Cyberinfrastructure, Service Science, and the Role of Interdisciplines

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1 Introduction

The increasing entrenchment of cyberinfrastructure (CI) is bringing about significant change in the way the world approaches science. Now, more than ever, large scale endeavors and complex projects are becoming possible, leading scientists, institutions, and agencies to embark upon questions that were previously impossible to ask and possibly answer. Several forces are at play here, including the networked nature of computing, coordination and cooperation among academic, industrial, and governmental institutions, the realization that service delivery is a valid area of innovation, and the blurring of the boundaries between traditional disciplines. This field paper is an attempt to survey a sampling of the relevant literature to explore the ways in which information technology and frameworks of provisioning in knowledge production are relevant to the legitimacy of contemporary science within the framework of the cyberinfrastructure movement. Further, as the cyberinfrastructure movement is in its early stages as an object of development, what are options for proceeding along this path in a deliberate and constructive way?

This paper will follow a line of thought through several areas of literature. The general structure is as follows. First, I will examine general theories and definitions for infrastructure, concentrating on the canonical examples - railroads, electrical power, roadways, and the Internet. This section will include a discussion of Bowker and Star's concept of infrastructural inversion, addressing some problematics of defining a topic as expansive and complex as infrastructure. Following this, a look at the current concept of cyberinfrastructure as an extension of the traditional. What is the same, and what changes with the appending of *cyber-* to the term?

In the next section, I examine the linkages between the cyberinfrastructure movement and the emerging SSME (service science, management, and engineering) field being advanced by IBM. In their respective agendas, both CI and SSME have identified a strong need for interdisciplinary views and individuals. Service science, however, is also being cast as an interpretive framework and toolbox of methods for understanding the innovation and delivery of services. In this section, I will make the claim that cyberinfrastructure can largely be defined as an instance of service science.

To expand upon the need for interdisciplinary development in CI, I will then turn to Scott Page's forthcoming book, The Difference: How the Power of Diversity Creates Better Groups, Firms, Schools, and Societies. After making a case moving from the logic of diversity (Page's argument) to a logic of interdisciplinarity (hinted at, but only mentioned in two passages in the book), I will draw on the interdisciplinary studies work of Lisa Lattuca, Julie Klein, Veronica Boix Mansilla, and Howard Gardner as positive examples and explore some criteria and interpretive frameworks of inter- and trans-disciplinary science put forth by Michael Gibbons and Helga Nowotny.

The next section will commence with an argument that in order to achieve interdisciplinary synthesis, we must begin with language. A brief discussion of the typical model of moving from pidgin to creole will occur, contrasted by a discussion of Christopher Alexander's concept of a pattern language. The pattern language idea has moved out of the architectural realm in recent years, and has been applied to advances in computer science, public health, public policy, international development, education and learning management, social activism, business, etc. I will provide a number of these examples of how pattern language development has been engaged in various disciplinary initiatives, and how it may be of benefit to the cyberinfrastructure movement. The section will wrap up the thoughts in the preceding sections by grounding the ideas in James Scott's observations about how many large-scale endeavors to "improve the human condition" have failed in catastrophic ways, a cautionary for a heady project like cyberinfrastructure.

Finally, I will offer four dissertation ideas under development on

- Exploring possible tensions in the political ecology of constructing legitimate science at the NSF Office of Cyberinfrastructure
- A historiographic analysis of nineteenth and twentieth century paradigms that are embedded in the cyberinfrastructure movement
- Representing the advance of cyberinfrastructure enrollment as an "ecology of games" with a focus on agent-based modeling and organizational complexity
- Comparative study of lexicon development in cyberinfrastructure and eScience environments using the pidgin-creole and pattern language models

The drive behind these proposed questions is a desire to contribute to a greater understanding of science policy, the reconstruction of science in a networked environment, the new (political?) lines of inclusion and exclusion represented by cyberinfrastructure and service, and what this may mean for the legitimate roles of science, technology, and disciplines in a new era of research and knowledge production.

2 Infrastructure and Cyberinfrastructure

2.1 Assembling What Lies Beneath

The complicated, ever-present systems that undergird the operational existence of society have come to be studied as "infrastructure", a compound of the Latin *infra-*, meaning "below" and *structus* or *struere*, meaning "to build or assemble[1]." There are several accounts for the introduction of the term, some claiming its use in 19^{th} century France and others marking 1927, when the American military culture began to use the term to describe the interconnection of roadways, electrical resources, waterways, etc. Despite the origins, the term generally refers to the heterogeneous interconnection of systems that support the fluidity of services and interactions that are the attention of everyday matters. It is because of this supporting nature that the *infra-* tag is important. Infrastructure lies below the attention of those who use it. It is typically transparent, only becoming visible when it does not function properly. There are several canonical pieces describing the development of infrastructure, which I will briefly outline. One of the most concise and well-formed is found in the section entitled *Dynamics* in a recent report to the National Science Foundation on Understanding Infrastructure: Dynamics, Tensions, Design [47]. I will mention the main points, but leave the fleshed-out description to the report, rather than recreating it in entirety here.

The history of infrastructure draws from many examples ranging from the expansive and impressive sewer systems in Paris [84], to the HAFRABA Association's plans for a German Autobahn that was realized by Hitler [118][119], to the rise of railways [58], electrical power [60][70], and telephone/telegraph systems [59] in the United States [18]. More recently, the compelling infrastructure story has been told around the development and adoption of the Internet [1]. The earlier descriptions of infrastructure growth, especially those told by Friedlander, comment that historical U.S. infrastructures have grown with substantial private and government subsidization, and often with governmental regulation. Even modern infrastructure stories, particularly those from the literature on megaprojects[2] [6][54], include the political tensions of funding and coordinating large-scale public goods development. Curiously, the story of the Internet, while still rife with politics, government investment in the early stages of ARPANET and NSFNET, and attempts at regulation (as seen with the recent controversy over net neutrality), does not have the same spectre of ongoing centralized governance hovering over its advance.

Despite these differences, historians, philosophers, and sociologists of science and

[1]From the 2006 Random House Unabridged Dictionary

[2]Megaprojects, according to Bent Flyvbjerg, a leading scholar in the area, are infrastructure projects that typically cost more than US$1 billion, and are usually public goods such as bridges, tunnels, transnational thoroughfares, toll collection systems, etc. Flyvbjerg shows evidence that most megaprojects are of substantial risk and have a high incidence of failure, especially in terms of budget control and timelines.

technology have come to describe commonalities of what we identify as infrastructure. Susan Leigh Star and Karen Ruhleder have outlined a list of attributes found in infrastructures [116]. Specifically:

Embeddedness: Infrastructure is sunk into, inside of, other structures, social arrangements, and technologies.

Transparency: Infrastructure is transparent to use in the sense that it does not have to be reinvented each time or assembled for each task, but invisibly supports those tasks.

Reach or scope: This may be either spatial or temporal – infrastructure has reach beyond a single event or one-site practice.

Learned as a part of membership: The taken-for-grantedness of artifacts and organizational arrangements is a sine qua non of membership in a community of practice. Strangers and outsiders encounter infrastructure as a target object to be learned about. New participants acquire a naturalized familiarity with its objects as they become members.

Links with conventions of practice: Infrastructure both shapes and is shaped by the conventions of a community of practice; for example, the ways that cycles of day-night work are affected and affect electrical power rates and needs. Generations of typists have leaned the QWERTY keyboard; its limitations are inherited by the computer keyboard and thence by the design of today's computer furniture.

Embodiment of standards: Modified by scope and often by conflicting conventions, infrastructure takes on transparency by plugging into other infrastructures and tools in a standardized fashion.

Built on an installed base: Infrastructure does not grow de novo; it wrestles with the inertia of the installed base and inherits strengths and limitations from that base. Optical fibers run along old railroad lines, new systems are designed for backward compatibility, and failing to account for these constraints may be fatal or distorting to new development processes.

Becomes visible upon breakdown: The normally invisible quality of working infrastructure becomes visible when it breaks; the server is down, the bridge washes out, there is a power blackout. Even when there are backup mechanisms or procedures, their existence further highlights the new visible infrastructure.

Is fixed in modular increments, not all at once or globally: Because infrastructure is big, layered, and complex, and because it means different things locally, it is never changed form above. Changes take time and negotiation, and adjustment with other aspects of the systems involved.

It is with these defining attributes of infrastructure that we move forward. Of course, there is no guarantee (or implication, for that matter) that this list is exhaustive. As we study and understand infrastructure further, more patterns and interpretations may emerge.

2.2 Systems and Hughes' LTS View

Thomas Parke Hughes, historian and sociologist of science, is arguably one of the most prominent figures in generating widely-accepted theories concerning infrastructure and its rise. Hughes cast the growth of infrastructure not as a grand scheme that is conceptualized from the outset; rather, he described the local and entrepreneurial construction of *systems* that, over time, are assembled into larger systems, networks, and networks of networks (or *internetworks*, to employ a phrase used by Paul Edwards[3]). In Hughes' view, systems are differentiated from innovation or inventions by the fact that they are constructed to deliver a *service* rather than a *function*. A primary example is the attribution of the lighting system created by Thomas Edison [71]. While others had already invented the light bulb, Edison was the first to consider not only the immediate effects of the bulb, but the larger set of innovations that were required to deliver not just light, but the service of lighting (transformers, cables, power supplies, etc.) Systems are conceived and constructed, then, by a *system builder* who is entrepreneurial in nature. Thus, Hughes provided both an actor and a mode of agency to the construction of infrastructure or, as Hughes' theory has come to be known, LTS or Large Technical Systems.

The pattern of infrastructure development described by Hughes follows a proscribed path as follows [70].

1. *Invention* – At the basic level, the fundamental elements that are to be later assembled must be built. Typically, this is at the level of the individual technology (i.e., the light bulb).

2. *Development* – Still at the level of the individual technology, the efficiency and design are refined.

3. *Innovation* – This is the point at which the system builder/entrepreneur conceives a wider application and the systemic requirements that must be assembled to construct a locally-working instantiation.

[3] An excellent point was made by Marianne Ryan of the University of Michigan School of Information on March 28, 2006, regarding the systems/networks/internetworks view of infrastructure. Specifically, she cautioned that these terms are structural, whereas infrastructure itself is functional. While the structural terms are quite helpful in demarcating the historical periods in the growth of infrastructure, these transition points should become blurred, seamless, transparent, and largely irrelevant once an infrastructure reaches the point when it is working properly. By extension, we may also ask whether these terms are only useful in historical analysis of infrastructure, or if they may assist in the ongoing dialogue of infrastructural inversion.

4. *Technology transfer* – After one successful copy is created, the system must be able to survive in other environments. Since the context varies, adoption after transfer leads to changes in the system that allow contextual adaptation (and, arguably, systemic robustness).

5. *Growth* – When a large enough number of separate installations exist, standardization takes place. The system can be recreated with less overhead and cost of making mistakes.

6. *Competition* – Separate systems of standards emerge and vie for dominance in supplying the system.

7. *Consolidation* – The differentiated market tends toward either monopoly or oligopoly structure and standardization achieves a certain measure of closure. From here, systems (or in further cycles, networks) can be linked to scale up toward working infrastructure.

Edwards points out that the diffusion and adoption rates of these large technical systems follow a typical S-shaped curve [47, excerpted from Grübler and Nakâcenoviâk 1991]. Other LTS scholars, though, suspect that this may be an overly deterministic view, and that later phases of infrastructure building may be punctuated periods of equilibrium and disequilibrium [117][120].

Not to be missed in Hughes' estimation of large technical systems, nor to be betrayed by the privilege given by the term's focus on the technical, there are undoubtably social aspects to infrastructure. As pointed out by Erik van der Vleuten, in reference to Hughes' 1987 article,

> Another original LTS argument that is still important is that technical infrastructure elements are increasingly intertwined with non-technical ones [70]. In the establishment phase(s) technical designs are adapted and coupled to an actor playing field, organization structures, marketing strategies, legal frameworks etc; in the expansion phase such sociotechnical intertwinement is further strengthened to the degree that technical and non-technical elements interlock and make the whole thing difficult to change [121].

Based on this interpretation, it may be more prudent to think of Hughes' view on infrastructure as Large Sociotechnical Systems, not just built for actors to use, but to incorporate them into the structure itself.

