Building a Transdisciplinary Trading Zone: Knowledge Sharing and Integration in a Heterogeneous Milieu

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ABSTRACT

The numerous transdisciplinary research initiatives currently addressing a variety of complex social issues could benefit from a deeper understanding of the ways in which intellectually diverse groups work together to address problems. This research focused on a small group of investigators in a transdisciplinary institute as they sought to work collaboratively in the domain of infectious disease research. The unit's members described many challenges and successes that provided insights into the character and dynamics of transdisciplinary research, including how members developed a shared conceptual framework. The process proved enormously complex and was the product of long-term interactions among group members. Because participants were rooted in different disciplines and did not share professional trajectories, communication and understanding took extra effort, patience, and the development of a counterintuitive set of cognitive skills. Over time an integrated work process evolved within the group through a combination of strong interpersonal relationships, the mediating role of interactional expertise, and the development of shared boundary objects. Group members began working more closely with other team participants throughout the lifespan of projects. That experience over time allowed individuals to connect the details of their work together with the overarching goals and strategies of the group. This study employed the theory of trading zones to illustrate the ways researchers worked across boundaries to establish shared ideas, values, and goals. It developed and applied the concept of a transdisciplinary trading zone to describe the group's ability to coordinate its action despite both epistemic and communication barriers. Ultimately, the researchers studied sought a balance between being "productive," understood as

providing practical tools to industry and government, and generating novel scientific solutions to complex research problems. The group's success in securing a shared research aspiration despite its member's disciplinary and professional differences resulted from an iterative process of interaction that included learning from failed attempts and a constant and persistent negotiation of goals and values among those involved.

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Chapter 1

Introduction

I have a long history with interdisciplinary studies and practice as I have long been drawn to multiple ways of understanding the world. My intense curiosity about the fundamental physical processes of nature was never satisfied by one conceptual framework. Eventually, after gaining familiarity with multiple systems of representation in academic and practical settings, I began seriously to consider the question of how knowledge, both experiential and extracted, is translated and transferred between or even among individuals and systems.

One summer I worked as an intern conducting ecological research on a small island off the coast of Maine that serves as a seasonal breeding ground for around 2,000 seabirds. In addition to learning how to avoid the constant rain of bird droppings, I was exposed to several competing natural resource claims that commonly surround environmental issues. Our research focused on ecological processes and seabird biology in the context of an actively managed wildlife preserve where some species were valued over others and steps were taken to protect or control the favored or less-favored populations.

At the time, I was disconnected from the broader decision-making processes that evaluated whose values and knowledge were most appropriate to make such judgments among species. I relied on a predominantly reductionist method of research and broke problems into separate pieces, generated hypotheses that were tested through quantitative methods and statistical analysis, and came to an appropriate conclusion in the context of relevant disciplinary knowledge. I was by no means sheltered from other ways of viewing the world, but it was not until later experiences, despite my long-held curiosity, that alternate representations began to make sense to me and influence the way I value knowledge.

Ultimately, I began to ask questions that could not be explored exclusively from a natural science perspective. My interest shifted to the broader social context and the meanings ascribed within, and outside of, different forms of knowledge and scientific research. I started to see connections between these often separate ways of representing and understanding that could potentially be integrated into a more complete awareness. But how could knowledge be moved between/among these systems of thought or co-created through a coordinated effort?

The need, or at least an aspiration, to mobilize a diversity of professions and disciplines representing multiple perspectives to define and solve complex social and scientific problems collaboratively is receiving increasing academic and popular attention (Stokols 2006; Pohl and Hadorn 2007). These types of efforts are inherently challenging, but potentially more rewarding when addressing issues "where facts are uncertain, values in dispute, stakes high and decisions urgent" (Funtowicz and Ravetz, p. 744). Scientists trained in increasingly specialized fields may lack the capacity independently to develop productive connections to other fields of inquiry or to comprehend the broader significance of their work (Burger and Kamber 2003). Further, pressure is intensifying on the academy, partly by government funding sources, to conduct research that addresses socially relevant issues, irrespective of their often bedeviling complexities (Horlick-Jones and Sime 2004).

Many scholars, employing an array of analytical lenses, have examined group efforts to work across disciplines and sectors (Galison 1997; Collins, Evans et al. 2007; Klein 2008; Stokols, Misra et al. 2008; Jenkins 2010). Transdisciplinarity is one common conception that encompasses these types of endeavors at the science-society interface where groups comprised of a diversity of participants intentionally seek to integrate knowledge (Hadorn, Hoffmann et al. 2008); trading zones is another, but focuses on incommensurability issues between disciplines and sub-disciplines that impede cross-disciplinary communication (Galison 1997).

Empirical assessment of trading zone theory has only recently begun (Jenkins 2007; Jenkins 2010). Additional work is necessary to build a more complete understanding of group efforts that overcome the deep communication issues inherent in cross-disciplinary forays (Collins, Evans et al. 2007). Transdisciplinarity, on the other hand, is rich in practice-based recommendations extracted from a multitude of transdisciplinary projects (Hadorn, Hoffmann et al. 2008), but lacks a fully developed theoretical grounding (Zierhofer and Burger 2007). In particular, major elements of the so-called building blocks of transdisciplinarity remain to be clarified (Klein 2004).

Research Goals

The main impetus for this research was to understand better the group dynamics of an intentional effort to share and integrate knowledge among group members with diverse disciplinary perspectives. My first research question was:

- *Did group members (of the group whose efforts I examined) manage to co-produce knowledge across the disciplinary barriers inherent between separate systems of symbolic representation and manipulation? If so, how?*

Another issue this research sought to address was value conflicts among group members. In this case a tension arose in the group I studied between members with previous experience in academia and those with experience in industry. Each sector tends to favor different valuations of knowledge, and institutional and organizational goals influence group values and ultimately their aspirations. My second research question asked:

- *What did group members value and how did these values influence group goals and outcomes?*

The concept of trading zones offered a useful lens through which to view communication issues among a diversity of disciplinary perspectives (Galison 1997). However, the group I set out to analyze represented an intentional effort to develop and espouse a transdisciplinary research approach. One common conception of transdisciplinarity describes it as a process of integrated knowledge co-production through the generation of a shared conceptual framework (Rosenfield 1992; Abrams 2006; Stokols 2006). My original study strategy was to use each frame separately: trading zones to understand communication barriers, and transdisciplinarity to which to compare my study group's dynamics as a normative model for practice and to explore value alignment and knowledge integration. As it turned out, interviews with group members were better understood through an integrated concept of transdisciplinarity and trading zones. Each frame provided insights to strengthen the other that together constituted a more complete description of knowledge integration and the development of a shared understanding and value(s) alignment within the group I examined.

