects that would usher in a broader cross-disciplinary vision in NSF.

The first dialectical tension on the institutional level lies at the intersection of science and technology. NSF was established to fund scientific discovery, but OCI’s mission is to build technological infrastructure. Given its focus on broader impacts (which is not direct scientific discovery or intellectual merit) and budgetary commitment to HPC (which constraints its ability to fund new CI and non-HPC projects), the first dialectical tension in the funding infrastructure of cyberinfrastructure is between funding science or funding technology with NSF money.

5.2. Juggling priorities of *both* NSF *and* local states, home universities, and other federal agencies

Although NSF OCI is the primary investor of CI development in the U.S., there are other influential co-investors, including many federal agencies, local states, home universities of supercomputer centers, and affiliated sponsors of research laboratories. This can be seen in the example of TeraGrid (TG). The deputy director of the TG Grid Infrastructure Group (GIG, which consists of key administrators from TG-participating supercomputer centers) in Illinois explains, "There isn't a single source of funding for TeraGrid. Our funding sources are quite diverse. They go actually outside of what you would consider even traditional funding sources of each RP…" (24 April 2008). RPs, or resource providers, are the 11 participating supercomputer centers, national laboratories, and universities across the U.S.

These RPs are directly affiliated with their home funding sources. For example, SDSC is sponsored by the University of California, San Diego; NCSA by the University of Illinois, Urbana-Champaign; TACC by the University of Texas at Austin; ANL and ORNL by the Department of Energy; NICS and NCAR by the NSF; LONI by the State of Louisiana; and Indiana University and Purdue University by the State of Indiana. When RPs depend on funding from multiple sources (i.e., the notion of *financial compensations* in the communication of funding infrastructure), the consortium of TG presents an interesting organizational dynamic in which the 11 RPs have to juggle between priorities (in terms of *explicit policies* and *implicit ideologies*) of both NSF and multiple federal agencies, local states, and home universities. In addition, cyberinfrastructure development is influenced by the community of scientist users who participate in the funding and planning of CI projects (Ribes and Finholt 2008).

CI development at these 11 partner sites is influenced by their local states. An administrator of a supercomputer center in Ohio says, "So you get federal funding, … state funding, … or you could have multiple sources of income supporting a center like ours… Some of them might be quite intimately involved in the governance [of the center]" (28 January 2008). A local state's involvement can also be seen in the example of LONI. LONI was started by an investment of $40 million over a 10-year period by former Louisiana Governor Kathleen Babineaux Blanco. A systems administrator at a national laboratory in Illinois shares:

> LONI… They were trying to get seven campuses, six public, one private, the state's hospital system, Barksdale Air Force Base, and a number of private companies, to all get onboard to build this huge state-wide fiber network and also to buy hardware… I was totally afraid that was going to be derailed… [What] smoothed it over is the fact that the State itself picked up most of the bill, rather than trying to split the costs amongst everyone (18 November 2008).

These examples from Ohio and Louisiana demonstrate that local states often influence the operation of a supercomputer center and act as a resource provider for CI development.

Supercomputer centers are also influenced by their home universities. An OCI program officer explains, "A high-end computing center… [receives] some ongoing maintenance investments from the university" (28 February 2008). The deputy director of TG GIG quoted earlier also explains, "Most of the people who work for me on GIG-related activities don't report directly into me. In actuality, very, very few of them do. They all have a direct line reporting into the local institution where that work is being performed" (24 April 2008). As a result, a center often aligns its mission with the overall mission of the university. For example, the University of Texas at Austin has an integrative slogan that states, "What Starts Here Changes the World." TACC at the university has a mimicking slogan of "Powering Discoveries that Change the World." The symbiosis of slogans allows for the university president to use its supercomputer center as an example in her/his funding appeals and for the center to subsequently benefit from the fundraising effort. The example of TACC's matching slogan is an example of *implicit ideology* in the communication definition of funding infrastructure.