2.3 Standards and Gateways

As systems become networks, interoperability becomes a critical concern [31]. Since systems change and adapt during the technology transfer process, they may become incompatible as they stand when a link is attempted. To solve this problem, two solutions are developed and may work separately, or in tandem, to promote this interoperability. First, standards are agreed-upon sets of specifications in design. Examples of standards include the Stephenson gauge in railway construction [100], communication and scheduling in the train industry [133], the convergence to a 120 volt current in the United States [71], and information technology specifications such as the MPEG-2 codec suite [21]. Gateways are specific tools used to bridge systems. Examples of gateways include plug and socket adapters of all sorts (AC/DC electrical converters, USB and Firewire, DVI and VGA), platform-independent software development environments, and web ontology languages. Egyedi describes the role of standards and gateways in maintaining flexibility in infrastructural development [48]. Specifically, she claims that the extent to which an infrastructure remains flexible is determined by the standardization of the gateways that exist. To this end, Egyedi presents a hierarchy with examples of standardized gateways.

Deg. of Standardization	**Scope of Gateway**	**Examples**
High (modeled)	Meta-generic	OSI
Medium (standardized)	Generic	XML, Java, ISO container
Low ("improvised")	Dedicated	AC/DC rotary converter

Table 1: Relationship between degree of standardization and scope of gateway solution (from Egyedi 2001)

Standards themselves, though, are not without their own politics and struggles. Egyedi, in addition to Hughes, points out that standards undergo competitive processes and wrestle for dominance. Of course, those who have a stake in the entrenchment of a particular standard will fight to establish it, for adoption of a competing standard means loss of investment. Feng describes two major themes in standards adoption [50]. First, standards may fall into an *ideology of circulation*, which promotes the transfer of standards by acting as a lubricant of network efficiency. The underlying premise here is that standards exist to serve the greater enablement of those who use infrastructure. The opposing ideology, the *ideology of power*, recognizes that standards may be emblematic of hegemony, giving privilege to some and excluding others. This view of standards may be interpreted as one type of *infrastructural orphan* described by Leigh Star (though her primary purpose in describing orphans is to bring attention not to vested parties that stand to profit, but to those who are excluded from the ideology of circulation[4]).

[4]While publications on this concept are as yet forthcoming, Star spoke of this idea at the History and Theory of Infrastructure workshop, as well as delivered a December 2006 lecture entitled "Orphans of Infrastructure: Engendering, Commodifying, and the Making of Non-People."

2.4 Reverse Salients

When major breakthroughs are made, it is not uncommon to look back and see that several innovators made the same discovery at roughly the same time, though it is clear that there was no communication among them. This has given rise to the concept of "an idea whose time has come." Still, there is no mechanism in the aphorism to explain why this happens. For instance, the method to measure the parallax of a star was discovered in 1838 by three independent scholars, Bessel, Struve, and Henderson, each working independently and without knowledge of the others' work [86]. Science and technology studies are filled with similar phenomena.

Hughes addressed this problem with the first plausible and non-mystical explanation [70][71]. The idea of the *reverse salient* was drawn from a military examples, where the advancing line of soldiers is held back at one point. Another apt metaphor for reverse salience is that of moving a rubber band across a piece of wood with a nail sticking out. The band remains straight until the nail is encountered, but when the band snags on the nail and the edges of the band keep advancing, tension builds at the point of the snag until something gives (in physical terms, this would usually be the rubber band snapping, but for our purposes, let us assume that the band is indestructible and can pull the nail out of the board.) Suddenly, the band snaps back into place. Hughes' explanation was that apt and savvy innovators can sense this growing tension in systems, and know where to look for new ideas. Then, he believed, it stood to reason that several people, all sensing an opportunity and working on similar problems, would produce solutions in a relatively short time frame.

The reverse salient is the explanation for the realization of technologies (both human and non-human, social as well as mechanical) that appear to allow systems to grow, connect, and advance. Through Hughes' explanation, we can provisionally understand how and why infrastructure slowly assembles as the need for coordination scales upward.

2.5 Path Dependence and Determinism

[5] When we speak of standards, gateways, reverse salients, and more generally, the history of infrastructure, we cannot escape the clear role of temporality and sequence. Decisions made early cascade into later decisions, both in limiting and enabling terms. This speaks directly toward Egyedi's focus on the need for gateway flexibility [48]. In the study of infrastructure, the issue of standardization is key to gaining an appreciation for the ways in which heterogeneous systems of processes interface to form a larger, working whole. On the technical side, standards work to promote interoperability, linking together various technologies and innovations. Additionally, scholarship has made a strong case that standards are also a field to be studied socially,

[5] In the interest of disclosure, a significant portion of my discussion on path dependence is taken directly from a short paper I wrote in a Winter 2006 course entitled "Systems, Networks, and Webs: The History and Theory of Infrastructure."

involving issues of information dispersion or diffusion, enrollment, and communities of practice [14][55][128]. In both cases, attention is paid to the histories of standards emergence. The antecedent events to the formation of a standard are widely considered to be the basis for causal explanations. Further, historical analysis and rich description of the various political, social, and technological events leading to infrastructure are considered by some a foundation for determining a causal path [89].

In terms of standards emergence, economists Paul David and Scott Page use the development of the QWERTY keyboard standard as emblematic of their respective theories in path dependence. The main point on which they differ, however, is the necessity of event ordering in describing that path dependence. It is non-trivial to note that both perspectives are strongly based in the neoclassical economics perspective, which may have significant departure from purely qualitative accounts of historical events, imparting causality through proof. That is to say, economic explanations often imply "it makes sense that things have unfolded this way, because they are axiomatically consistent," as opposed to narrative accounts of "it seems that event X precipitated events $X + n$." Page in particular raises interesting and counterintuitive points about situations in which the existence of events matter, but not always their particular order. To be clear from the onset, I am not advancing the idea that historical analysis' claim that specific events or episodes do not have effect on the subsequent ones at all; however, I make the claim that there may be vignettes or periods in infrastructure stories where tipping points occur, and during those periods, the ordering of events is not the focus of the narrowly defined path dependence.

The functionality of standards in building and maintaining infrastructure are many. Patrick Feng provides five specific purposes for standards-setting [50]. Of the five functions of standards, two are oriented toward technical goals (uniformity in production and compatibility in technologies), two are social (standards as justice and standards as hegemony), and one a hybrid (objectivity in measurement). As I will explain, the interpretation of path dependence is strongly influential in advancing the understanding of standards in both social and technological frames, and by extension, infrastructure.

Paul David, Oxford economist and one of the most persuasive advocates of path dependence, has provided ample explanation regarding the standardization of the QWERTY keyboard. He asserts that the history of development, and the specific order of events in which QWERTY was diffused through the population is a necessary condition for its entrenchment as a dominant standard [29]. In the ensuing years, many have reacted to David's assertion that history is the driving force behind the economic development of standards "lock-in" as a concept. In response, he clarifies by defining his terms in a less qualitative way, turning to both positive and negative externality explanations, describing path dependence as an ergodic process[6] [30].

[6] For clarification, an ergodic process is a positive recurrent aperiodic state of stochastic systems; tending in probability to a limiting form that is independent of the initial conditions. That is to

What, specifically, does this mean with respect to standardization and history? First, an explanation of David's theory. Using the QWERTY example, David readily admits that the empirical evidence regarding keyboard layout suggests that QWERTY is not, in fact, the most efficient design. This is in direct conflict with standard economic theory, which assumes that the utility maximization equilibrium is achieved by the most efficient or highest quality solution. The Dvorak Simplified Keyboard (DSK) consistently is shown to be superior in terms of typing speed and user accuracy. Why, then, is it not the standard? David tells a tale based on positive externality and network effects of technology adoption and standardization. With aggressive marketing campaigns, the QWERTY keyboard was introduced to the population through typing competitions showing that they layout was superior with respect to other existing solutions at the time. This, of course, was largely a function of the physical characteristics of the technology. Since manual typewriters were dependent on metal arms moving upward to strike the paper, a fast typist would find that the arms would hit one another and she must slow down in order to work the machine properly – a less than efficient solution, and according to economic theory, a non-equilibrium point. QWERTY, at the time, provided the least mechanical problem, since the layout provided the most distance between arms of the most commonly typed letters, thus minimizing mechanical problems. Further, there were marketing tricks achieved by QWERTY; namely, the word TYPEWRITER could be typed without removing one's fingers from the top row. This gave the impression to buyers that the QWERTY keyboard was the superior product. Now, back to the network effects argument. Once typists were trained in the QWERTY system, a company who had a battery of trained typists would experience standards "lock-in" – a state where the transaction costs of switching to another product are higher than the perceived long-run gains that the new technology would bring. This network effect worked from both sides – the employer and the employee. Employers would experience a dip in productivity during a period of training in another typing system, as well as incur the cost of replacing physical equipment. Job seekers who were called upon to type were most likely to market QWERTY typing skills over other systems, since the companies had invested heavily in QWERTY equipment, thus there was little to no incentive to pursue training on other systems, since they were unlikely to be encountered in the work environment. David argues that the convergence of these externalities, and the diffusion patterns of the QWERTY keyboard form a historical path upon which the standard is based. With respect to defining this convergence as an ergodic process, the strict definition also implies a certain level of technological determinism. This is unsurprising, since modern economics as a field is defined primarily by deterministic equation modeling.

It is clear that David believes that in the matter of standards and infrastructure,

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say, it makes little difference what the initial state of a system is. The convergence of probabilities based upon history iteratively narrows the choice set of future interactions, and eventually becomes a single path by which one may travel. Is this not the essence of determinism?

history matters. He does admit that there may be other externalities that influence the path dependence of a standard; however, his rhetoric indicates that historical order is the most influential when viewed through the lens of transaction cost economics and a focus on positive externalities.

In David 1997, he issues a challenge to the academic community, stating that no one has offered a clear explanation or set of definitions that suggest anything other than the strict view that history matters and that path dependence is strictly ergodic. Scott Page – economist, political scientist, and complex systems theorist at the University of Michigan – has taken up this charge and offered an alternative explanation to the strict ordering of historical events in the story of path dependence and standards emergence [97]. While Page does not refute the idea that history matters at all, he takes issue with the idea that all events must happen in a specific order. He defines another possibility, *phat* dependence [7].

Page makes the distinction between different types of processes. The exemplars chosen by David are typically *Bernoulli* processes - which are by nature ergodic. On the micro-level of interaction, many processes follow a non-ergodic *Polya* process, by which the independence of a long-range set of events is in question. This differentiation brings forth the idea that there may be different levels of analysis that may be applied to history, and that this is significant with respect to interpretation. As Page states, "Even though the Polya Process is only phat dependent, this does not imply that the real world situations it has been used to describe do not depend on the order of the path. Those are, of course, empirical questions. Evidence tilts strongly in favor of both types of dependence."

According to Page, the root causes of path dependence lie not within positive externality; rather, the negative externalities promote the path, and positive externalities only exaggerate the aggregate effects. Negative externalities, in fact, cause historical dependence. Page argues, again through the case of the QWERTY keyboard standard, to suppose that there is another competing design, ZRJSOC. He shows through a series of examples that in a differentiated market (which we shall assume exists, both in the typewriter examples, and in the markets supplying the component systems for building infrastructure), individual consumer choices in adopting standardized technologies may be the source of positive externalities for the choice made, but do not in fact generate negative externalities for substitutable products. That is to say, if one can make multiple choices, choosing a QWERTY device may raise the value of all those owning them, but it does not lower the intrinsic value of the ZRJSOC device. If two technologies are sufficiently competitive, buyer will end up buying both in the long run. This leads us to the fact that negative externalities, which create history dependence (developed on pp 30-31 of Page's article, but not repeated here) are the precursors of constraints – the harbingers of infrastructural

[7] Phat dependence is related to, but not the same as path dependence. The name is a clever rearrangement of the letters in the word *path*, indicating that history matters, but the order may not always.

convergence. As Page points out,

> Any large public decision, be it a prison or university takes up space and requires money. Both create negative externalities with future public projects. Obviously, the more money and space a project demands, the greater its impact on the path. Small projects are less likely to influence the path of history than are large projects. That is not to say that smaller decisions cannot accumulate over time and restrict history to certain paths, but that any big project crowds out other projects.