This integrated approach also made sense considering the main tension in the group arose not between academic disciplines or backgrounds and education, but between members with experience in industry, who primarily viewed knowledge as useful, versus members with academic experience, who valued research and publications over tools and products. The transdisciplinary research frame provided insights into how the group's research process evolved, but the trading zone frame was needed to address specifically how group members generated a shared understanding and accomplished knowledge integration. The concept of trading zones provided a complementary perspective to help fill in some of the gaps in the transdisciplinary literature concerning the dynamics of intra-group development of shared understanding and language.

This study sought to contribute to the need for more empirical evidence concerning the utility of the concept of trading zones. Further, the concepts of boundary objects and interactional expertise proved useful in combination with the idea of trading zones to attain a more complete understanding of transdisciplinarity and shared conceptual frameworks. These two constructs, trading zones and transdisciplinarity, were blended into a more complete theory of transdisciplinary trading zones that provided a more comprehensive understanding of the empirical evidence I collected. I describe the integrated construct of a transdisciplinary trading zone that emerged in the process of this research in Chapter 7.

Chapter 2 provides grounding in transdisciplinarity as a strategy for addressing complex social problems, a vision of knowledge, a concept and theory, and a research method. It begins with a broad definition of transdisciplinarity that captures its key characteristics and analyzes different modes of cross-disciplinary work in relation to that description. The concept of a shared conceptual framework is introduced in this chapter and then explored further in Chapter 7. The research site is described in Chapter 3, including a brief history of the Virginia Bioinformatics Institute (VBI) and the Cyberinfrastructure (CI) Group within that organization. This chapter also sketches the Institute's organizational structure and my study group's disciplinary diversity.

The theoretical framework outlined in Chapter 4 employs actor-network and trading zone theory. Actor-network theory focuses on relationships among people, but also between the people, things, and ideas that constitute a "network of association", or the physical embodiment of knowledge, commonly expressed as technology (Latour and Woolgar 1986; Law 1992; Czarniawska and Hernes 2005). Multiple conceptions and stages of trading zones are outlined in this chapter as well as specific means for overcoming communication barriers to secure shared group aims. Knowledge and knowing are explored in this section too in order to understand better how it is, and under what circumstances, ideas are transferred or integrated across disciplinary boundaries.

Chapter 5 connects these theoretical frames to a qualitative methodology that guided me through data collection and analysis. Chapter 6 presents the study's findings. Finally, Chapter 7 delves into the means by which the CI Group overcame communication barriers. Group members employed standardized methods, boundary objects, interactional expertise, and trust to construct a shared mental model and metalanguage. The chapter also develops the concept of a transdisciplinary trading zone and argues the construct enhances understanding of the study group's ability to coordinate research practices in spite of communication and knowledge barriers.

Chapter 2

Transdisciplinary Research Approach

> One appropriate definition of transdisciplinarity is that it is the transformation, restructuring, and integration of knowledge from multiple perspectives such as to produce a new holistic perspective. The notion that the prefix "trans" in transdisciplinarity carries with it a process notion is an especially cogent one. This affects the various ingredients that, taken together, comprise transdisciplinary efforts; cooperation; appreciation; disaggregation, or taking apart; aggregation, or putting together; modification; and transformation (Sage 2000 p. 251).

An evolving transdisciplinary research approach (TDR) to complex scientific and social problems during the last two decades represents a reaction to the increasing specialization of disciplinary research that has thus far demonstrated limited ability to generate solutions to thorny social, economic, and environmental challenges (Klein, Grossenbacher-Mansuy et al. 2001). I follow McDonell's (2007 P. 27) definition of discipline "as residing in a cultural formation comprising a group of people who, both explicitly and implicitly, share and practice a form of scientific or professional knowledge which they regard as distinct."

Avowedly transdisciplinary research teams are currently addressing an array of issues, including public health, environmental and social sustainability, urban planning and international development concerns (Albrecht, Freeman et al. 1998; Klein, Grossenbacher-Mansuy et al. 2001; Balsiger 2004; Hadorn, Hoffmann et al. 2008; Stokols, Hall et al. 2008; Stokols, Misra et al. 2008). These represent intentional efforts to transcend the limitations of traditional disciplinary practices of knowledge production and their subsequent applications. At the core of transdisciplinarity is, as Stokols has suggested, "the *integrative quality and scope* of transdisciplinary research products (e.g., hypotheses, theories) that set them apart from the more traditional intellectual products of unidisciplinary science." (2006, p. 67) At the same time, transdisciplinarity is also about beauty, imagination and building a space for creative problem analysis and innovative knowledge production that can be applied in multiple settings (Somerville and Rapport 2000). Transdisciplinarity represents both of these perspectives, an imaginative and cognitive process of knowledge sharing and integration.

There are many examples of projects purportedly employing a transdisciplinary approach (Rosenfield 1992; Klein, Grossenbacher-Mansuy et al. 2001; Abrams 2006; Stokols 2006). These efforts generally exhibit a common set of characteristics that distinguish transdisciplinary from interdisciplinary and multidisciplinary approaches, but some ambiguity still exists about distinctions among them. In particular, one frequently identified aspect of a transdisciplinary process, the creation of a shared conceptual framework among researchers, has not been fully developed in the literature (Zierhofer and Burger 2007; Kessel and Rosenfield 2008).

Views of transdisciplinarity in the literature

There are many examples of research efforts in which core characteristics of transdisciplinarity may be identified. First and foremost transdisciplinarity is, as Balsiger (2004 p. 415) has stated, "above all, a principle of research." Definitions and descriptions of TDR are as diverse as the various views that generate them. Each grouping listed below represents a perspective embodied in the TDR literature.

- Strategy for Addressing Complex Social Problems
- Vision of Knowledge
- Theory or Concept
- Research Method

Rosenfield (1992, p. 1351) has provided a useful classification of the forms of cross-disciplinary work that also helps characterize transdisciplinary research. The first level she has described is *multidisciplinarity* where researchers work from within their discipline on a common problem in either a sequential or parallel fashion. This is a typical practice in building construction, for example. Each practitioner participates in constructing one building, but works solidly from their discipline or profession as they do so. The architect conceptualizes the design of the structure and turns it over to an engineer or building construction manager, who then applies his or her disciplinary knowledge to move the conceptualized design toward a material manifestation. The various subgroups of builders (plumbers, carpenters, roofers, etc.) create the material structure. These specialists work from a common plan and share information, but each sub-process of production is segmented and conducted in a mono-disciplinary fashion. Electricians design and install electrical wiring and systems, plumbers do likewise for water and waste systems, and so on.

Interdisciplinarity, the second level of integration in cross-disciplinary work, occurs when participants work primarily within the confines of their disciplinary perspective, but also jointly on a common problem with members of other disciplines. For example, an architect, engineer, and numerous building construction professionals might work together to design and build a suitable living space for a client. An interdisciplinary approach can lead to new insights due to a more open flow of information and cooperation, but each representative of the engaged disciplines still applies their individual expertise to the building process, and retains generated knowledge within their own discipline (Rosenfield 1992).