CI projects are influenced further by federal agencies. For example, a senior project director in California explains, "NASA [National Aeronautics and Space Administration], for some period of time, had a rule that all major projects funded by NASA had to have something on the order of 2%, or some number like that, of their budgets into education outreach" (1 February 2008). Federal agencies can require recipients to share their research findings through educational and outreach efforts. Moreover, some federal agencies have explicit policies requiring applicants to make data public. An example comes from a senior scientist at the Department of Energy (DOE) as he comments, "in NIH [National Institutes of Health], you have to have a data policy to get funding [but] … you [don't] have to have one for DOE funding" (7 February 2008). A data policy requires a funding recipient to make public the data collected during the project for re-use beyond its original scope after a stated period of time. This means federal agencies can obligate the recipients to hold and share the data for the larger research community. Federal agencies demonstrate their priorities by obligating funding recipients to have broader goals and to advance societal goals to a wider population while doing the specific work they are charged to do. These *explicit policies* exemplify our communication definition of funding infrastructure.

The second dialectical tension at the institutional level lies at the intersection of the NSF, local states, home universities, and other federal agencies. Although TG is the flagship CI project of NSF, its RPs centers have to juggle between NSF's vision for TG and the priorities of multiple other sources of funding for each site. While these priorities may not be in direct conflict, fulfilling them simultaneously presents the second dialectical tension in the form of 'both-and'. This is an important point because Fairhurst (2001) posits that a dialectical inquiry does not privilege a stronger force over other ones in a dialectical relationship. All forces are important in our consideration. Additionally, centers' attempts to fulfill multiple *explicit policies* and *implicit ideologies* represent the influence of *financial compensations* in the communication definition of funding infrastructure. The 11 RPs do experience conflicts over the need to cooperate in building TG and the need to compete for the same limited NSF funding. This dynamic is called 'coopertition'. This particular tension, which emerged from our data, was previously observed by Zimmerman and Finholt (2008) in their evaluation study of the TeraGrid.

5.3. Providing *either* unrewarded service to the cyberinfrastructure community *or* building an individual tenure case

Researchers depend on scientific reputations as the primary currency for their careers (Whitley 2000). Traditionally, scientific reputations, tenure promotions, and hiring decisions are based on scientific productivity demonstrated by discovery contributions and peer-reviewed publications (Hofer et al. 2008). Although there have been discussions about distinguishing between and acknowledging both "discovery contribution" and "infrastructural contribution" (Birnholtz 2006, p. 1768) in big science, which cannot be conducted without the appropriate technological infrastructure, counting publications remains the primary model for tenure promotions and hiring decisions in academia. This situation presents a dialectical tension at the individual level for scientists who use CI because their science cannot be done effectively without their involvement in the development of the CI tools their science depends on.

Given CI's relatively young history and its technical complexity, tools are custom-made innovations by technologists and scientists. On one hand, tool development depends on technologists. A CI project manager from a university 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 and give them options" (25 January 2008). On the other hand, CI tools are science-driven, and scientists play an active role in the production of these tools. An administrator at a supercomputer center in California adds, "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). This is problematic because scientists are not formally trained as skilled programmers. Getting the code up to production quality is time intensive, and scientists are often unfamiliar with software engineering's best practices, such as the capability maturity model, which is a development model elicited from actual data.

Furthermore, the need for co-production brings scientists directly into the CI community. As the deputy director of TG GIG in Illinois shares, "We integrate the [scientist] users so tightly into all aspects of TG from the management decision making right down to what's the needs in the specific area. It's so tightly integrated that we really see the [scientist] users as part of [TG]" (24 April 2008). This involvement affects the scientific productivity upon which a scientist's career depends; building cyberinfrastructure presents a direct competition for the scientist's time, which is also needed to build his/her individual tenure case and scientific reputation. A leading researcher in water resources engineering in Illinois confesses:

> Right now, cyberinfrastructure slows down my research because we're not there yet, at the point of the Atkins' vision. We're at the point of prototyping and developing what might be possible. That process of working with NCSA and other organizations to define what cyberinfrastructure should be and to prototype early cyberinfrastructure, that's—you've got to be willing to take a hit on your research to do that… It's a very time consuming process and it's not something that makes my research … easier… It is not helping me get it done faster … (22 April 2008).

Pioneering scientists are motivated to usher in the vision of cyberinfrastructure articulated in the Atkins Report referenced in the introduction of this article. This vision inspires scientists to prototype CI despite risky time investment and reduced research productivity. However, in general, short-term and long-term orientations and obligations influence the willingness to sacrifice the present for the future (D'Alessio et al. 2003). The quoted excerpt above demonstrates the notion of *salient motivations* in the communication definition of funding infrastructure.