David and Page present theories of standards development that are, in fact, highly compatible. More to the point, Page is careful not to directly discredit David's highly entrenched (though hotly debated) view of path dependence. Both theories claim that history does matter when assigning causality to large scale phenomena - those that are adequately described as Bernoulli processes. They agree that the state dependence of a standard is a matter of the states that came before it; however, the road taken to that path, the process, may have variance. As Page posits, "For obvious reasons, these processes generate history dependent outcomes. the history determines the state and the state in turn determines the distribution over outcomes." Adhering to the definition of an ergodic process, if the probability distribution over this set of outcomes becomes sufficiently narrow, path dependence is the result. If a wider distribution is observed, a case for phat dependence may be mounted.

At its core, the implied and largely unstated difference between the two theories lies in the level of scale in forming an analysis. In the case of QWERTY, David concentrates on standardization as a stationary, ergodic state dependent process. Each preceding episode of entrenchment of the QWERTY design generated strong positive externalities, with the aggregate effect generating negative externalities, not for other designs, but for the industries and firms (both traditional firms, and the job-seeking workforce that must make itself marketable) as a function of limited resources (capital to invest in design-specific equipment, and time and effort for learning a system, respectively.) As Page points out, on the individual level, the advancement of QWERTY did not generate negative externalities for other designs themselves, and consequently, the sequence of adoption of the QWERTY standard over others was relatively inconsequential at the micro-level. It was not until the network effect of QWERTY had reached a sufficiently large level that path dependence was a certainty. This is the foundation of David's argument, in which the aggregate (and correct at this level of scale) observation that positive externalities drove the closure of the QWERTY standard. David, however, may be erroneously assuming that these same positive externalities were the driving factor in adoption at the individual level. Page makes a convincing case that this is not the entire story. Not surprisingly, this is quite in line with the standard "complex systems" point of view – that micro-level interactions (without negative externalities) lead to macro-structures with emergent properties (clearly identifiable negative externalities.)

How, then, can these concepts of path and phat dependence be extended to inform the role of standards development in the field of technological infrastructure? One example can be found in the study of technological innovation as viewed through the patent literature. Most technologies created in the modern era are composite technologies, comprised of patents held by a range of firms. For example, MPEG-2 technology, used in the encoding and decoding of video and audio, is the standard used in creating a number of devices (VCR, DVD, MP3 players, media applications, etc.) This standard, administered by the MPEG-LA group, was defined by identifying the essential nonsubstitutable patents required to execute the technology. Was the evolution of the MPEG standard path or phat dependent? Of particular relevance is that a patent pool was formed around the MPEG standard, giving legitimacy to the standard by creating positive externalities for those who hold patents in the pool license portfolio, and negative externalities for those who do not, and for consumers who own technologies that do not incorporate the standard. In this sense, the emergence of the MPEG standard would seem to fit well with David's path dependent theory. Looking at the micro-level history of the standard formation, Page's theory of phat dependence may also prove to be informing.

Carl Shapiro hypothesized the existence of patent thickets - areas of high density in patent space where cross-citation is particularly heavy, denoting the inter-relatedness of innovation in a particular area [108]. It has been shown that standards and patent pools tend to form within existing patent thickets [22]. Since a patent pool is dependent upon a standard of technologies against which essentiality may be evaluated objectively, we can turn to the emergence of the patent thicket to see the nature of path dependence in the area of innovation. For example, if an eventual technology that forms a patent pool contains, say, 15 essential patents (which, given the history of pool development, are culled from a larger number of highly related patented technologies, i.e., a thicket. The MPEG patent pool contains 65 patents; however, these were culled from the inspection of over 800 patents submitted for evaluation), does the order in which the last three (or any number. I have chosen three for the sake of argument) are invented matter?

According to Shapiro, the criterion for defining a patent thicket lies only in the recognition of a dense area in the patent space. Research is currently being conducted to measure the minimum density by which one may identify thickets [23]. Assuming that this minimum density can be identified, a standard may be formed around the emerging technology. It does not matter in what order the essential patents were invented and filed, since the formation of the standard is only started when the recognition of this density occurs. In this case, the formation of the standard is a non-ergodic process, as the paths which gave rise to a number of the component technologies are likely not co-dependent. Further, once the standard is developed, the remaining three pieces of technology required to construct the device are likely to be created quickly. Why, one is tempted to ask? Here we can return to Hughes' concept of the reverse salient. Given that the standard exists, and enterprising innovators will be able to clearly see which aspects of the technology standard are unfulfilled, they will fill in the needed gaps, and the order in which these patents are filed may again not matter. This is not to say that several innovators will not create solutions that are redundant or substitutable; however, the formation of a patent pool around a standard disallows the inclusion of substitutable components. Thus, the patent pool itself may be path dependent, but the formation of the standard on which it is based is likely phat dependent, as may be the evolution of the composite technology itself.

As it would seem, the process begins as non-ergodic, enters a period of ergodicity around the time of standard-setting, and may or may not enter another period of lower-level ergodicity until convergence, but this latter period does not undo the effects of the middle period (aligned with the observations made by van der Vleuten and Summerton). This, of course, is speculation. Research in this area may concentrate on the timelines upon which a particular thicket is identified, essential patents are filed, and a composite technology comes to bear.

In the end, it is clear; history does matter. The extent to which it matters, though, is a question of the level of scale at which historical analysis is conducted. It is indeed unnerving, especially to historians, to think that the sequence of events are not the root of causality. This fear is not unfounded, and economic theory supports this principle in many, if not most cases. On counterpoint, once the level of analysis focuses on sufficiently short term, small, or individual histories, Page's concept of phat dependence gains traction. As an analogy, this differentiation between large scale Bernoulli processes and small scale Polya processes may be mirrored by the differences between classical Newtonian physics and the later recognition and adoption of quantum physics. The simplicity of the classical approach holds and is accurate when looking at phenomena at a sufficiently large scale, but these rules do not perform as expected when observing elementary particles. So it may be with path dependence in the economics of standards. Traditional historical analysis is quite accurate in assigning causality through the observation of sequence, but when aggregating microlevel phenomena, such as individual consumer choices, these same assumptions of sequence causality may not be as persuasive. In short, telling the story of standards development, and their eventual role in the construction of infrastructure, may require a blending of both types of dependence, path and phat.

In terms of determinism, historical economics provides a strong argument that once a certain level of enrollment is achieved, the constraints generated by negative externalities may be quite causal in directing development along a certain path. For those who are forward-looking enough, predictions about the eventuality of infrastructural forms may be more accurate, and decisions may be made regarding whether this is a sufficiently optimal outcome, or whether changes need to be made early on, before the onset of lock-in. Path dependence seems to be a moderately strong statement of determinism, while phat dependence, claiming that outcomes are independent of sequence or initial conditions, points toward undeniably strong deterministic interpretations. It remains to be seen whether this is problematic for scholarly communities;

however, it casts a shadow of doubt over those arguments that reject determinism outright.

2.6 Infrastructure as a Term Without Closure

The academic study of infrastructure tends to use historical examples. Infrastructures are identified after they have become ubiquitous. While they may not have achieved closure of the systems involved, they must achieve a certain level of stability to gain transparency. Still, they shift, grow, and take on new meanings as other systems are built and changed around them, and ultimately connect to them in new ways. Bowker and Star provide one of the field's most concise and well-used descriptions of analyzing infrastructure and making the transparent visible. It bears discussion, though, that there are limitations to any lens for examining infrastructure. For a target that is constantly shifting and of such sprawling complexity, any tool bears periodic examination. Following is a reaction to the first chapter of Sorting Things Out: Classification and Its Consequences. [15]. While the discussion raises more questions than it could possibly hope to answer, the hopeful point to be made is that open questions remain and any framework for looking at infrastructure can be a contested tool.

This opening chapter of Bowker and Star's book on infrastructure introduces the concept of infrastructural inversion as a technique for understanding and analyzing the complexity of infrastructure. The title of the chapter, "Tricks of the Trade," implies that there are lessons learned in constructing useful stories of infrastructure; however, there seem to be more than tricks at work. Rather, there are several theories and models that come together.

The first point made is that good information infrastructure is invisible, forgotten, or transparent to the user. It is unclear whether this is simply a characteristic of good design, or that it is beyond the routine cognitive abilities of people to hold such complex structures in mind (or whether it is useful to do so...getting into the Heideggerian tool-being dichotomy [66][67].) The first paragraph indicates that unless we have reason to consider the nature of the infrastructure itself, issues of scale related to defining the boundaries of an infrastructure make it inefficient to consider the totality of the system. At the bottom of the page, the authors mention "we can achieve a deeper understanding of how it is that individuals and communities meet infrastructure." Is this to say that individuals are separate from infrastructure, or that communities are not examples of social infrastructure[8] (or that social infrastructures are different from other information or technological infrastructures?) The next page makes a statement which does not bear out by the end of the chapter. Specifically, the authors claim that infrastructural inversion is not simply descriptive, but exposes the

[8]This is, of course, making the assumption that the idea of infrastructure can be extended to human or social systems, or systems that rely on both in chains. This interpretation would be consistent with the Latourian description of human-technology chains in systems [82].

causal factors in the operation of systems. Looking at the list of attributes that define infrastructure, none address causality directly. For convenience, a recapitulation with a few interjected notes, infrastructural attributes are:

- *Embeddedness:* How do we measure embeddedness? At what threshold is an element or system" embedded enough," and what purchase do we gain by saying it is so?
- *Transparency:* Infrastructure is never transparent to everyone at all times. Actors can concurrently embody multiple roles, and the electrician who uses a television at home and also repairs power lines cannot be assumed to be aware of electrical infrastructure in one situation and not in the other. It is possible that transparency can only be claimed contextually or temporally.
- *Reach or Scope:* This is defined by Bowker and Star as spatial or temporal. Are there any other ways to define scope that would be helpful?
  - Economic
  - Speed (in terms of bitrate transfers within technological networks or diffusion rates of diseases)
  - Physical properties of materials (such as hydrophobic and hydrophilic properties within protein infrastructures)
- *Learned as a part of membership:* This crosses over with Etienne Wenger's descriptions of communities of practice and legitimate peripheral participation [128], as mentioned in the original; research on virtual environments shows that this process of learning is not completely understood, and that implicit social structures can be transmitted quickly through decentralized means [80].
- *Links with conventions of practice:* Could this be in line with Karl Weick's theory of enactment [127]? Various other theories of organizational routines?
- *Embodiment of standards:* Even standards are a tricky and shifting platform upon which to stand, as shown by Forster and King discussing standards in the air cargo industry. The caution is well-deserved in stating that standards must be generated below the level of the work, or else contend with significant organizational and work culture barriers [57].
- *Built on an installed base:* This indicates that history is important. Is the nature of infrastructure path dependent [29], or phat dependent [97]?
- *Becomes visible upon breakdown:* or, clearly, upon infrastructural inversion, or in the case of cyberinfrastructure, when it is the constant object of discussion.

- *Is fixed in modular increments, not all at once or globally:* But how do we discern the proper units of scale or aggregation for analysis? These choices, in themselves, are constraining in interpreting and telling infrastructure stories. This also seems to indicate that it is not useful to understand infrastructure as a "snapshot" and that infrastructure is about process - following information or resources through the network to see where they go. This is descriptive of propagating and/or causal effects. Is this where the causal argument is being made? If so, it is not explicit.

The example of infrastructural concerns that used the infrequency of unusually long concerts is engaging. Why are full performances of Wagner's Ring Cycle difficult to produce, save the simple fact that it is difficult for performers? The same argument applies to unusually short concerts. No one would pay for parking, nor would a performance house likely rent out space for a 15-minute piece. Can it be said that in order for infrastructure to work well and efficiently, there is a "sweet spot" or, in economic parlance, "bliss point" for resources? Incidents that are outside of this sweet spot are the ones which tend to make us sit up and take notice. Spectacle is always – spectacular. It is a matter of concern (in the Latourian sense [83]) when we see a staging of the Ring Cycle, or an art installation that is larger than life. Are we in awe of the art, or in awe of the infrastructure that has become highlighted? The comment regarding the fact that the size of doorways in museums and galleries are an infrastructural limitation of art installations, and "These constraints are mutable only at great cost, and artists must always consider these before violating them." Now that digital art is gaining ground, these traditional infrastructural constraints seem to fade in relevance, making way for an entirely new set of infrastructure and attendant enablements and constraints.