Transdisciplinarity, however, suggests that researchers generate a shared conceptual framework or some form of meta-level coherence that draws from each participant's perspective, but is strengthened through the integration of disciplinary knowledge (Rosenfield 1992; Sage 2000; Stokols, Fuqua et al. 2003). Problem solving that proceeds in this way results not only in a unique process, but also promotes novel outcomes. What would a building look like if the architect sat down with the engineer and the building contractor before drawing up blueprints? Now imagine encouraging the members of the group to challenge each other's disciplinary assumptions or professional norms to generate shared goals and means of attaining them. That would be a transdisciplinary approach to construction. If these individuals are asked to address a common problem, designing a livable house that is beneficial to both home owner and community, for instance, what might be accomplished via an integrated analysis that is not otherwise possible through either mono-disciplinary, multidisciplinary or even interdisciplinary efforts[1]? To differentiate further:

> I would like to suggest that we call "multidisciplinary studies" a collaboration among experts, members of different disciplines, where the relation among them is associative, i.e., where the work of each of them is added to that of all the others. These are very common in many fields. In "interdisciplinary studies," I suggest the connection is relational, i.e., where the disciplines collaborate in such a way that each takes up some of the assumptions and worldviews and languages of the others. And "transdisciplinarity" would therefore exist where the integrating relationship is taken to the extent of there being a transcendent language,

[1] See Ramadier (2004) for examples in urban planning and Rosenfield (1992) for examples in public health.

> a metalanguage, in which the terms of all the participant disciplines are, or can be, expressed. (McDonnell 2000, p. 27)

This transcendent or metalanguage has also been described as a shared conceptual framework (Rosenfield 1992).

Shared Conceptual Framework

Many transdisciplinarity analysts have adopted Rosenfield's (1992) argument that a shared conceptual framework is a definitive characteristic of this form of research (Parkes, Bienen et al. 2005; Stokols, Hall et al. 2008). In this view TDR is a process through which a shared conceptual framework is generated, one that does not otherwise exist. Rosenfield has identified the central use of a common frame as a distinguishing factor between interdisciplinary and transdisciplinary research. As she has observed:

> Representatives of different disciplines are encouraged to transcend their separate conceptual, theoretical, and methodological orientations in order to develop a shared approach to the research, building on a common conceptual framework. Such a framework can be used to define and analyze the research problem and develop new approaches for health care that more closely represent the historical and present-day reality in which health problems are situated. (1992, p. 1351)

Rosenfield described an approach adopted by a group of health science researchers she investigated in which individuals from different disciplines contributed to a multidimensional understanding (creation of a holistic model of reality, centered around a contextual issue) of both the problem under study and potential solutions to it. The effort Rosenfield examined included malariologists, sociologists, epidemiologists, economists, anthropologists, regional planners, vector biologists, demographers, and immunologists. As she described the result of this project:

> Only then were they able to develop new social and medical science concepts and approaches to disease control. They redefined the concept and meaning of malaria in a mobile population and developed more feasible ways to assess and control the disease in that context. …when the team moved as one almost from the beginning, and showed openness and readiness to consider and combine diverse concepts, the transdisciplinary process was initiated. (1992, pp. 1351 - 1352)

Rosenfield stopped short of providing detailed recommendations for action and did not describe a process for participation in the implementation of solutions. Also, she argued that institutional and financial obstacles proved greater than conceptual ones in the case she explored. Unfortunately, Rosenfield provided few details about knowledge integration, intra-group conflict or other specific indications of progress that might conduce to creation of a shared conceptual framework.

Transdisciplinarity can be viewed as a process through which different disciplinary perspectives, much like sensory perceptions, are integrated toward coordinated thought and action. This is similar to individual cognition when the richness of information processed by the human brain results in action. Individuals make innumerable choices as they process sensory information that are then compared to memories of experiences that identify which stimuli to notice, which to ignore, which require immediate action and which to store for later use. Disciplinary science has trained researchers to be very adept at collecting and filtering particular types of information using specific tools and techniques that are potentially very powerful, but at the same time can limit knowledge diffusion across disciplines. The potential of TDR is not just to increase the breadth of problem solutions, but also to apply a diversity of perspectives to create a shared aspiration around what to look for, how to look for it and why even to investigate in the first place.

One major hurdle or challenge regarding shared aspirations and understanding is communication between and among individuals possessing different ways of knowing generated through diverse systems of representation. In a group characterized by disciplinary diversity, it is almost as if one person can only hear, one can only see, one can only smell, and another can only touch. How do they communicate each sensation to one another if each has never experienced the sensations others are describing, let alone the differing interpretations being supplied to describe those perceptions? The result is a gap in understanding and a potential tension among researchers. As Hall, Stevens et al. have suggested:

> Participants from different disciplines animate situations in strikingly different ways, but these differences can either go unremarked or be put into coordinated use without explicit, shared understandings. … Working conversations between disciplinary specialists are places in which differences in perspective lead people to see and act on represented objects in different ways. Under what conditions do participants in these conversations notice and use disciplinary differences to change existing systems of representation? 2005, P. 124)

The construction of a shared conceptual framework is a process through which researchers work together to develop a strategy to integrate these different perspectives (Sage 2002). Part of this approach must include decisions about the capacity of different members to fulfill different roles in a coordinated fashion. Participants must consider what resources should be sought and how they should be allocated in the most effective, efficient, and ethical manner. The complexity of these types of projects is difficult to overcome through design (a priori), but must flow from a work process that allows an organic emergence of strategies within the context of each TD project (Gibbons, limoges et al. 1994; Pohl and Hadorn 2007). In effect, the work itself must create an extended peer review process that opens up a multi-sectoral debate to the level of existing norms and policies attending the issue at hand (Funtowicz and Ravetz 1993; Pereira and Funtowicz 2006). Ideally, the transdisciplinary approach expands participation both vertically, through sectors, and horizontally, through disciplines in an attempt to understand a problem better, craft an effective solution and implement that selected alternative (Parkes, Bienen et al. 2005).

Vertical participation and integration refers to the cross-sectoral dimension of transdisciplinary work, bringing together academics, public officials, political representatives, and community members directly affected by a problem or challenge. Not all members participate at all times, but participants from each sector–public, nonprofit, for-profit–potentially have relevant knowledge to increase the success of both finding and implementing possible solutions (Pohl and Hadorn 2007). Horizontal or cross-disciplinary participation is also a necessary component of transdisciplinary work as each discipline possesses different capacities to bring to the effort. Of course, a transdisciplinary research approach is no panacea for all social ills and it is not appropriate for all problems (Gibbons, limoges et al. 1994). Disciplinary science is more effective when the research scale is small and the scope is narrow. But as the reach of an effort increases and the scale of research broadens, a transdisciplinary approach becomes more effective. Such efforts will also require more time and effort (Funtowicz and Ravetz 1993; Pereira and Funtowicz 2006). Increasing the heterogeneity, scale, and scope of investigation and the research team necessarily leads to a slower, more intensive effort. Working across disciplines, while increasing the capacity of a group to address a problem more comprehensively, also introduces a whole new set of challenges, including finding ways and means for those involved to communicate and coordinate across disciplinary boundaries (Ramadier 2004).