CI development is time consuming because it is in its infancy and this generation of scientists co-producing it faces a serious dilemma. Ribes and colleagues (2005, 2008) documented that pioneering geo-scientists actively participate in expert workshops and work with technologists to choose and build 'ontologies' (or formal conceptual maps of knowledge domain) for data integration and sharing. A technologist in Texas laments, "[The] generation 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). Building CI competes with producing science in both time and attention.

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. A senior social scientist in California concludes:

> 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. So the people who have the most energy and the most ability to do it have very, very good institutional reasons for not doing it (14 April 2008).

The need to obtain tenure, as articulated in the quote above, represents the notion of *financial compensations* in the communication definition of funding infrastructure. The implied unrecognized service work by pioneering scientists who helped build CI despite no rewards exemplifies the notion of *salient motivations* in the definition. When junior scientists are driven by the immediate need to build their tenure cases, they often 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).

The classic assumption about academic progress is especially true in our interviews; faculty in universities live by tenure. When junior scientists in academia are under immense pressure to publish to build their tenure cases, CI development creates competing demands on their time to do science and publish. However, without the necessary CI tools, no science can be completed. Environmental uncertainty, scarcity of resources, and conflicting interests influence everyday activities in organizations (McGrath and Kelly 1986). The drive to publish good science versus the involvement to build CI tools as service to the community creates the third dialectical tension in the funding infrastructure of cyberinfrastructure. When this tension intersects with the first tension of funding science or technology, the complexity in CI development is compounded: NSF funds science (and not sustainable technologies), and academia is about research (and not building technological infrastructure). When cyberinfrastructure tools are supposed to be built by academics on NSF money, there is a serious mismatch and/or conflict of interests.

Two situations exist when a scientist is not directly involved in building CI with the larger infrastructure community. First, graduate students become the programmers. A leading researcher in chemical engineering at a university in Massachusetts reveals, "So probably the correct way to do this would be to have the government pay chemists to hire computer programmers to work with them… [But] we're using our chemistry graduate students to write the software" (2 February 2008). In other words, some graduate students become those who provide service to CI community. Second, using graduate students to write software leads some scientists to downgrade the science they do. A leading physicist in Louisiana recalls an observation, "Typically, the fluid dynamists have no expertise in software engineering or parallel computing… But they're often willing to do work on problems that are less sophisticated computationally… because they have … their graduate students … keep the software…" (18 February 2008). Scientific discovery is compromised when scientists downgrade their science because of CI's technological complexity.

The first dialectical tension at the individual level lies at the intersection of service and research credit. Scientists are faced with the dilemma of providing unrewarded CI service or conducting the discovery science on which their tenure cases, their careers, and their scientific reputations depend. This dilemma is the third dialectical tension in the funding infrastructure of cyberinfrastructure. Although the third tension is framed as a dilemma between providing unrewarded service and building a tenure case, the temporal tension experienced by individual scientists is apparent. Temporal tension is also experienced by technologists.

5.4. Spending time *both* on virtual organizations *and* at a local supercomputer center

Many CI projects depend on collaborations among technologists across multiple supercomputer centers. We use the label of ‘supercomputer centers’ to generically refer to different types of RPs, similar to those supporting TeraGrid. Along with dispersed scientists, technologists from different centers form a virtual organization (VO) around a CI project. Their participation in distributed CI projects is important because it brings external funding to the local center. In the mean time, because technologists are full-time employees of the local center, they are expected to contribute to work within a center and the home university or federal sponsor.

A CI project only contributes to a portion of a participating center’s total funding. Zimmerman and Finholt (2008) explain, “TeraGrid is only one activity and one source of funding for the resource providers. The percentage of each RP’s budget and staff that is supported by the TeraGrid award varies across sites” (p. 16). Therefore, at any given time, many centers are involved in multiple external projects while providing computing services to their home sponsors. This arrangement also translates into the daily work arrangement of many technologists. A technologist at a supercomputer center in Illinois shares:

> I’ll redefine in-house to be in-house within [our center (an RP)]. We actually do a fair amount of that kind of work as well... Maybe a quarter to a third of our work is actually internal to [our center] itself. And then [our university] versus the world… That’s probably the other 2/3. We do get more [on campus] questions than off campus just because we’re here. But it’s not the case that all [on campus] staff have access to our machines. They still have to go through the allocations process and submit their proposal and things like that. It’s just a small subset of [our university] (2 September 2009).