A subproperty of ubiquity is interdependence. While this makes sense in a practical way, it does not follow from the preceding sentences, "This categorical saturation furthermore forms a complex web. Although it is possible to pull out a single classification scheme or standard for reference purposes, in reality none of them stand alone." The implication from the statement, as given, is that all things that are interdependent are ubiquitous. This is simply not true. It would seem that the opposite is really what the authors are trying to say. That is, that all things that are ubiquitous are interdependent. Even this is not necessarily true. Either way, it seems only reasonable to say that ubiquity and interdependence are correlated - and that they seem to be strongly correlated in the case of infrastructure, possibly enough to suggest causality, but the simple argument put forth is not enough to establish this link. Further on page 38, the "in between" spaces are discussed – the places between established standards and the undefined or undefinable parts of infrastructural modularity. What really happens here? Are these the domain of ad hoc behaviors? How does this operate? Infrastructure works, so these ad hoc methods must work as well. This phenomenon seems like a prime target of research. Fertile ground for developing theories. The last sentences on the page, "It is a struggle to step back from this complexity and think about the issues of ubiquity rather than try to trace the myriad connections in any one case. The ubiquity of classifications and standards is curiously difficult to see, as we are quite schooled in ignoring both, for a variety of interesting reasons." This sounds more akin to philosophy than science. To reground in science, the explanation offered is aligned with Russell's views in "The Cost Structure of Sensemaking," suggesting that these unexplored spaces and difficulties in mastering the complexity carry too high a cost in assimilating the conceptual residue in our current understanding of infrastructure [103].

The discussion of materiality and texture makes some good points, but may be limited in requiring classifications and standards to have a physical component. Specifically, in <u>On the Origin of Objects</u>, Brian Cantwell Smith puts forth the idea that ontologies (which are undeniably systems of classification and standardization) are not anchored to the physical constancy of objects, and are in persistent states of flux, constructed from multiple stances of interpretation, each correct in its own right [113]. Materiality and texture are attributes of physical systems of which we consistently make use in constructing classifications and standards, but they are by no means necessary and/or sufficient conditions for a working ontology. "When we think of classifications and standards as both material and symbolic, we adapt a set of tools not usually applied to them." Are there cases where this is not useful? This section invokes an ANT approach to explaining infrastructure, which is anti-theoretical. Is this helpful?

The section on indeterminacy of the past strongly implies "remediation" and "postdictive interpretation." Again, anti-theoretical in the sense that if postdiction is the interpretive lens, a theory of infrastructure would not satisfy the often-adopted requirement that theory be predictive [102]. The passage goes on to comment on multiple voices and silences. This is reminiscent of Kuhn's observation that in order for theory to progress, we must disavow and forget previous theoretical explanations [79]. In parallel, in order to embrace a new, more robust classification system, we must also forget the previous classification, denouncing it as archaic. This is not so easily done when the infrastructure is ubiquitous and the cost of shifting high. For example, the Dewey Decimal System is still entrenched in today's library classification structures, where psychology remains a subclassification of philosophy and unrelated to the natural sciences; curious in an age when the academic practice of psychology research is firmly rooted in the tradition of mainstream (and traditional) practices of scientific method.

The next section exposes my clear tendency toward using the most recent classification systems to interpret phenomena. The example of classification of English, Irish, Scots, French, etc. in an age that had no concept of "national genius" seems refutable. If there is available data to prove that factions developed along these nationalistic lines, the argument that the peoples involved were unaware of the delineations loses salience, regardless of whether the language to describe the factions existed at the time. Very often in clustering or sorting, we know the attributes in order to discern objects before we have decided the names of the bins in which we place them. The phenomena persist. In a similar vein, the rise of "revolution' through Marx's writings does not nullify the fact that revolution existed before Marx's observations. Revolution is a purely postdictive interpretation. How does one realize that one is in the middle of revolution, or when it will end? Arguably, the world is in a constant state of revolution, so creating classifications to aggregate historical events in an interpretable way is a useful tool, whether anachronistic or not. This is not to say that it is not important or useful to understand what classifications were in existence at the time, and the infrastructural constraints that may have influenced the historical event; however, modern science should feel obligated to bring its accumulated knowledge to bear in reinterpreting historical events to discern patterns accurately.

In the following section on infrastructure and politics, the question arises: Should classification schemes, and the way we define infrastructure, first be designed and then implemented or applied, or should they be emergent? This is like a snake biting its tail. The structures of the physical world, of cognitive structures and ideas (even of semiotic relationships) have inalterable and irreversible properties resulting from their path-dependent histories. Thus, there are emergent aspects that can be called infrastructure. Within these constraints, we form strategies, policies, laws, and politics to make the most efficient use of the existing infrastructures that we can. Which came first? Do they co-evolve? This seems likely. The section concludes remarking that it is difficult to manage the politics and policy creation process because while people are concerned with infrastructure, they are rarely looking at the same parts of it while using parallel language. Once again, we see problems regarding levels of scale and aggregation. Bowker and Star refer to this as granularity, but the fact remains - we need to be more attendant to matters of scale and the scales that matter, rather than simply labeling and shelving the issue.

After a description of the interaction between psychological/psychiatric practice, insurance requirements, and the DSM (One may ask here, what "shadow systems" are in place, and what can be found there [109]? Are these strong boundary objects [115]?), the chapter ends with the statement that schizophrenia may only be defined in one way. Specifically,

> This blindness occurs by changing the world such that the system's description of reality becomes true. Thus, for example, consider the case where all diseases are classified purely physiologically. Systems of medical observation and treatment are set up such that physical manifestations are the only manifestations recorded. Physical treatments are the only treatments available. Under these conditions, then, logically schizophrenia may only result purely and simply from a chemical imbalance in the brain. It will be impossible to think or act otherwise. We have called this the principle of convergence.

There are two descriptions needed, and we are provided with one. The first, as rightly pointed out, is *convergence* – the path or process. The missing element is *closure*, which defines the point at which convergence is reached and does not change significantly, the result of the ergodic process inherent to path dependence. What, then, are the tips and tricks in interpreting infrastructure that Bowker and Star promise at the outset? The ending statements about infrastructure being a matter of deals in backrooms filled with smoke relegates it almost entirely to the difficult realms of ethnographic sociological inquiry. This is methodologically limiting. The study of infrastructure, it would seem, is a melange of theories, methods, and tools, drawing from sociology, complex systems, anthropology, psychology, library science, technology studies, computer science, history, and philosophy. The closing thought about this is that infrastructure, based in classification systems and schemes, and as presented by Bowker and Star, tends to be rooted firmly in the problem of language games that Wittgenstein presents in Philosophical Investigations. That is to say, classification systems are sets of rules – language rules saying, "A belongs in category X and not Y, and B belongs in category Y and not X." As Wittgenstein points out:

> This was our paradox: no course of action could be determined by a rule, because every course of action can be made out to accord with the rule. The answer was: if everything can be made out to accord with the rule, then it can also be made out to conflict with it. And so there would be neither accord nor conflict here. It can be seen that there is a misunderstanding here from the mere fact that in the course of our argument we give one interpretation after another; as if each one contented us at least for a moment, until we thought of yet another standing behind it. What this shows is that there is a way of grasping a rule which is not an interpretation, but which is exhibited in what we call "obeying the rule" and "going against it" in actual cases. Hence there is an inclination to say: every action according to the rule is an interpretation. But we ought to restrict the term "interpretation" to the substitution of one expression of the rule for another [129]

2.7 Infrastructure Goes Cyber

In January 2003, a blue-ribbon panel appointed by the National Science Foundation released a groundbreaking report on the future of scientific research in the networked age [9]. Dubbed "The Atkins Report" (after Daniel Atkins, former dean of engineering and founding dean of the School of Information at the University of Michigan, and the chair of the NSF panel producing the report), the report laid out an initial consolidating vision for a trend that was already underway within the science and engineering research communities. Recognizing that the fundamental nature of how science is conducted vis-à-vis the advancing adoption of information technologies[9], and that this endeavor requires the linking together of many heterogeneous systems, cultures, actors, and resources along a wide spectrum of scales, it became immediately apparent that the task at hand was managing a form of infrastructure. Since the Internet is the primary mode of information transmission in this environment, and a differentiating term was needed to identify the agenda to those with funding power[10], the term *cyberinfrastructure* was chosen. The Atkins Report formally introduced the term into the NSF base of literature. Within the report, cyberinfrastructure is defined as follows.

> 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[11].

Within this definition, we clearly see strong elements both on the technical and social sides, remaining faithful to the descriptions of general infrastructure that have come before. This indicates that the blue-ribbon panel also believes that cyberinfrastructure, like previous infrastructure, must address both technological as well as organizational and individual development issues.

The interim years since the original release of the Atkins report have seen a proliferation of reports pertaining to cyberinfrastructure needs and states within various disciplines[12]. Curiously, but not unexpectedly (as will be discussed in a later section

[9] There is a large literature on the enablement of distance-based work that is relevant to this line of thought, specifically that of Computer Supported Cooperative Work (CSCW). While an examination of this literature is outside the scope of this paper, one of the dominant lessons learned in the field is that distance and the absence of co-location significantly affects production [96]. Further, within the CSCW field, the focus on collaboratories suggests that distributed teams of collaborating scientists and engineers are becoming more common in the scientific research, possibly more in number than independently-working researchers [51][52].

[10] This story was anecdotally expressed by Suzi Iacono, acting division director for Information and Intelligent Systems, NSF Directorate for Computer and Information Science and Engineering (CISE) at the "History and Theory of Infrastructure: Lessons for New Scientific Cyberinfrastructures" workshop at the University of Michigan in September 2006.

[11] Emphasis not included in the original.

[12] The NSF Office of Cyberinfrastructure web site has catalogued 29 major reports on cyberinfrastructure, referred to as the "Cyberinfrastructure and X' reports" (where X is a domain science). The current list can be found at http://www.nsf.gov/od/oci/reports.jsp

on interdisciplinarity), the Cyberinfrastructure and X reports are primarily focused on the needs for funding and cyberinfrastructure development support that do not transgress the boundaries of X. In contrast, the Atkins report also clearly states

> There exists universal sentiment in the community that significant discovery has been enabled by the PACI[13] centers, and that many, even more significant discoveries will be possible in the future. A good portion of these are anticipated to occur at the intersection of disciplines as well as in the context of societal implications, and made possible by Grid and related capabilities. Multidisciplinary teams will continue to proliferate, and efforts must be made to support them[9, Appendix B].

In addition, a pervasive theme throughout the Atkins report is the strong need to develop a multidisciplinary workforce to engage, advance, maintain, and manage cyberinfrastructure and cyberinfrastructure-based work. The content of the Cyberinfrastructure and X reports indicates that domain sciences have not yet internalized this agenda into their own. This fact represents an obstacle in shifting the culture of networked science and engineering to engage and consider cooperative relationships in domain sciences outside their own.

In June 2006, the newly anointed Office of Cyberinfrastructure (OCI) at the National Science Foundation issued a drat release of the updated vision, a follow-on to the 2003 report [10]. The report was much shorter, oriented toward action, and laid out specific goals in a five-year plan (2006-2010). A shift in tone can be detected in this report toward the prioritization of the technological – petascale computing facilities, middleware and software development, Grid facilities, data, data analysis, visualization, and so on. Making a new appearance in the 7.1 report is the language of *services* created for and adapted to the needs of cyberinfrastructure (which will be discussed in the next section). The final section does address the need for training to create professionals who can advance this type of innovation, but the social and organizational transformations needed to adapt to cyberinfrastructure seem largely to be de-emphasized. The reasons for this are not obvious to the casual reader, nor are indicated in the text itself. This trend feels reminiscent of earlier infrastructure projects, when the goal of system-builders was primarily to link together objects, systems, physical and tangible resources. Edwards argues that cyberinfrastructure is still in the early system-building stages, and has not yet reached the expansive and ubiquitous designation of "infrastructure." Unlike previous infrastructures, though, cyberinfrastructure is being approached as something to be built out of sheer will and coordination, rather than the slow, organic, long time cycles of past projects that we retrospectively label as infrastructure.