At its core, the concept of transdisciplinary science acknowledges both the strength and weakness of disciplinary paradigms. In traditional disciplinary inquiry what the narrow focus of the specialist gains in depth, is sacrificed in breadth and adaptability. The TD approach attempts to overcome the barriers created as a result of fragmented and specialized knowledge production while retaining the strengths obtained by specialists through their circumscribed focus and disciplinary foundations. Transcending disciplines represents an explicit attempt to generate more comprehensive intellectual products (Stokols 2006). Further, transition from knowledge production to community use is not just an afterthought, but a primary goal of TDR, not unlike the policy utilization problem (Webber 1986). At the very least, the transfer of knowledge generated in TDR to policy-makers is a primary goal. Transdisciplinary knowledge is aimed both at addressing practical problems and producing the knowledge necessary to generate solutions to them (Hadorn, Hoffmann et al. 2008). In effect, transdisciplinarity has become an essential mode of thought and action (Klein 2004).

Unfortunately, the transdisciplinarity literature has not yet developed a nuanced understanding of the TDR process from the perspective of the researcher. I am left to ponder to what extent integration is attained or is even attainable in a transdisciplinary research effort. For what ends and through what means is it attempted? Further, how are value claims negotiated? How is meaning constructed within projects, given the barriers between or among disciplinary understandings? These questions can be loosely gathered under the heading of knowledge integration and evaluation across disciplinary perspectives. I investigated these concerns by interviewing researchers in the Cyberinfrastructure (CI) group of the Virginia Bioinformatics Institute (VBI) about how they seek to produce knowledge via a TDR process.

But, as noted above, I also turned to the theory of trading zones to understand better the barriers to communication and integration of knowledge in the CI Group. This is not to imply that the transdisciplinary literature is devoid of theoretical insights. Rather, trading zones provide a complementary perspective to help fill in some of the gaps in transdisciplinary literature concerning intra-group formation of shared understanding and language. At the same time, the theory of trading zones lacks empirical evidence that I hope to contribute from an exploration of the CI Group as a trading zone. Boundary objects, interactional expertise, inter-languages and shared mental models are also useful contributions from trading zones that add to a more complete understanding of transdisciplinarity.

By overlaying TDR and trading zones, I constructed a theoretical frame that provided a more comprehensive understanding of the empirical evidence I collected from the CI group. These theories and methods are developed further in chapters 4 and 5, but I first provide an introduction to my research site.

Chapter 3

The Cyberinfrastructure Group

My first introduction to the Virginia Bioinformatics Institute was in a local pub, of all places, at which I was introduced to its Scientific Director and Cyberinfrastructure Group leader. At the time it did not mean much to me because I was conducting research on the Forest Service/Nature Conservancy Fire Learning Network initiative. I believed microbiology was part of my past life having spent two years in a microbial ecology lab earning a Master of Science degree, not my future research site and focus. As it turned out, I eventually secured a graduate research assistantship at VBI to study transdisciplinary science. That connection eventually shaped my entire research focus.

The Virginia Bioinformatics Institute is a unique place. VBI was created in 2000 at Virginia Tech as a center for bioinformatics research. As the new century dawned, biotechnology was beginning to receive recognition as a new and promising domain ripe for scientific discovery. Starting with only 5 members, VBI quickly expanded over the next 10 years to more than 240 personnel who currently occupy 130,000 square feet of working space, with an additional building under construction. Integral to the Institute's success is a formidable array of shared computational and laboratory resources that support research in the life sciences. VBI research groups include:

- Network Dynamics and Simulation Science Laboratory
- the Cyberinfrastructure Group

- Biochemical Networks Modeling Group
- Medical Informatics and Systems
- Synthetic Biology Research Group

VBI was at first an intimidating place to someone who was, to my knowledge, its only social scientist. My biology background was a comfort that not only helped get me the assistantship, but also assisted in my interactions with CI group members. Talking about biology gave me credibility, capacity to understand the research underway and a convenient topic of conversation. I also must admit the way I think about problems will likely always be shaped to some degree by a biological perspective. This was an advantage when talking to the biologists and bioinformaticians in the group. At the same time, it was not as useful for understanding the perspectives of the software engineers or computer scientists who make up the majority of the CI Group. However, I soon learned most of the non-biologists were at least partly fluent in biology because it is CI's domain of interest and expertise.

The group builds cyberinfrastructure[2] that supports infectious disease research while pursuing scientific discovery. But as the leader of the CI Group (Personal interview 2009) described that purpose or focus to me, it went beyond computers, data and software to include "people and the relationships between people and groups, analysts and all sorts of things … I saw the group doing." The unit includes individuals with knowledge of the following subjects and more: evolutionary biology, microbiology, genetics, immunology, software engineering, software development, computer science, computational biology, bioinformatics and statistical genetics. These individuals are also connected to a very large number of external collaborators. As its director described observed to me, the CI Group has multiple characteristics:

[2] Cyberinfrastructure includes data, computers, and people supporting scientific research and knowledge production.

> The [CI] Group is my research group and my strategy was [that] we were going to need people who understood microbiology, to say it broadly, but in particular bacteriology. From a sort of an engineering perspective it was very important for the group to contain very serious software professional engineers, and I distinguish software engineers and software developers from say computational scientists in general simply to say their product is actually embodied in real software that operates, since the scale of resources we were seeking were going to require that our information systems be available sort of on a 24 by 7 by 365 lights out environment, that really meant we needed to have people who could produce and test and quality assure professional quality code. And so in addition [to] the engineering perspective, then I would call it the annalist computational perspective for people who I guess they would more canonically be called bioinformaticians or a statistical geneticist or annalists of some sort, people who can use the engineered systems, plus the data in them to essentially make scientific discoveries. And establish and maintain collaborations with the very, very large number of external collaborators that we need to maintain to be successful. (Personal interview 2009)

Group Structure

These engineered systems, or cyberinfrastructure, support a broad research agenda comprising many overlapping projects. Group members often worked on multiple projects, and many components of these endeavors were strategically linked to economize work across them. For example, building infrastructure and software to handle bacterial genomic data for one project could also be used to handle viral genomic data from another initiative. The CI group is a multi-project, multidisciplinary research effort. Group members brought diverse research experiences from academia and industry into the group resulting in a professional staff composition of decidedly mixed origins.