As illustrated in this case, technologists attend to responsibilities internal to the center, and on- and off-campus scientists who have been allocated resources on the supercomputer at his center. In this case, technologists have to attend to a mix of local and virtual expectations daily.

CI development depends on a VO of technologists. The basic level of a VO in TG is called a ‘working group’, a specific collection of people from several sites who work on a common problem. Examples of a working group include networking working group, scheduling working group, development working group, etc. The deputy director of TG GIG states, “This is where the physical rubber hits the road—gets done—at TeraGrid” (24 April 2008).

However, virtual management of VOs and working groups is complex. As full-time employers of centers, many participating technologists report directly to their local superiors. It is difficult for virtual leadership to have a real effect when a virtual follower is not directly paid by the virtual leader for the expected work (Gibbs 2009). A social scientist in California recalls:

> We had one guy who was in charge of a working group, a development working group across six or seven universities and he said, 'Well, it is real tough because I don't sign anybody's paycheck. I don't have a lot of leverage to get people to do what they said they would do' (5 March 2008).

The same dynamic also plays out between technologists and scientists. A geochemist at a university in New York shares:

> I have to deal with this team of [technologists]… who did not report to me… Because they didn't work for me, because it was only a small part of their agenda, they were not really that motivated and that enthusiastic… It was just part of the work. And then it goes slow… as when it's sort of ad hoc and on the side (29 January 2009).

The leader-follower dynamic expressed in the quotes reveals a non-standard work arrangement (Ballard and Gossett 2007) unique to CI projects. Technologists are expected to work for and attend to a range of commitments and responsibilities from distributed CI projects, such as the TeraGrid. However, these virtual commitments are short-term and external responsibilities are part-time. A dialectical tension arises when these short-term commitments and part-time attention and responsibilities are embedded within the standard work arrangement at the local center, leading to the need to devote work time to both virtual organizations and local centers.

Many technologists are working on a part-time basis on CI projects. Only a minority of contributing technologists are full-time. A social scientist in California reports:

> [A] lot of the people involved in the cyberinfrastructure building projects are working on it part-time… Usually there is a project manager and some technological people who are on the project 100% of the time. But after that there [are] usually technologists who are working just a percentage time on the project. (5 March 2008).

Work time theoretically corresponds to salary percentages. However, it is difficult to divide daily work time and attention based on strict pay percentages. In practice, daily work time and attention are often driven by emerging issues. Therefore, this part-time arrangement can lead to a situation where a technologist is torn between multiple demands. A social scientist in Michigan observes:

> If you are a TeraGrid person, like a staff person who is 100% funded by TeraGrid, you probably know that and you know you have a specific set of

> tasks. But if you are someone at a TeraGrid site and you are 25% TeraGrid and 75% elsewhere [locally]… You have that dual issue thing… [of] where do I put most of my time?... You probably see it more in something like TeraGrid where you are kind of torn between the two (24 March 2009).

This new form of non-standard work arrangement—one in which workers have to juggle between their 'fixed' and 'flexible' spatio-temporal presence in interrelated local and virtual organizations—creates the fourth dialectical tension in the funding infrastructure of cyberinfrastructure. Although funding agencies can require more detailed reporting of how employee time billed to projects was spent, this dialectical tension requires technologists to fulfill multiple expectations and temporal demands simultaneously.

5.5. Building cyberinfrastructure *either* for one's theory/methodology *or* a competitor's theory/methodology

Scientists form groups and communities based on different theories and methodologies. Theories and methodologies form the foundation of the 'paradigm' (Kuhn 1962) and the 'intellectual organization' (Whitley 2000) of a scientific field. Methodologies are especially important because strong fields are methodological in nature (Fuchs 1991), and they constitute the social and technical orders of a field (Knorr Cetina 1999).