What, then, if any purchase do we gain by appending the term *cyber-* to infrastructure? The descriptions laid out by the Atkins report and the current 7.1 Vision Document articulate at various points all of the attributes of infrastructure described

[13] Partnership for Advanced Computational Infrastructure

by Star and Ruhleder as goals [116]. There does not seem to be a strong case built yet for considering cyberinfrastructure as fundamentally different than other historical infrastructures, save for the increased sense of intangibility or elusive to define qualities of the medium being transmitted (data and metadata, as opposed to trains, goods, cars, electricity, etc.) Perhaps novelty and lack of retrospection tempts us to think, "Oh, but this is different, and needs to be approached in a new way." It may be that the purpose of the new term is political in nature (as suggested by Iacono), or only serves to market and encourage enrollment into the agenda. It may also be the case that we are re-inventing the wheel, so to speak, by adding the words *virtual* and *cyber* by believing it to be something new. The closest articulation to the difference, less than compelling, is the statement in the introduction to the Atkins report,

> The term *infrastructure* has been used since the 1920s to refer collectively to the roads, power grids, telephone systems, bridges, rail lines, and similar public works that are required for an industrial economy to function. Although good infrastructure is often taken for granted and noticed only when it stops functioning, it is among the most complex and expensive thing that society creates. The newer term *cyberinfrastructure* refers to infrastructure based upon distributed computer, information and communication technology. If *infrastructure* is required for an *industrial* economy, then we could say that *cyberinfrastructure* is required for a *knowledge* economy[14].

Although standard arguments exist that the rise of the network society and economy have fundamental differences from ages preceding it [17], it is not a foregone conclusion that these alter the fundamental nature of infrastructure, cyber- or otherwise.

3 Cyberinfrastructure as Service Science

3.1 A Science of Service?

Knowledge-based work and commerce have become increasingly important in a global society, and studies in Service Science, Management, and Engineering (SSME) are emerging as a valuable disciplinary framework for modeling the role of knowledge innovation. In 2005, approximately two-thirds of the U.S. GDP resulted from service-based work, and more than 70% of the U.S. labor force was employed in the service sector [101][130]. Looking at the historical proportions of GDP represented by various industry sectors recorded by the U.S. Department of Commerce (Figure 1), it is clear that services have continued to grow over a long period of time, surpassing physical goods and distribution industries circa 1990. Considering the rising trend of service-based industry (Figure 2), there is little reason to believe that this trend will not continue to rise in the near future.

[14]Emphasis contained in the original.

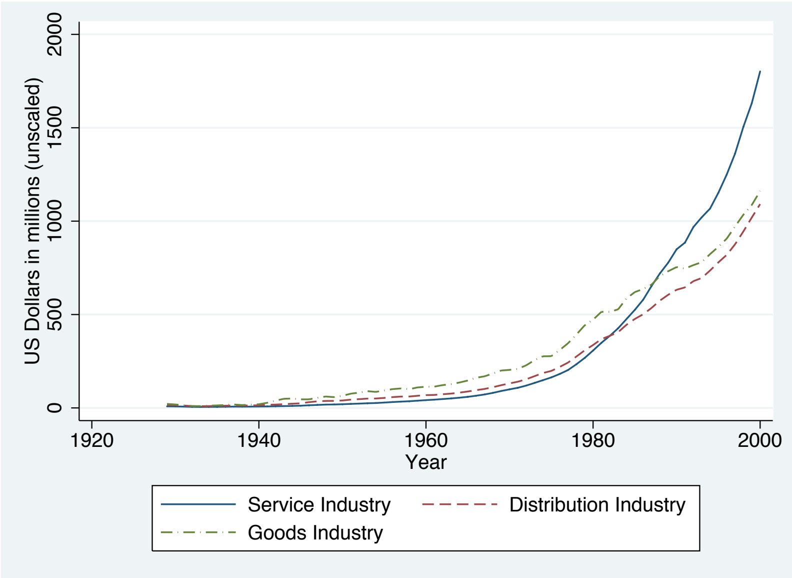

Figure 1: Growth of GDP-based industries in the US, 1928-2000

15

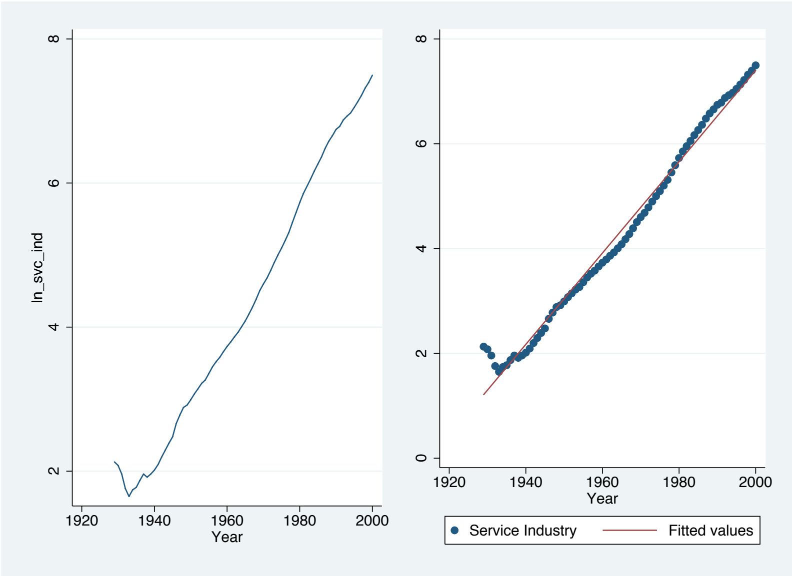

Figure 2: Log-Linear Graph of Service Industry production with fitted regression, 1928-2000

[15] Raw data for Figures 1 & 2 provided by US Department of Commerce, NIPA datasets

The history of production is filled with examples of innovation and process development related to physical or tangible goods. Firms have weathered the shift from agrarian production to the industrial revolutions and on to the manufacturing ages of Taylor and Ford [94]. Service researcher Roland Rust articulates [104]

> Academic research has revealed that the service sector is now dominant in every developed economy. The goods sector is shrinking as a proportion of the overall economy; and as goods increasingly become commodities, service is becoming the key differentiator, even in the goods sector. Thus, to compete effectively, all companies must become service companies.

Now that the service industry has achieved such prominence as a profit-generating sector, firms must once again shift; yet, few fundamental theories and models exist to advance our knowledge of service development. The creation of new knowledge, services, and intangibles that drive competitiveness and innovation are critical to the global economy, and the need is clear for greater understanding of how these evolve. Once considered as a "value added" proposition (and typically an afterthought to extract further value from previous goods sales), services are coming into their own as a separate primary value and innovation stream. Services, for this purpose, are defined in a particular way. In a colloquial sense, they have been referred to as "anything you cannot drop on your foot [19]." An early definition provided for services gives:

> A service is a change in the condition of a person, or a good belonging to some economic entity, brought about as the result of the activity of some other economic entity, with the approval of the first person or economic entity [68].

This definition, however, is a bit unwieldy. IBM has made their conceptualization of the term more explicit, stating:

> A service is a provider/client interaction that creates and captures value.
>
> ...
>
> The provider and client coordinate their work (co-production) and in the process, both create and capture value (transformation). Services typically require assessment, during which provider and client come to understand one another's capabilities and goals. In the case of the doctor/patient interaction, the patient checks to see if the doctor is licensed and/or accredited and if he or she has the right specialty for the given illness. The doctor also conducts an assessment to determine the patient's medical history, gather information on the current ailment, and verify insurance or payment details. All of these steps factor into both sides capturing value from the services engagement. Obviously, for IT

and business services, these assessments can be far more complex, but the processes and measurements are similar [16].

Like Star and Ruhleder's list of attributes common to infrastructure, some of the attributes of services include [20]

- Close interaction of supplier and customer
- Nature of knowledge created and exchanged
- Simultaneity of production and consumption
- Combination of knowledge into useful systems
- Exchange as processes and experience points
- Exploitation of ICT and transparency

The SSME agenda is largely the brainchild of Jim Spohrer and Paul Maglio of the IBM Almaden Research Center; however, a short look back in history is useful, as IBM has been involved in information technology services provision for over 60 years. With such a long tradition of providing services in addition to equipment, it is understandable why IBM would then be leading the charge of the SSME discipline.

In 1946, former dean of Allegheny College and IBM mathematician Cuthbert Herd was appointed as the director of Applied Sciences at IBM. This appointment coincided with the introduction of the IBM 600 series, most notably the IBM 602 and 604 [2]. Hurd began to recruit a small force of "Applied Science Field Men" to handle field sales, all of whom had degrees in mathematics or physics, several with Ph.D. training. The positions that evolved, however, came to involve far more than sales. As regional representatives, many of the field men grew their roles as traveling systems experts, visiting client sites and working for longer durations with scientific teams to configure, write software for, and provide solutions customized to each client site. For example, Lloyd Hubbard, one of the original field men for the southwest U.S., became a permanent fixture at Los Alamos Scientific Laboratory as a equipment and research liaison between the facility and IBM. Through a number of these field men, Hurd established the beginning of an institutional division of providing services to clients that would follow through and grow to the current day, allowing such IBM divisions such as Global Business Services.

3.2 Creating an Interdiscipline

Even with the business case for services innovation neatly laid out by the IBM team, the issue remains that little is understood about the theoretical bases of the SSME-based field. To answer this need, IBM has issued the call for academics to assist

[16] Taken from the IBM Services web page, *Services Definition* at http://www.research.ibm.com/ssme/services.shtml

in establishing service science as a recognized interdisciplinary area of study. The question arises: Is there an actual need for service science as a discipline, outside the business interests of IBM, and by extension, other firms who wish to gain advantage in the service economy? The case of problematics is left until the end of this section. For now, let us proceed under the assumption that a science of services can and should be established within the academy.

Spohrer, in a first move to establish the academic study of service, outlined a mapping of the fundamental concepts of SSME to academic departments, highlighting the interdisciplinary nature of the field [114]. He cites ten disciplines that are believed critical to developing a well-rounded view of the requirements involved in the enterprise.

1. Economics and Law
2. Operations Research
3. Industrial Engineering
4. Computer Science
5. Information Science
6. MBA and Management Consulting
7. Management Information Systems (MIS) and Knowledge Management
8. Organizational Studies and Organizational Learning
9. Urban Planning, Ecosystem Services, and Nature's Services
10. Complexity Science and Complex Adaptive Systems for Social Systems Research

It is interesting to note that of the ten items, two are typically in one department (IOE - #2 & #3), three are commonly in business school programs (#6 - #8), and several are established interdisciplinary programs in their own right (#1, #5, #9, and #10).

Later in 2006, at an IBM-sponsored summit on SSME, another group from Carnegie Mellon University provided a different grouping with a set of strategies for legitimating the place of SSME as a discipline [110]. In addition to CMU, several other universities have taken steps to install formal programs including UC-Berkeley [65], Arizona State University [13], Princeton, and Said School of Business at Oxford. Each program highlights three key sectors. First, the fact that there is a wide range of research opportunity for PhD-level candidates to contribute to a new field. Second, that funding opportunities are available in partnership with government and industry. Third, and possibly the strongest practical argument, that the SSME discipline will provide undergraduate and masters students the skills needed to survive and advance in a knowledge economy.

Whether service science will emerge as a legitimate science, or will become another "flavor" of curriculum within engineering, information science, or business (much as neuroscience proved over time to stand on its own in some institutions, while in others it was part of the medical program or psychology department) is unpredictable. The efforts of IBM and its allies are carving a niche, to be sure. The lure of funding, placement, and open research areas is seductive; however, as will be discussed at the end of the section, there are cautions along this path.

3.3 Casting Cyberinfrastructure as a Set of Services

Leigh Star remarks that cyberinfrastructure is not about building machines; we already have those, and in that sense, cyberinfrastructure already exists. The task at hand, she believes, is creating and defining the relational capacities between technical, sociotechnical, and social/organizational systems that are positioned to benefit from a working cyberinfrastructure[17]. Expressing cyberinfrastructure as a set of relational capacities is strikingly aligned with the SSME agenda of providing services to bring more value to socially-situated information technologies.