Research groups in academia are typically led by a Principal Investigator (PI) and a small number of graduate students, undergraduates, and supporting staff.

This is a generalization, but the main point is that research in academia emanates from the PI who secures funding and sets the agenda. In contrast, research conducted in a commercial setting may have a PI-type leader, but duties and responsibilities for the effort tend to be distributed across more people. Managers are responsible for managing, biologists for doing biology and the investigative agenda follows company interests. These teams are well connected, at least within the company, and share common goals set by administrators. Again this is a simplified model, but a useful one to which to compare the mixed backgrounds of CI Group members.

The organizational structure of the CI Group is a product of both intentional design choices and the institutional environment of which it is a part. It is difficult to pull the CI Group away from VBI completely for a thorough examination but I can point out some of the important connections between the group and its parent organization. CI Group is an integral part of VBI, relying on and contributing to the Institute's infrastructure. From a biological perspective this would be described as a symbiotic relationship. CI Group shares VBI core facilities, computational and laboratory, institutional administrators and staff, human resources, office space etc. with other Institute researchers and groups. VBI, although enjoying an unusually high level of autonomy, is a research institute at Virginia Tech with all the benefits and constraints that such status yields at a major research university. As one CI Group member observed:

> I mean nominally this is an academic group, so it's part of the university and the head is a professor and it's unique in some ways. But then what makes it different I guess from most academic places is that there's, I think even coming from the president of the university, a directive to make products. Make some money. I've never seen that in any other academic place. Maybe I just haven't seen other places like that. I think any place would want you to get patents and grants but here, I've heard more like kind of company kind of goals, but it's still couched in an academic framework. (Personal interview 2009)

This description reveals one aspect of the intersectional space the CI Group inhabits in which values and goals are drawn from both academia and industry. An important connection to reiterate is the dual role of the CI Group leader and, until recently, the Director of VBI. His vision and leadership have shaped both the Institute and the CI Group in many similar ways. Transdisciplinarity was at the core of his vision of moving the Institute and the CI Group beyond a typical academic model toward a more integrated form. This perspective is a main reason for the hybrid character of the CI Group.

However, the CI Group leader is not the group's only PI: the Group also includes other PIs as well as professional managers and other researchers fulfilling duties typically carried out by a PI in an academic setting. At the time I conducted interviews there were five members of CI Group with the title PI, Co-director, or Project Manager. One Co-director had previously spent many years in industry developing commercial-level software. Another Co-director, also with experience in industry, was very much grounded in biology and genetics and the third was an engineer with an MBA and project management experience in academia. Each brought a unique perspective to the group based on their professional and academic experience and education. Each contributed to the intellectual and disciplinary diversity of the unit.

The co-director system partly evolved out of necessity as the Institute grew and the group leader's role as VBI's director consumed more of his time and attention. But this structure also aligned with a transdisciplinary model geared toward knowledge integration and an industry-like division of labor. As one CI Group member described the group's organization: "I think in a project like this it's not strictly research, it's not strictly product development. It's a mix." (Personal interview 2009) The diverse backgrounds of the Co-directors and the rest of the group are important to explore further, but that issue is loosely coupled with funding so I turn to that subject briefly.

CI Group is one of the most well-funded research groups within VBI, recently winning a federal award that is the largest ever received at Virginia Tech. I will take up this point again later when examining the relative success of the group, but for now I want to sketch the forms of funding CIG has received and the impact of those resource streams on the unit. The unit's research is funded through grants and contracts. This is a very important distinction because it exemplifies as well as contributes to a central tension within the team. Contracts are presently the dominant source of funding for CI. Contracts require products and deliverables (like industry) and knowledge application is imperative, while grants are geared more toward scholarship through publications. A focus on the usefulness of knowledge is of increasing interest to government and industry funders alike. As Horlik-Jones and Sime have noted:

> Arguably, the more profound influence has been increasing pressure on the academy to demonstrate a capacity to generate knowledge that can address societal problems and contribute to economic competitiveness. Government sources of research funding increasingly seek evidence of applicability as an important indicator of performance. (2004, pp. 442-443)

The recent large award to CI Group was a contract renewal with the National Institute of Allergy and Infectious Diseases (NIAID) to continue building and maintaining infrastructure for the PathoSystems Resource Integration Center (PATRIC) project. The PATRIC project is a dominant effort in the unit and at the time of my interviews, group members had recently finished the proposal for the contract extension and received notice of success. Although this was a renewal, group members nonetheless had to compete with other, more established research institutes, for the contract. Receiving this award not only suggests that the PATRIC project was successful, but as expressed by one group member, it also signaled the CI Group had developed a shared vision it could express persuasively to NIAID.

Group Composition

Group members supporting bioinformatics infrastructure typically work on tasks related to building software, systems engineering, and web-based services. Biologists in the group conduct research on bacterial and viral genomes as well as act in a design and quality control role to advise on building and testing software tools and applications. By studying the genetic information of organisms and their relatives that cause disease, CI Group's goal is to advance knowledge and tools that could lead to preventive therapies and potential cures for diseases. The computer-oriented members of the group consist mainly of computer scientists, or those concerned with data systems and processing information, and computer software engineers who write computer code designed to process, store and manipulate genomic information. Bioinformaticians inhabit something of an intellectual middle ground between the biologists and the computer scientists.

In many ways the bioinformaticians form a distinct discipline. It is useful to conceptualize bioinformaticians in the CI Group as falling somewhere on a spectrum with the tendency to think like a biologist at one end, and the proclivity to think like a computer scientist or engineer, at the other end. Some bioinformaticians began their careers in biology and later gained expertise in software engineering while others began in software or computer science and subsequently developed proficiency in biology. Each individual has a unique story about how they came to be involved with bioinformatics. The diversity of CI Group and its relative insulation from disciplinary departments coupled with an intention to pursue, and organizational support for, a transdisciplinary research approach provide an interesting opportunity to investigate the dynamics of cross-disciplinary knowledge border crossings in an organizational setting.

Chapter 4

Theoretical Framework

Theory poses a perplexing paradox. On the one hand, going into field research without a well-developed theory can lead to unfocused and unproductive research. Without theory it is hard to know what to look for and how to analyze it once found. On the other hand, to develop theory too fully before going into the field creates a potential tautological situation where theory can impose structure on data (through me, the research instrument), rather than allowing the data to speak to theory (Latour 2005). In other words, it is akin to the cliché of running around with a hammer thinking everything looks like a nail. Some methodologies require high levels of theory development prior to data collection while others require a less robust frame. Nonetheless, even from within the shelter of an established theory, this tension concerning the timing of theory development must still be addressed.

My approach borrowed from actor-network theory and trading zone theory, but also incorporated concepts from the TDR literature. Much like the cross-disciplinary team I studied, the foundation of my theoretical perspective was mixed. I interpreted my data based on concepts drawing on those views and constructed a more comprehensive understanding that reflected elements of each, but represented an aggregation of something more than the individual parts.