The ideological tension begins with the various groups of scientists involved in CI projects. As previously explained, CI is built based on collaborations between scientists and technologists. Not only do scientists present a research problem to technologists, they frame the problem and imply the correct approach to address it based on their theoretical and methodological orientations. In other words, CI development is driven by the scientific problems and the theories/methodologies of the scientists involved.

Different groups of scientists often hold different approaches to and opinions of a common scientific problem. They are trained to argue and debate these differences in a competitive spirit. An administrator at a science center in California shares, "the scientific process of going to graduate school and … becoming an accredited scientist is a very cutthroat process… So people that are successful in that environment… tend to be … very good at … promoting their own approaches…" (26 January 2009). The cutthroat competition also manifests in CI projects. An administrator at a supercomputer center in Illinois recalls a revealing example:

> We've been in disputes with people essentially having two different, not quite theories, but two 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).

This observation is particularly forceful in the data. It is important because Fuchs (1992) argues that "[t]he choice between competing paradigms is not simply a choice between true and false, but one between conflicting scientific lifeforms and organization… this choice is at least partly driven by social and political forces…" (p. 152). Another social scientist in Michigan shares:

> TeraGrid has been opportunistic. That's been appropriate—you can't necessarily know what's coming down the line, so you have to jump at different opportunities as they arise… 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. It really is what kind of happened, except it was a little more subtle than that because the noisiest people are the ones that have the most prominence in the community and who are more assertive (17 March 2008).

Funding is limited, CI development is time-intensive, and many contributors work on multiple CI projects on a short-term and part-time basis. Given these conditions, contributors to CI development may overlook the ideological wars invisible to most non-scientists. Therefore, the fifth dialectical tension in the funding infrastructure of cyberinfrastructure lies in the ideologically contested terrain (Edwards 1979) among scientists with different theories and methodologies.

Through an organizational communication lens, we interpreted the key elements of salient motivations, financial compensations, explicit policies, and implicit ideologies as communication arrangements that make up the funding infrastructure of cyberinfrastructure. We explored five dialectical tensions across three levels of institutions, individuals, and ideologies that hold these arrangements together. At first glance, the tensions appear as oppositions and contradictions that need to be resolved. In the next section, we argue that these tensions are in fact necessary for cyberinfrastructure development in the early 21st century U.S.

6. Discussion

A study of dialectical tensions focuses on the ways in which oppositional forces create situations that are 'both-and' or 'either-or'. Our discussion follows Tracy (2004) and Gibbs' (2009) call to embrace the contradictions in the themes. Dialectical tensions may be the driving force for change in a system that is uncertain and evolving (Putnam 1986). Therefore, we reinterpret the tensions identified as necessary for a dynamic stability in CI development across various levels. Subterranean oppositions and contradictions capture the interdependence between the forces involved. If one ceases to exist, the remaining forces will not be able to sustain CI development.

Our aim for this article is to show that CI development is co-sustained by a range of institutions, individuals, and ideologies, as illuminated by a dialectical lens. On the institutional level, science, technology, local states, home universities, and federal agencies co sustain CI development in the same economic and policy environment. On the individual level, participants in CI development need to work for unrewarded service for today and for a secure career for tomorrow, for the virtual and for the local, for the self and the community. On the ideological level, competition between scientific groups indicates vibrancy in a field, and scientific progress depends on vibrant competitions. By involving multiple ideologies, we recognize that CI is a meta-phenomenon beyond the constraints of theoretical, methodological, and intellectual boundaries.

7. Conclusion

Our analysis reveals *how* funding affects the cyberinfrastructure foundation laid, *who* completes the work, and *what* the outcomes of the funding are. There are outcomes and implications at the three levels of analysis. At the ideological level, the implication of theoretical/methodological disputes over CI is long-term. The notion of competing groups can be understood as Ribes and Finholt's (2008) notion of 'political constituency' in 'community'. At any point in science, research can take many different directions (Latour 1988). At this point of CI development, the winning scientists get their theoretical and methodological approaches built into the design and logicistics of how CI enables science. The winning scientific approaches become the 'installed base' (Star and Bowker 2006), and a future CI tool "wrestles with the inertia of the installed base and inherits strengths and limitations from the base" (Star and Bowker 2006, p. 231). Once installed, the winning scientific approaches become "widely shared paradigmatic research practices" (Fuchs 1991, p. 296) over time and give strength to future proposals that fit this privileged base in competition with others for funding.