Interestingly, the National Science Foundation has interest in the SSME agenda, but has yet to link it to the activities at the Office of Cyberinfrastructure. For example, program officers at the NSF Division of Manufacturing Innovation have stated [101]

> NSF is a natural home for the engineering of services based on fundamental scientific understanding of human cognition and knowledge representation. The relevant scientific fields include biology, chemistry and physics which contribute to neuroscience; computer science, mathematics, and engineering for information processing; and social and behavioral economics for cognition. But engineering enables the focus on service delivery that directs the science towards innovative outcomes and system delivery.

This is strongly aligned with the section in the NSF OCI 7.1 report on *Plan for Cyber-Services and Virtual Organizations (2006-2010)* [10]. The parallel descriptions for service needs have been articulated within the NSF. Now, the connections need to be made explicit and plans for development laid out. It is not a large leap to believe that if the intensively IT-based private sector is innovating around services, that an IT-intensive endeavor such as cyberinfrastructure will face many of the same needs. Framing the appropriate areas of the cyberinfrastructure agenda to benefit from the advances made in the new service science discipline may prove symbiotically beneficial to both movements.

[17]Expressed at the History and Theory of Infrastructure workshop.

3.4 Potential Problems of the SSME Agenda

Another result of short discussions with Leigh Star and Geof Bowker has generated the idea that the construction of a new science or academic discipline around services may be worthwhile, but that the origination within and primary sponsorship of a new science by an industry player (in this case, IBM) is not free of problems. As early as 1918, Thorstein Velben, then President of the University of Chicago, strongly warned against the involvement of business and industry in the pursuit of academic knowledge and science [124]. According to Veblen, the academy and the disciplines must be dispassionate and unconcerned with the applied nature that business would bring to research. To be fair, in Veblen's opinion, the application of science to worldly problems is not an ignoble pursuit; however, the university is not the place for this to happen. Instead, he believed, trade schools, polytechnics, and other institutes were well-suited to this purpose. Of course, the current state of the university is to a large extent a realization of Veblen's fears. The industrialization of knowledge and sponsorship of research by agenda-driven parties is now commonplace [2][16][63][93], and many of the discoveries in basic research have come through funding intended for applied innovation. Indeed, the current rhetoric described by many, including university presidents James Duderstadt of the University of Michigan and Nannerl Keohane of Duke University (both emeritus), positions the university as an *enterprise* [42][73]. Duderstadt remarks that the intertwining of the university and industry funding is a necessary relationship to sustain the research university in troubling financial times. If this financial bind is the case, it stands to reason that the launching of a well-funded disciplinary initiative provides strong incentive for the research university to support and pursue it. As Jasanoff points out with respect to scientific research and regulatory policy-making [72], a parallel argument can be made for industrial sponsorship: the vested interests of those who engage in industry-defined research (or in a more general argument, applied research) have the incentive to "tell [industrial funders] what they want to hear, " presumably to ensure future funding. This fact stands in direct opposition not only to Veblen's cautioning, but to the nature of science and research as free of biases and agendas.

How, then, may an academic discipline of service science proceed without being inexorably couched in IBM's profit-driven agenda? The answer to this is not particularly clear, yet has serious impact for the construction of service science, and by extension, the future of cyberinfrastructure. It is my hope that the extension of this field paper, and the dissertation research following can inform this area in a substantive way.

As mentioned in the number of documents on defining service science and the need for a multidisciplinary cadre of academics and professionals, I turn to explore the ideas of inter-, multi-, and transdisciplinarity in the next section, offering some perspectives on why the integrative approach is not only preferable, but crucial to the success of cyberinfrastructure.

4 The Logic of Interdisciplinarity

4.1 Proving the Value of Interdisciplinarity

It is a popular idea that diversity is an important, if not fundamental, element to the structure and advancement of various systems. Beginning with the well-established evolutionary metaphor popularized by Darwin in his 1886 treatise, the preferred and robust method for improving the chances of survival is by exploring the design space thorough trials of variation or diversity [28]. In the subsequent 150 years, the evolutionary metaphor and value of diversity has been applied to phenomena ranging quite far from the original biological context, becoming ubiquitous with many descriptions of dynamic change[18]

Until recently, the application of the diversity metaphor to social dynamics has been precisely that – a metaphor. While a useful tool in shedding light on the mechanisms of social structure and change, it does not have the traction of a stronger tool – proof. Scott Page (the same Page discussed in the earlier discussion of path and phat dependence) has taken a step in remedying this shortcoming. In his forthcoming book, he provides an economic proof of the value diversity provides in advancing social systems [98]. He begins with a description of a set of counterintuitive results from a set of agent-based simulations run during his early career, where groups of heterogeneous agents with moderate ability to solve sets of problems consistently outperformed homogeneous groups of agents with high (and relevant) ability. This discovery led to an economically-based examination of how domain knowledge and tools for inquiry may be defined and categorized, and who the interaction of differing tool sets can lead to higher performance. Page describes the toolbox for diverse thought in terms of four elements:

- *Perspectives:* individual interpretation of objects, situations, and other stimuli. The frameworks chosen to arrange the elements of a problem.
- *Heuristics:* the rules or patterns applied to describe patterns within one's perspective, and the strategies for moving through a search space for an optimal solution.
- *Interpretations:* the formulation of perspectives, heuristics, and elements into words, providing a conceptual mapping of the problem at hand.

[18] As is likely evident, I disagree with this widespread subscription to the evolutionary metaphor. First, this is owing to the fact that Darwin's described mechanisms of evolution are only one of many. Other models and algorithms exist under the general category of evolution that bear stronger resemblance to contemporary dynamics. For example, Lamarckian evolution, where phenotypic changes in one generation are immediately incorporated into the genotypic structure of offspring, has much closer relevance to the evolution of code bases and libraries in open source programming projects. The point here is that the evolutionary metaphor has been applied carelessly in many cases, leading to diluted power in communicating the value of diversity.

- *Predictive models:* Assembling the information about the situation to create models that lead to better expectations of behaviors or outcomes.

The observation that a framework or perspective is necessary to solve problems is certainly not new. Kuhn clearly puts forth the claim that scientific inquiry is primarily advanced by the subscription to and application of a particular framework [79]. In addition, economist Herbert Simon echoes this sentiment with his claim, "Solving a problem simply means representing it so as to make the solution transparent. [111]" Page applies these claims with the logic that if a perspective is key to solving a problem, then an array of perspectives increase the probability of finding the right perspective that will render a complex or multidimensional problem (or subset of that problem) transparent. Heuristics, according to Page, provide us with sets of actions that may be taken in response to an experienced or observed situation (for example, "It is starting to rain, so we should find shelter." or "It is starting to rain, but we will get just as wet whether we walk or run, so we might as well walk.") Again, the multiplicity of heuristics provides an increased set of options for action when searching a solution space. Interpretations, as a mapping of concepts into language, provide a method of communicating these options among actors. In the case of homogeneous high-ability actors, the shared language may promote efficiency in making sure all group members understand the elements in play, but may concurrently limit the ways in which the solutions may be described, leading to the problems of groupthink (as played out, for example, in the events that led to the explosion of the NASA Challenger shuttle [123]). Predictive models, in Page's view, are most effective as simple and crude constructs that (in my interpretation) form an internal Bayesian model that accounts for prior experiences and over time refines the expectation of outcomes. Since each person's experience set is different, the increased set of prior experiences provides more robust examples upon which to form a posterior distribution of expected outcomes. Page spends most of the remainder of the book exploring concrete examples of each of these elements, accompanied by economic axioms and thought experiments.

The point here is that Page provides a solid and probabilistically-based proof that diversity, in many situations and environments (though not all), leads to more optimal outcomes in problem solving than reliance on a well-developed, but inflexible framework. Page consistently chooses the word diversity to describe this state, and only engages the word interdisciplinary twice within the entire book; however, I believe the transfer of the concept to the interdisciplinary dialogue is clear. As we ask and seek to answer more complex questions, an increased representation of perspectives, heuristics, interpretations, and predictive models only serve to increase the probability of finding a suitable solution.

One interesting example given by Page, and bears strong synthesis with the activities seen in interdisciplinary academic environments, relates to the relatively new phenomena of "X-Prize" competitions, where a complex and difficult problem is put forth by a sponsoring individual or institution[19], and an open competition for the solution ensues. Page provides evidence that the consistent winning teams of X-prizes are interdisciplinary in nature, providing workable solutions faster than assembled teams of experts from one field alone. Clearly, this is the basis of many contemporary problems in academic and scientific research as well. The activities at Bletchely Park, a British endeavor to break the German Enigma Code during World War II, brought together mathematicians, linguists, engineers, cryptographers, and even crossword puzzle experts. This is a recognition that the value of interdisciplinarity has been recognized by research communities for quite some time, and that we have long known that there are certain classes of problems that extend beyond the ability of a single discipline to provide solutions [69].

4.2 A Short History of Interdisciplinarity as an Object of Study

Interdisciplinarity, as a topic of modern inquiry, first became popular in the 1920s. Although arguments are made that interdisciplinarity has been a root element of knowledge discourse since Plato's advancement of philosophy as a unified science (which was overturned by his student, Aristotle, and the entrenched ideal of delineating between categories of object, knowledge, and representation, leading to the basis of our current paradigm of scientific inquiry [7]), the historical discussion of interdisciplinarity with respect to research in the academy becomes interesting and relevant to the topic at hand with the opposition to the "craft exclusiveness" of the disciplines generated by a group of scholars at the University of Chicago: Dewey, Veblen, Mead, Angell, Boas, and Merriam [75]. Their attempt to cross-fertilize the social sciences lagged, but gained more widespread attention in the 1930s and 1940s. This school of scholars took upon themselves the task of unifying the social sciences through rational positivism.

Still, the enrollment in the idea of interdisciplinarity remained confined to a corner of the social sciences, and through the early 1970s, when the metaphors of "bridge building" and "restructuring" were introduced by the British Group for Research and Innovation in Higher Education. During this time, several examples of interdisciplinarity were generated as concrete instantiations to which those wishing to advance the agenda could point. In terms of a field, general systems theory rose as an exemplar of synthetic thought. As a concentrated example, Shannon's work at Bell Labs in information and communication theory was heralded as a skillful weaving of several fields to produce an interdisciplinary piece of knowledge.

Within the academy, the period from 1970 to 1985 saw the rise of several inter-

[19] Recent examples include: the first private manned spaceflight, NetFlix's call for improving the accuracy of their recommender system by 10% or more, and creating a method for genomic processing that costs less than $1000. More examples can be found at xprize.org, the website of the X-Prize Foundation.

disciplinary centers in the form of area studies and various forms of cultural studies, including the legitimation and institutionalization of departments for women's, African-American, Asian, Latin, and later, Queer studies [77]. Klein claims that during the 1970s and 1980s, continuing through to the present, interdisciplinary studies in the social sciences (and spilling over into design and engineering) were propelled by the fields of urban planning and STS (Science and Technology Studies) as a form of social and academic reaction to the growth of technological research in the cold war era, and detecting a need for a strong science program that approached problems from multiple perspectives [76]. From the 1980s and onward, we can see within the academic (and related academic circles), the founding of an increasing number of interdisciplinary endeavors, including but not limited to complex systems departments and the Santa Fe Institute [125], information schools, bioengineering, neuroscience, and media studies (of the type found at the MIT Media Laboratory.) In 1996, Lisa Lattuca published a dissertation at the University of Michigan School of Education, producing an ethnographic review of the extent to which researchers in the sciences, social sciences, and humanities engaged in interdisciplinary research [85].The conclusion of the study was that interdisciplinarity is happening within the academy at high levels across the domains; however, many researchers, especially those who are mid-tenure, are loathe to admit to this type of scholarship, feeling that the reward structures in place, and the general disposition of disciplinary scholars is a quite real impediment to advancement for those who actively practice interdisciplinary work as their primary bread-and butter-science. She indicates that there is a strong need for the reconceptualization of science and discipline, stating that the evidence from her interviews with many faculty from different departments suggest that the strongly held boundaries of the disciplines are firmly in place despite the popular rhetoric.