Actor-Network Theory

Actor-Network Theory (ANT) means many things to many people. It has evolved out of Bruno Latour's studies of the practice of science and has been further developed by several other prominent scholars (Callon 1986; Law 1992). But for the purposes of my research I focused mainly on the version Latour (2005) shared in *Reassembling the Social: An Introduction to Actor-Network Theory*. Latour's fundamental argument involved rethinking what exactly constitutes the "social". He confined his definition to "the social not as a special domain, a specific real, or a particular sort of thing, but only as a very peculiar movement of re-association and reassembling. … It is visible only by the *traces* it leaves (under trials) when a *new* association is being produced between elements which themselves are in no way 'social'" (2005, p. 7-8). Social forces are enacted through relationships and do not exist as some ethereal force. There is no "social" world parallel to the physical world producing separate influences on how people behave. For example, Latour argued against the use of a "social context" to "account for the residual aspects that other domains (psychology, law, economics, etc.) cannot completely deal with" (2005, p. 4). ANT takes as its starting point that what is labeled "society" or "social forces" is the puzzle to be solved and not the antecedent conditions that explain "society" (Latour 2005). In other words, an organization is an effect of organizing, not a thing in and of itself.

On the role of the sociologist Latour offered this bit of advice:

> But in situations where innovations proliferate, where group boundaries are uncertain, when the range of entities to be taken into account fluctuates, the sociology of the social is no longer able to trace actors' new associations. … The duties of the social scientist mutate accordingly: it is no longer enough to limit actors to the role of informers offering cases of

> some well-known types. You have to grant them back the ability to make up their own theories of what the social is made of. (2005, p. 11)

My research followed the "actors themselves" in order to capture what was "not yet–a sort of social realm." (2005, p. 12) Latour agreed with Tarde that these collective assemblages of the whole, or *networks of association* as he called them, not society, are composed of incremental small elementary acts. (1899/2000, p. 35) Latour proposed focusing sociology on connecting and reassembling "how things, people, and ideas become connected and assembled in larger units". (Czarniawska 2006) The French anthropologist drew a parallel between this move away from the sociology of the social and the move from a "pre-relativist" to a "relativist" perspective in physics. His hope was that suspending commonsense notions of what the "social" is would lead to asking basic questions that could in turn trigger advances in social science. Capra (2002) has offered a similar argument concerning the paradigmatic shift in physics from the Newtonian study of objects to the Quantum examination of relationships.

This insight meant I focused my research on the way researchers described their own struggles to produce knowledge, rather than seeking to fit those to any preconceived notion of what should constitute transdisciplinary research. My approach was thoroughly grounded in empirical evidence. Instead of walking around with a field guide trying to classify research practice as multidisciplinary, interdisciplinary or transdisciplinary, I undertook to do the reverse. I interviewed and observed researchers to understand how they constructed their own categories of knowledge and generated meanings from those constructs.

Latour's notion that there is no group without grouping is a good example of a focus on relationships rather than "objects" and provided an important starting point for my analysis. Categorizing people as a group likely would have resulted in a focus on the team as an object, rather than the actions of the people who daily form and (re)form and maintain the group or network of associations. People constructed the CI Group, not social forces. Individuals and their intention to work together despite communication challenges and value disputes hold it together today.

Latour's (2005) networks of association also include physical objects, ideas and people. To him, what is important is the influence objects have on the way people think, behave and even imagine: "An invisible agency that makes no difference, produces no transformation, leaves no trace and enters no account is *not* an agency. Period. Either it does something or it does not. If you mention agency, you have to provide the account of its action. … or it becomes "conspiracy theory not social theory". (Latour 2005, p. 53) Latour was very clear that objects do not possess any level of intentionality, merely the capacity to affect human behavior. The agencies with which ANT is concerned are only the ones that can be proven empirically. Traces of agency can be found in writing, conversation and the physical environment, left behind by people as they construct and maintain networks of association.

I have only highlighted a few key concepts of Actor-Network Theory that specifically relate to my research interests and methodology. For various practical and theoretical reasons I did not practice ANT as Latour (2005) suggested it should be employed. One main difference between my work and Latour's approach is that he based his methodology in anthropology and ethnomethodology, both of which rely primarily on observational data. I primarily collected interview data from CI Group members to understand better how the group addressed cross-disciplinary communication challenges. Actor-Network Theory provides a useful theoretical foundation, but I also turned to the concept of trading zones to develop a more complete understanding of CI Group's cross-disciplinary dynamics.

Trading Zones

"The space–partly symbolic partly spatial–at which the local coordination between beliefs and action takes place. It is a domain I call the trading zone ". (Galison 1997 p. 784)

Galison (1997) borrowed the concept of trading zones from anthropology to describe the dynamics he observed in laboratories in which experimental, instrumental, and theoretical physicists sought to work together on collaborative projects such as RADAR. He noted many subtle yet distinct cultural differences that created communication and coordination barriers among investigators assigned to that path-breaking initiative, despite their shared discipline. These dissimilarities included various conceptual tools, technical language, and experimental procedures that resulted from their specific disciplinary acculturation and research experience. These "groups with very different systems of symbols and procedures" somehow managed to overcome gaps in communication and understanding through trade, or as Galison put it, they participated in "*local* coordination despite vast *global* differences". (Galison 1997, p.783)

Galison proposed communication issues were addressed through the development of an inter-language in the context of research practice. At the same time he also sought to "*expand* the notion of contact languages to include structured symbolic systems that would not normally be included within the domain of "natural" language". (Galison 1997 p. 835) Galison's inter-language included scientific instruments and their usage. He specifically contended trading zones are not a matter of translation, rather a more comprehensive web of relationships, much like Latour's networks of association, that included things and ideas embedded in systems of representation and discovery. Galison was interested in the transformational aspect of knowledge created through co-production, not just the transfer of ideas from one culture or sub-culture to another. The inter-language generated by the subcultures of physics was expressed as new language, but also as the technology itself. This new form of communication was generated as ideas, tools, and instruments developed to work on joint technological problems—such as the development of RADAR. Engineers and theoretical and experimental physicists had to find ways to communicate despite differing conceptions concerning some of the most fundamental aspects of nature, such as, in this case, the function of the electron.

The inter-language necessary to produce RADAR evolved from two "parent" languages (Galison 1997). Galison described the inter-language as developing over time and progressing through stages similar to the progression described in anthropology by which a new intermediate language emerges from constant contact between two cultures speaking different tongues. It began as common words, "jargon", then moved to a more complex "pidgin", and finally to a full-blown new language or "creole". A creole, like the one that developed in Haiti, displays characteristics of its parent languages, but a native speaker of either "originating" language does not fully understand the new creation.