A conscious effort to align implicit ideologies among competing groups of scientists can begin in short-term projects in order to improve CI continuity and alignment toward ushering in long-term CI vision. One such example could be treating databases as boundary negotiating artifacts (Lee 2007) in organizing scientific collaboration (Bietz and Lee 2009). Projects can employ intentional interoperability strategies for data integration (Ribes et al. 2005) and data curation (Karasti et al. 2006) to facilitate future CI convergence and sustainability.

Furthermore, VO surrounding CI projects can serve to blur existing group boundaries. Bird et al. (2009) characterized VOs in the context of CI as non-linear, emergent, and self-organizing. By building dynamic and expanding VOs around CI projects, ideological groups may become more inclusive and ideological boundaries may become more permeable. Individual and group contributions can become self-amplifying when diverse participants build a moral community and set up a structure that in turn produces other structures (Browning et al. 1995; Browning and Shetler 2000).

At the individual level, interdisciplinary co-production between scientists and technologists is the foundation of early CI development. This implies that it may be necessary for more future scientists to become technologists and vice versa, forming what we call scientist-technologist users and technologist-scientist developers. The emergence of these hyphenated transdisciplinary individuals is important because meaningful CI development depends on effective and efficient synergy between the knowledge and skills represented by the two groups. Although it is important to have specialized scientists and technologists on CI projects, these hyphenated transdisciplinary individuals can serve as ‘glue’ between the two traditional groups.

Furthermore, as the need for hyphenated transdisciplinary individuals increases on CI projects and in universities, it may be necessary for future academics to maintain three concurrent roles: researcher/professor/technologist. The constant need to upgrade technological competence in order to conduct research (NSF 2007a) and to teach (Borgman et al. 2008) is further stimulated by rapid CI development. In order to fulfill today’s demands and adapt to environmental changes (O’Reilly and Tushman 2008; Raisch and Birkinshaw 2008), future tenure promotion criteria may include technology components as significant items. If these criteria evolve, more academics would likely increase their salient motivations towards CI development.

In the case of technologists, constantly changing activity cycles (Ballard 2008) can negatively impact CI development. When the brain is occupied by multiple separate and non-related tasks concurrently, the ability to exercise quality decision making decreases (Lehrer 2010). CI development involves sophisticated technologies and cutting-edge science. When it is based on short-term commitments and part-time attention of a distributed group of technologists, its progress is compromised. Future CI projects can reduce the impact of such an arrangement by developing a clear management structure and defined chain of commands. Perhaps scientists need to be funded to hire long-term and full-time technologists to co-produce sophisticated CI tools.

At the institutional level, funding affects CI development through federal agencies, local states, and home universities of individual scientists, technologists, and supercomputer centers. However, the vision of large-scale and big science depends on today’s CI activities (Jirotka et al. 2006). One implication is for institutions to begin encouraging joint usage of existing CI through explicit policies. This may require that funding agencies be sensitive to the simultaneous demands placed on supercomputer centers due to their multiple funding sources, including how these demands are compounded by what Zimmerman and Finholt (2008) term ‘coopertition.’

While NSF provides funding for cyberinfrastructure development in natural science and engineering, CI development is also stimulated by research activities funded by the National Institutes of Health in domains such as biomedicine (Buetow 2005; Stein 2008), public health (Contractor and Hesse 2006), and clinical research (Grethe et al. 2005) in the U.S. This observation implies another possible dialectical tension between the two distinct funding agencies. This possible tension deserves future research attention.

Finally, the interviews in this study suggest a necessary misalignment of missions and priorities within NSF between funding science or technology. This misalignment is necessary in order for cyberinfrastructure to emerge in the early 21st century science. As the need for new and more CI resources continues to increase, the criterion of 'broader impacts' can further solidify OCI as a cross-directorate and cross-disciplinary cyberinfrastructure funder for the entire scientific community. The bold symbolic version of this implication is for NSF to consider adding 'technology' to its name and, thus, become the National Science & Technology Foundation.

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