4.3 Through a Lens of Interdisciplinarity – Best Practices

Departing from Lattuca's cautionaries, other groups are finding thriving interdisciplinary scholarship in pockets of the academy, in industry, and funded by the government. The Interdisciplinary Studies Project, a part of Project Zero at the Harvard Graduate School of Education, has done significant work since the late 1990s in identifying and examining exemplary institutional projects that are defined by their interdisciplinary nature. Led by psychologist Howard Gardner, the project has used qualitative methods (mostly ethnographic) to identify qualities of high-performance groups. As predicted by Page, the diversity of scholarship represented in these groups is consistently cited as the factor that leads them to produce innovative science.

The first major piece published by the Project Zero group produced a definition of interdisciplinary understanding. By examining students' modes of learning in two cross-disciplinary courses merging historical and scientific lenses, applied to issues in (1) Nazi concepts of obedience and authority and (2) eugenics, Mansilla, Gardner, and Miller show that students' command of critical engagement is enhanced by considering multiple views contingent upon "(1) an emphasis on knowledge use, (2) a careful treatment of each discipline involved, and (3) appropriate interaction between disciplines. [88]" After establishing this working definition, the group turns from ordinary knowledge acquisition in a multiple-lens environment to the issue of knowledge production, specifically focusing on "exemplary interdisciplinary work [87].

For these analyses, three highly visible projects were chosen: the MIT Media Laboratory, the Santa Fe Institute, and CIMIT (Center for Integration of Medicine and Innovative Technology.) The findings of the studies acknowledged that even though superficial qualities differ among the organizations (such as local versus virtual collaborations, organizational goals, funding structures, size, etc), the practitioners of exemplary interdisciplinary science identify a core set of requirements including particular strategies to bridge disciplinary differences: fluid integration, translation, and explicit integration. Practitioners also identified (and these are similar to the categories in Page's toolbox) common skills that "allow researchers to navigate the interdisciplinary terrain: analogical thinking, common languages, and metadisciplinary views[20][39][40][41].

Finally, in a 2004 paper, the group performed a meta-analysis of the previous studies (which grew to include examination of groups at Xerox-PARC, the Santa Fe Laboratory for Arts and Sciences, and the University of Pennsylvania Center for Bioethics.) The final report identified three main themes to guide future understanding of interdisciplinary environments and projects [91]:

1. Challenges of Work Across Perspectives
    - (a) Differing units of analysis – in short, scales, methods and tools matter. The reconciliation among the tools used by collaborating disciplines is a process of negotiation, and relies upon the willingness of each group to positively consider the legitimacy of methods that are not its own.
    - (b) Communicating across perspectives – negotiating the lexical and linguistic conventions of each community of practice. This subject is taken up in detail in the next section on pattern language.
    - (c) "Measuring up" to differing, sometimes conflicting, standards – different disciplines have differing views of what constitutes rigor and acceptable standards for validity. As with other aspects, this is a constant negotiation and confrontation of assumptions embedded in each disciplinary culture.

[20]Michael Finkenthal puts forth the claim that western culture has centered itself around a Galilean-Newtonian paradigm of disciplinary thinking which has gone largely undisputed by the scientific community. By tracing the ingrained nature of classificationist approaches from early Greek scholars to the present (in a surprisingly short volume), he concludes that the rise of interdisciplinarity is an intermediate form that creates tension leading to a new metadiscipline, forcing us to re-examine the relationships and ontologies that construct the scientific understanding of the world [53].

2. Making Integration Happen: Cognitive Bridges

    (a) Reasoning through analogies – promotes the active mapping of one cognitive domain to another. When one discipline teaches another through analogy, each group can expose new perspectives, relationships, and properties to the other.

    (b) Creating compound concepts – the active construction of language that hybridizes the related content of different domains, and the adoption of these terms by all actors. This process anchors the legitimacy of the boundary-spanning (compound) concept.

    (c) Building complex and multi-causal explanations – while this approach seems uncomfortable in that it defies the accepted Occam's razor approach to science, the added efforts may be worthwhile in reconciling the explanatory perspectives brought by multiple disciplines may expose inconsistencies, gaps, or otherwise ignored or erroneously-taken-for-granted aspects of a single disciplinary view.

    (d) Advancing through checks and balances – engaging other disciplines that can challenge the disciplinary assumptions in play, keeping each group "intellectually honest."

    (e) Bridging the explanation-action gap – realizing that certain disciplinary perspectives privilege explanatory aspects of inquiry, while others are more appropriate for defining paths of action or solution. This strategy makes the relationship between the two explicit and demands a balanced approach.

3. Explicitly Acknowledging Different Degrees of Integration (definitions taken directly from Miller, 2004)

    (a) Mutual ignorance – Individuals demonstrate a lack of familiarity with, and even hostility toward, other disciplinary perspectives.

    (b) Stereotyping – Individuals show an awareness of other perspectives and even a curiosity about them. Still, there is a stereotypical quality to the representation of the other's discipline, and individuals may have significant misconceptions about the other's approach.

    (c) Perspective-taking – Individuals can play the role of, sympathize with, and anticipate the other's way of thinking. Individuals raise objections to their own preferred ways of thinking by taking account of other approaches. Individuals demonstrate less naïve or stereotyped representations of other disciplines.

    (d) Merging – Perspectives have been mutually revised to the point that they are a new hybrid way of thinking, and it is difficult to distinguish separate disciplinary perspectives in the new hybrid.

Each of these aspects of interdisciplinarity found by the Project Zero team has been, at different points, acknowledged as a point of concern for the cyberinfrastructure agenda. This can be seen in online blog transcripts discussing the social aspects of cyberinfrastructure[21].

4.4 Cyberinfrastructure, Interdisciplinarity, and the Need for Training

The value of and demand for interdisciplinarity is exerting itself as a critical component of the cyberinfrastructure movement as well. During a recent University of Michigan conference, "History and Theory of Infrastructure: Lessons for New Scientific Cyberinfrastructures," several comments were made regarding the need for interdisciplinary training, especially with regard to new PhDs who may, in time, take the reigns of leading and coordinating large-scale projects of the type that cyberinfrastructure engages. In particular, William Dutton of the Oxford Internet Institute spoke of the need for "extreme multi-disciplinary training [44]." Similar sentiments have been expressed within the SSME community, with HP Labs Bristol claiming the need to create a new form of polymath who is able to span the requisite disciplines needed for understanding of the new field [92], and Jim Spohrer of IBM, one of the creators of the SSME agenda, outlining the various academic fields that are necessary to assemble a basis for a new interdiscipline of service sciences [114].

The stated need for interdisciplinarity is echoed on a larger level as well. The current state of doctoral education, ostensibly the primary source of scientists, administrators, coordinators, and leaders in the cyberinfrastructure movement (as well as the upwardly trending nature of cross-boundary inquiry more generally), needs to undergo transformation with regard to fundamental perceptions of the role of interdisciplinarity as well as the reward structures in place for pursuing such work. As it stands, interdisciplinary studies are at odds with the entrenched disciplinary and subspecialized structure of the academy [64]. Helga Nowotny describes this tension as rising from a transformation from *Mode-1* knowledge production, where traditional disciplinarity and progressive subspecialization (and, by inference, balkanization) is the mode of inquiry, to *Mode-2* knowledge production, to which Nowotny ascribes particular qualities, many of which are regular features of cyberinfrastructure-based projects [95]. Nowotny enumerates these qualities as:

1. Contextual application of research: "...contemporary research is increasingly carried out in the context of application, that is, problems are formulated from the very beginning within a dialogue among a large number of different actors and their perspectives."

2. Heterogeneity: "...multiple actors bring an essential heterogeneity of skills and

[21] To be found at http://icd.si.umich.edu/∼cknobel

expertise to the problem solving process[22]."

3. Transdisciplinarity: This is Nowotny's term of art, specifically referring to the joint production of new and hybrid concepts resulting from the fusion of disciplinary knowledge, rather than knowledge that simply forms in the interstices of disciplines, the elements of which are still assignable to one discipline's contribution.

4. Accountability: institutionalized responsibility to the production of such knowledge. While accountability is primarily an informal process, it is strongly embedded in organizational routines, giving it a semi-formalized nature. It is by this process that those enrolled into the transdisciplinary community of practice become aware of how scientific knowledge is produced.

5. Quality control: Nowotny admits to quality control being the "Achilles' Heel" of transdisciplinarity, since, unlike disciplinary sciences that have achieved relative closure on the definitions of acceptable and legitimate science, transdisciplinary endeavors must re-negotiate these criteria with each new configuration of multidisciplines. Here, she makes the interesting statement that a transdisciplinary project must go beyond each discipline being value-added, to being value-integrated.

As can be seen in Nowotny's criteria for transdisciplinary (and ignoring the semantic arguments, extending the concepts to the broader class of interdisciplinary) research, the cyberinfrastructure agenda has, and continues to struggle with all of these issues. Thus, if these issues are elements of interdisciplinarity, and cyberinfrastructure engages them at a fundamental level, then we can reasonably conclude that the cyberinfrastructure environment is inherently interdisciplinary. The question then remains, as stated before by Dutton, Spohrer, and others – where will we find, and how will we train those who are properly equipped to manage the cross-disciplinary complexity that is to be found in the future of cyberinfrastructure?

In a recent report on the future of doctoral education, The Woodrow Wilson National Fellowship Foundation states:

> ...further, bland praise of the interdisciplinary sacrifices intellectual opportunities of key import. The interdisciplinary often arises because the world beyond academia needs something that crosses the academic boundaries or because a scholar in one discipline is led by her research to questions that land her beyond the line. This is a freshening moment; it is the very history of knowledge in the making. But some such moments may be unique (some may even be unfortunate!) while others are endemic.

[22]In this same section, Nowotny also notes that "Universities are precisely the opposite type of such organizations. For the most part they are still highly hierarchical, fixed towards disciplinary structures. We find in Mode-2 almost the reverse of that."

> The deeply contentious nature of the interdisciplinary – it seeks, after all, a reorganization of knowledge – should lead to very exciting debate, allowing the traditional disciplines a new understanding of themselves in the process. And the variety of this genre, ranging from a single individual's perspective to the very different circumstance of a multidisciplinary group to which each individual brings a disciplinary perspective, barely gets acknowledged [131].

Across the academy, industry, and government, the consistent acknowledgment arises that inter- or trans-disciplinary knowledge, orientation, culture, and priority will be key requirements for the success of scientific research in general, and cyberinfrastructure and service science in particular. If taken, then, as a given requirement, how should we best proceed in these skills and recreate scientific and research cultures? In the next section, I propose a strategy that positions language as a fulcrumatic point for moving forward.

5 A Pattern Language for Cyberinfrastructure

5.1 Christopher Alexander and a Timeless Philosophy

In 1970, the University of Oregon engaged in a bold experiment. It turned over the construction of its campus to a Berkeley professor of architecture, Christopher Alexander. Alexander, though an architect by training and trade, was also a utopian philosopher who believed that the harmony between spaces and those who occupied them was created from a contextual understanding of how the spaces were used, interacted with the surrounding environment, and solved problems for the everyday person [3]. He noted that there are standard elements to design (in the case of architecture, windows, walls, pathways, benches, doors, etc.), and that for a given instantiation, the environment in which they take place create constraints which give rise to *patterns*. The people who occupy these spaces and engage in these patterns encounter problems or situations to be resolved. Alexander felt that by designing with the involvement of the residents or users, a careful and explicit consideration of the relationships among situations, elements, and design, and above all, the creation of a locally relevant and adapted language to describe those relationships, the outcome of this method of construction would promote a beautiful, functional, harmonious and fluid cadence to life.

In The Timeless Way of Building, Alexander laid down the axioms for his philosophy of design [5]. Here he constructs what can be considered a reference ontology for describing the patterns that arise in the use of spaces. The reference ontology can then be employed again and again to derive local and contextual ontologies for each instance of building. The basis of the method can be found in the accompanying volume, A Pattern Language, in which Alexander reveals the step-by-step method for working with local residents, identifying patterns, constructing language, and implementing in design [4].

The genius of Alexander's method, though, was that it was not really about architecture. The ideas presented in the pattern language idea were recognized to be fundamentally about problem solving, information flows, and the local and contextual construction of resolutions to infrastructural tensions. An excellent and concise definition of a pattern language can be found on Wikipedia, repeated here.