Collins, Evans and Gorman (2007) set out to describe other resolutions to disciplinary communication issues not captured by Galison's concept of inter-language through a general model of trading zones. In order to explain these alternate mechanisms to address deep communication issues, they divided Galison's concept of a trading zone into four distinct ideal types organized along two dimensions or axes. One axis captured the composition of the group, from homogenous to heterogeneous, while the other described how trade is accomplished from collaborative to coercive means. (Collins, Evans et al. 2007, p. 659)

The "inter-language" trading zone is representative of the full blown "creole" that Galison theorized. In its ideal form, participants are homogeneous, but trade through mutual agreement, such as was the case for biochemistry, which emerged at the intersection of two disciplines, biology and chemistry, but is now defined as distinct. The "subversive" trading zone and the "enforced" trading zone are both a result of coercion. The difference between the two is how each emerges: "whereas in the enforced trading zone scientific authority was imposed by institutional means, in a subversive trading zone it gradually supplants the alternatives until it becomes the socially appropriate response." (Collins, Evans et al. 2007, p. 660) One language becomes dominant in both zones, but through different means. Microsoft's Windows operating systems and VHS are technological examples where the dominance of one technology has a coercive effect on its users, who are in effect thereby homogenized by a lack of other technological options. The "enforced" zone is comprised of heterogeneous cultures where one culture dominates trade through coercion. Collins, Evans and Gorman described it as a trading zone:

> … where the expertise of an elite group remains 'black boxed' as far as the other participants are concerned. The access of the non-elite to understanding of the elite culture is tightly controlled by those in power. At the same time the elite group will make little or no attempt to gain access to the expertise of the natives. In this model there is no attempt to reduce the cultural heterogeneity and all the control is from the top down. (2007, p.659)

They offered as one example rowers on a Roman galley, where the slave seagoers receive food, water, and are allowed to live in return for forced labor, but they only learn enough Roman language and culture to communicate concerning simple tasks. The fourth, and most pertinent ideal type of trading zone for my research is the "fractionated" trading zone in which membership is both collaborative and heterogeneous. Collins, Evans and Gorman divide the fractionated zone further into two subzones based on the means by which communication and coordination problems are addressed within it, boundary object fractionated trading zones and interactional expertise fractionated trading zones.

Boundary objects can create a common symbol, identity, goal or aspiration among a diverse set of participants. (Star and Griesemer 1989; Carlile 2002; Collins, Evans et al. 2007) An ideal type or object, such as a diagram, symbolically serves as a means of communication and cooperation. (Star and Griesemer 1989) The term "object" connotes not just physical things, but also ideas, measures, and symbols. (Galison 1997) Standardized forms are boundary objects expressed as shared procedures and methods of communication that stabilize coordination across communities. (Star and Griesemer 1989).

In the boundary object-trading zone, action is taken in the absence of a shared meaning through a focus on global objects that can be adapted to local conditions, such as specimen collection techniques or the state of California. (Star and Griesemer 1989) These objects mean different things to different people, but each can act as a placeholder for a common language of exchange. (Galison, 1997) The object provides a common site of focus, but is plastic enough to assimilate other goals, meanings, and interpretations while retaining the interest of several groups. In other words, trade can take place even though the value and meaning of what is traded may differ among traders because the boundary object itself is solid enough to cultivate agreement on terms of trade, and flexible enough to accept differing conceptions of worth. For example, one group may have paper currency that another group could not spend, but the second team may nevertheless value the paper as useful tinder for starting fires. The money represents dissimilar values for each group.

Interactional expertise is the second means by which trading may be achieved in a fractionated zone, in this case through experience with the language of other disciplines. Individuals may gain expertise though multiple perspectives in order to act as translators, but may also achieve sufficient competence to become contributors to multiple domains. (Gorman 2002; Collins, Evans et al. 2006; Collins 2007; Selinger, Dreyfus et al. 2007) In contrast to boundary objects, where a common language is lacking and meanings may differ, trade is accomplished with interactional expertise because experts can act as interpreters to facilitate personal and cognitive exchange.

These four types and two subtypes of trading zones are dynamic as groups may move in and out of zones and sub-zones at different times. Jenkins (2010) applied Collins, Evans, and Gorman's trading zone model to a case study in which he mapped the evolution of a trading zone as it began, changed, and failed. He found:

> … the forces that drove these transitions were either the development of new goals and/or the inadequacy of the trade to meet existing goals. Often the transition between trading zones can be abrupt, resulting in a change in circumstances. But in the case of interactional expertise the transition is lengthier, because a new linguistic skill must be learned and more intimate relationships developed. (2010, p. 83)

I sought to map and analyze the alignment of researcher goals and interactional expertise in the CI Group.

Gorman (2002) has also explored the importance of interactional expertise in trading zones. He distinguished among different stages of a trading zone based on the levels of this attribute achieved by participants.

- A stage 1 trading zone lacks shared expertise and the goals of the research are created in isolation before being passed along to experts who carry out the research.

- A stage 2 trading zone relies on members with interactional expertise to translate for other members to facilitate knowledge sharing. Contributory expertise is the highest level of interactional expertise and is achieved when an individual becomes sufficiently proficient in a second discipline that others would find it difficult to distinguish that person from others in that discipline. (Collins and Evans 2007)

- A stage 3 trading zone relies on individuals with contributory expertise not only to translate among the diversity of members, but also to make contributions that facilitate a shared vision that combines multiple perspectives into a distinctly new understanding.

These different conceptualizations of trading zones focused on interactional expertise and boundary objects are important building blocks of the theoretical framework I used to examine how the CI Group sought to generate knowledge across disciplinary boundaries. But what exactly did CI unit members mean to transfer and share?

Knowledge and Knowing

Knowledge integration and transfer were one primary focus of this study. But before taking a deeper look into the "how" of knowledge transfer it is important to address exactly "what" is being transferred and integrated. Knowledge is not simple to conceptualize or define. Plato's *Theaetetus* (201c-210b) provided an enduring definition that knowledge must be believed, it must be true, and it must be justified. There is some dispute concerning the completeness of this definition, but it provides a suitable base for the purposes of this study. I am interested in disciplinary knowledge and how it is generated through a shared system of representations and interpretations justified by present disciplinary members, but built on previous member's foundational scholarship and practice. Researchers organize information into arguments legitimated within these communities of disciplinary peers. Individual members engage in a "dialectical conversation" with the canonical texts constituting the ontology, epistemology, methodology and axiology of the discipline. Each discipline is comprised of sub-specialties developed by individuals that together represent the discipline. As Derry, Schunn et al. have argued:

> What must be recognized is that this integration and comprehensiveness is a collective product not embodied within any one scholar. It is achieved through the fact that the multiple narrow specialties overlap and that through this overlap, a collective communication, a collective competence and breadth, is achieved. (2005, p. 7)

What information or data is important to collect, what it means and how it is verified as truth are questions that constantly evolve and constitute the aggregation of what disciplinary members value, understand, and believe. These communities establish borders where some ideas are rejected and others are accepted as relevant to the evolving identity of the discipline. Normally these boundaries are evidenced in an academic setting as departments form around shared values, goals, and understanding. New students are recruited to practice and sustain disciplinary integrity. However, these borders present communication and coordination challenges in cross-disciplinary efforts. In particular, transfer and verification of knowledge across boundaries becomes quite difficult. Indeed, diverse disciplinary forms of knowledge justification and verification practices were an issue in the CI Group. In other words, group members had to accept, reject, or possibly assimilate knowledge based on their disciplinary-based perspectives of the foreign cultures of knowing[3] represented by other group members.