> A pattern language is a structured method of describing good design practices within a particular domain. It is characterized by
>
> 1. Noticing and naming the common problems in a field of interest
> 2. Describing the key characteristics of effective solutions for meeting some stated goal
> 3. Helping the designer move from problem to problem in a logical way
> 4. Allowing for many different paths through the design process
>
> Pattern languages are used to formalize decision-making values whose effectiveness becomes obvious with experience but that are difficult to document and pass on to novices. They are also effective tools in structuring knowledge and understanding of fundamentally complex systems without forcing oversimplification – including organizing people or groups involved in complex undertakings, revealing how their functions inter-relate as part of the larger whole [122].

5.2 Pattern Language as a Cyberinfrastructure Strategy

As can be seen, the definition of a pattern language bears strong synthesis with the tensions described in a recent report to the National Science Foundation regarding cyberinfrastructure [47]. Echoed in an earlier article by Smethurst, we can see a strong opinion that language is the place to begin for fostering the interdisciplinary relationship that is of primary concern in the cyberinfrastructure environment.

> For any member of a Community of Practice, there comes a time to interface with individuals and organizations which do not form part of the Community. The difficulty of this situation is the issue of language. Every Community of Practice – from physicists to painters to builders – has its own pattern language, its own way of expressing and discussing the unique qualities of its chosen art. This pattern language consists of the terms of art of the practice, the models that the Community uses to express itself and to translate reality, and the grammar that the Community uses to organize the models and terms of art.
> . . .

> Communities of Practice exist as their pattern language. This language must be robust enough to express the depth and breadth of the art form, and malleable enough to accommodate change and debate inside the discipline itself. This language must also be coherent enough to allow itself to be codified and translated to other Communities of Practice to be used and adapted to suit their particular needs and visions. All Communities seek to explore the white space. It is their method of exploration and their means of communicating their experiences of exploration that differ [112].

Over time, the method has been adapted to a number of other disciplines, showing that the method is flexible enough to be a viable candidate to be applied in the cyberinfrastructure field. Some notable examples of the cross-disciplinary application of the pattern language method can be seen in the construction of programming languages [49][56][90]. It is in this field that the method has been applied widely and gained great acceptance. It has also been found particularly useful in object-oriented environments, where the relational attributes between objects is of primary importance [62][99][132]. While a thorough understanding of how the pattern language has been applied in these fields is outside both the scope of this paper, as well as my technical competence, reading the articles makes it apparent that just as Alexander considered the physical environment to have consistent elements and rules for architecture, the programming communities that have employed pattern languages recognize a parallel quality to programming environments, where despite the lack of co-location, the cyberenvironment presents consistent elements, rules, and problems that may be addressed by making patterns explicit. Moving away from the strictly technical application of pattern languages, a number of social and sociotechnical communities have adopted the pattern language approach. Starting with the purely social, communities wishing to solve problems of sustainability and conservation have created a functional pattern language upon which to base policy discussions [35][36][37][38][46]. The concept has even been extended to the effective running of student study groups [74]. Turning to the most relevant cases, those that are applications of pattern language in the socio-technical realm, and of the most interest to the information sciences and STS fields, we see groups that have constructed patterns around IT-enabled and socially-responsible communication [25][105], project management and organizational change [26], learning management systems [11], user interface design [27][32][33][34], and service oriented architecture (SOA) at IBM [8]. As can be readily seen, the pattern language model has transferred effectively outside the original architectural milieu to address the needs of complex sociotechnical environments – environments like cyberinfrastructure.

5.3 A Competing Model for Lexicon Development

The competing model to the pattern language idea in cyberinfrastructure was put forth during the "History & Theory of Infrastructure" conference by JoAnne Yates. She stated that the process cyberinfrastructure system-builders should engage is based in the work of Peter Galison: establishing *trading zones*[23] and allowing language to develop from a *pidgin* to a *creole* [61]. The result of this protracted interaction and negotiation would eventually result in collaborative groups gaining interactional expertise, enabling fluid interaction [24].

The difficulty of relying on the pidgin and creole model hinges on the role of contingency in constructing the rules within the trading zone. Since a pidgin language forms between two communities engaging for the first time, it is functional but crude. In essence, it is an intermediate product in the establishment of interactional expertise. The creole language, fully formed and robust, is created by the generation that follows the pidgin-speakers – their children, so to speak. Pidgins and creoles are emergent language forms, arising not out of deliberate design, but out of the simple fact that they must come into existence for survival. As a result, they are contextual to be sure, but are not necessarily constructed to best suit the needs of problem solving. This is where the pattern language method surpasses the pidgin-creole model. It is specifically designed to solve problems in a contextual fashion. An additional and superior feature is that where a creole takes a minimum of two generations to form, a pattern language can be achieved in only one. It may be a relevant question to the system-builders (and moreover, the funding agencies) of cyberinfrastructure whether the sustainability of projects will be able to withstand the wait for two generations to pass before the trading zone becomes a comfortable and productive space.

5.4 The Tenuous Future of Cyberinfrastructure: The Need for a Common Language

In all of these examples, it seems reasonable to say that the the evolution of domain language, and for our specific purposes, pattern language, is an embodiment of praxis. Why does this have particular relevance to the cyberinfrastructure movement? In closing this line of thought, it seems prudent to ground the issues of language, interdiscipline, service, and infrastructure as the convergence of historical forces given new form in cyberinfrastructure.

The lesson of history here is that complex endeavors of large scale always promise great things; however, prescient catastrophic failure is always an element of such undertakings. While it is commonly observed that science is conducted locally and in a decentralized fashion, and that infrastructure grows out of linking those local contexts, placing the future of cyberinfrastructure in the hands of a centralized entity

[23]Trading zones are conceptual spaces in which two communities of practice are able to negotiate rules of engagement.

(the NSF Office of Cyberinfrastructure being the obvious focal actor here, but others may exist) is of exactly the type of authoritarian high modernism that James Scott admonishes in his statement:

> I believe that many of the most tragic episodes of state development in the late nineteenth and twentieth centuries originate in a particularly pernicious combination of three elements. The first is the aspiration to the administrative ordering of nature and society...
> ...
> The second element is the unrestrained use of the power of the modern state as an instrument for achieving these designs. The third element is a weakened or prostrate civil society that lacks the capacity to resist these plans [106].

The concentration of administrative responsibility in a governmental institution (OCI) speaks to the first element. The nature of reliance on political funding to sustain such scientific infrastructure is cautioned in the second element. The third element harkens back to Steve Shapin's statements that the public is incapable of competently taking part in the world of science and research [107]. The dangers of assuming that only the expertise of science resides in the practicing research communities to take part in cyberinfrastructure, and the competence of system-building is directed by a centralized authority, leaves us with a statement and four guiding principles tersely articulated by Scott, and in close alignment with Page's earlier statement about the strength of diversity (i.e., that a distributed and diverse set of practices that comprise cyberinfrastructure will show more robustness and optimization than a centralized and homogeneous group of planners.) With respect to grand plans to improve the state of human progress [106]:

> I would say that the progenitors of such plans regarded themselves as far smarter and farseeing than they really were and, at the same time, regarded their subjects as far more stupid and incompetent than *they* really were.
> ...
>
> - Take small steps – Presume that we cannot know the consequences of our interventions in advance. Given this postulate of ignorance, prefer wherever possible to take a small step, stand back, observe, and then plan the next small step.
> - Favor reversibility – Prefer interventions that can easily be undone if they turn out to be mistakes. Irreversible interventions have irreversible consequences.
> - Plan on surprises – Choose plans that allow the largest accommodation to the unforeseen.

- Plan on human inventiveness – Always plan under the assumption that those who become involved in the project later will have or will develop the experience and insight to improve on the design.

Of course, most, if not all of these principles have already been articulated by different observers of the cyberinfrastructure movement. Still, the simplicity of these four cautionaries bears repeating whenever possible.

6 Open Questions and Ideas for Future Research

As I come to the end of reading and putting together thoughts for this field exam, it occurs to me that much of the material represented in this paper can be considered an intermediate product to the direction I am considering for the dissertation.

6.1 Research Idea 1: Cyberinfrastructure and the Political Ecology of Legitimate Science

Through conversations with John King, Tom Finholt, Geof Bowker, Steve Jackson, Paul Edwards, and Steve Shapin, a related theme is emerging. I am curious to explore how cyberinfrastructure is positioned to alter the social and political sensibility of what it means to do legitimate science.

Becher and Kuhn state that a discipline is defined by the typology of questions that a community of practice deems to be legitimate [12][79]. The cyberinfrastructure agenda, as I have argued, is inherently interdisciplinary and is experiencing tensions in the formation of new working communities (due to the increased complexity of the research questions now considered possible.) At the same time, there is, I believe, a sociocultural conflation of science and technology, both within the public at large, as well as within the scientific community [95][107]. Through conversations with the above, it has been stated in several anecdotes that the vector of scientific progress is not free of politics, and that there may be evidence that political agendas have had a hand in inverting the logic of research directions. For example, the current CI agenda is particularly focused on the advancement of petascale computing facilities. On the surface, the argument for this investment is that advanced computing power is required to explore computationally intensive questions like understanding protein folding, climate models, and astrophysical phenomena. It has been suggested, as a counter-explanation, that instead, it is necessary to ask these types of questions to require the investment in ever-larger computing facilities, driven by a political agenda and belief that larger machines equate to global competitiveness and economic dominance.

If the latter interpretation has merit and can be justified, it leads to the question of: How do the political and social aspects of science and technology interact with what it means to do "legitimate science"? Or, employing the framework of service science, is the funding of cyberinfrastructure a new set of services to advance science and research...or is cyberinfrastructure creating a new set of services for politics? As a case to explore this question, I would like to examine the cyberinfrastructure movement as it is situated within the U.S. National Science Foundation. Through qualitative inquiry (ethnographic methods [78] and STS-based inquiry, particularly Latour's Actor-Network Theory-based methods [81][83]), and possibly quantitative methods (social network analysis, content analysis of related documents.) I would like to gain insight into the primary actors and relations of agency and contingency in constructing cyberinfrastructure, exploitation of the tensions in creating interdisciplines, and the formation of boundary objects that create new legitimacies in the interstices and breaches between traditional disciplinary cultures.

6.2 Research Idea 2: Unthinking Cyberinfrastructure

Another similar, yet somewhat less politically-driven topic is an examination of the historically embedded paradigms of scientific production that must be reformed for the cyberinfrastructure environment. Capitalizing on the work of Gibbons and Nowotny explored earlier in this paper, and engaging Immanuel Wallerstein's ideas of "unthinking science [126]," an STS-based project could examine the "Cyberinfrastructure and X" (where X is a domain science) set of reports for evidence of paradigmatic inertia and lock-in, using the general principles of infrastructural inversion as a guiding method [15].

6.3 Research Idea 3: An Ecology of Cyberinfrastructure Games – Incentives and Network Structures

A third topic of inquiry would be based upon the current work of William Dutton, Director of the Oxford Internet Institute. Similar to the earlier politically-charged framing of constructing legitimate science, we may also think of the normative processes in advancing and enrolling in cyberinfrastructure as an ecology of games [43][45].

The entrenched culture of data within science has a strong component of competition, which is challenged by the cooperative nature of cyberinfrastructure, open knowledge initiatives, and the push for broad metadata standards and generic gateways. The evolution of a working cyberinfrastructure could be modeled in a game-theoretic fashion, and employ agent-based simulation to explore parameters under which cyberinfrastructure initiatives are likely to succeed, and at what scale.

6.4 Research Idea 4: Comparative Models of Cyberinfrastructure Lexicon Building

A fourth, and more localized course of inquiry would be to expand upon the idea of using a pattern language model to ease the merging of disciplinary groups on cyberinfrastructure projects. This type of project would involve choosing a representative (or several) cyberinfrastructure project(s), and spend time working with the teams to implement a pattern language-building protocol.

There are several options with this plan. First, it may be advantageous to pursue some of this work through contacts in the United Kingdom, where the e-Science movement (the U.K. equivalent of cyberinfrastructure) is more mature, and established e-Science laboratories, which may have gone through the pidgin-to-creole transition, can be used for a comparative study with new endeavors that employ the pattern language method. This study can also combine both qualitative aspects in the form of interviewing actors for their interpretations of culture, production, and value of the research conducted, as well as quantitative measures of analyzing specific language constructs used between actors, and the rate of convergence to uniform terms (as found in memos, emails, formal and information communications, developed metadata standards, protocol descriptions, reports, etc.)

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