My theoretical approach to the issue of evaluation across knowledge boundaries is to address the integrity of cognitive processes that confirm true belief as knowledge. One main distinction concerning these thinking processes is whether justification is an internal or external process. (Alston 1989) However, my interest in knowledge transfer and integration between and among CI Group members does not require an exact definition of the nature of knowledge. What is necessary is a working definition to investigate the possibility of barriers that impede exchange in the CI Group and trades that might address those challenges.

Alston's (1989) distinction between internal and external justification of true belief intersects with my work through justification processes rather than any claims of absolute truth. I will use the term verification and evaluation in the same sense as justification since they are similar descriptors and relate to different CI Group members' ways of knowing. By ways of knowing I mean alternate epistemological means of constructing a justified true belief. The natural sciences rely heavily on empirical evidence to verify belief as truth and thereby construct knowledge. External verification could be viewed in terms of social cognition, or as a system of social justification expanded out of the mind into the world through language. Also, as Goodwin has pointed out, restricting cognition processes to the mind denies human ability to "secrete cognitive artifacts (including but not restricted to language) into the external world where they can shape not only our own actions, but also those of our colleagues and successors." (2005, p. 118) Boundary objects are one shared form of these

[3] I use the term culture in line with Galison (1997) to describe "groups with very different systems of symbols and procedures for their manipulation". The main cultural differences on which I focused where the different ways of knowing used to interpret and manipulate these different systems of symbols.

cognitive artifacts. Many actor-network theorists support this argument for the external embodiment of knowledge as John Law has suggested:

> 'Knowledge', then, is embodied in a variety of material forms. … (I)t is the end product of a lot of hard work in which heterogeneous bits and pieces – test tubes, reagents, organisms, skilled hands, scanning electron microscopes, radiation monitors, other scientists, articles, computer terminals, and all the rest – that would like to make off on their own are juxtaposed into a patterned network which overcomes their resistance. In short, it is a material matter but also a matter of organising and ordering those materials. (1992, p. 2)

Expanding the cognition process into the external world also has implications for the acts of knowing and learning. Cook and Brown have described the relationship between knowledge and knowing as a "generative dance". (1999, p. 383) Different ways of knowing are predisposed to dissimilar forms of knowledge. Qualitative versus quantitative research methods is a striking example of how the focus on textual data versus numerical data relates to epistemology.

One distinction worth establishing is between explicit, or formal, knowledge and tacit, or informal, knowledge. Explicit knowledge can be expressed through language, codified, shared and even stored. A simple example would be directions to a grocery store including distances, physical descriptions and geographical orientations (travel north on Main Street for 10 miles then turn left at the big red barn etc.). Tacit knowledge, on the other hand, is difficult to express and is generally described as skills gained through personal experience. As Nonaka has explained, "tacit knowledge consists partly of technical skills [and partly] of mental models, beliefs and perspectives so ingrained that we take them for granted and cannot easily articulate them". (1991, p. 98)

Explicit knowledge can be expressed through language, but tacit knowledge is generated through personal experience and is therefore more difficult to express. So, for example, if someone wants to know what will happen if they jump in a lake, that knowledge can be transferred from others through language, written or spoken, "if you jump in the lake it will be cold and wet, and if you can't swim you will sink to the bottom." Or, that knowledge can be generated through personal experience, by actually jumping in the lake and experiencing the results. The inverse is also valid to some extent since we use language to process and understand our experiences. That being said, let's not muddy the waters too much. In this lake example, tacit knowledge is experienced and explicit knowledge can be extracted, codified, and expressed through language.

Tacit knowledge is also difficult to express because it is often not fully understood by its holder, and because it can be technically complex and is contextually embedded in life experiences. Although difficult, Nonaka (1991) has outlined a process, or "knowledge spiral", by which tacit knowledge can be transferred in a manner similar to a master teaching an apprentice. However, Hildreth and Kimble (2002) have contended this argument is problematic and have argued instead that tacit knowledge is inexpressible and that apprentices do not "learn" from a master, but from experiences. The master guides the apprentice through experiences similar to those well-known by the teacher, thereby stimulating the production of a capacity by the apprentice and not the transfer of tacit knowledge. For their part, Hildreth and Kimble (2002) have described the different views concerning the transfer of tacit knowledge as a continuum. In their view, on one end is the claim (Polanyi 1967) that tacit knowledge is impossible to express while on the other end is the view that tacit knowledge is difficult to articulate (Teece 1998), but can be captured (Huang 1997).

Analytic skills and logic are more easily expressed and transferred than intuitive cognitive skills. To return to the lake metaphor once more, swimming can be explained as physical movements, but transferring the necessary tacit knowledge (muscle memory and cognitive skills gained through experience) actually to swim successfully is difficult[4]. Part of this is a failure of language and understanding, but this stumbling block also arises as a result of a lack of physiological structures supporting the movements. Learning to swim is a complicated process of conscious and unconscious cognitive and neurological processes. It is a recursive process of thinking, doing, evaluating, and eventually just doing without consciously thinking. Expressing tacit knowledge to others is difficult because such actions, as with swimming, are done without thinking. It is also a matter of combining multiple simple movements into a complex action. It is helpful to walk before learning to run because through walking many skills necessary for running are learned, practiced, and mastered. The same is true in the fine arts, music and science where simple skills and techniques are combined into more complex ones. But describing to others the "how" of walking or running or playing a Beethoven piano concerto is difficult, partly due to the complexity of these processes, but also because what exactly is being done is at least partially forgotten, at least consciously. Muscles still remember and the brain retains some level of involvement, but no longer on a conscious level. Athletes are aware of this process since thinking about an action while performing it is a distraction to doing it. The speed at which the brain and body need to process complex information and act on it cannot happen as efficiently and effectively on a conscious level. Becoming an "expert" in a particular domain takes thousands of hours of experience (Simon and Chase 1973) that must be distilled by the brain into concise movements and cognitive skills linking the mind and body, bypassing logical and analytical regions of the brain. As a result, these capacities are difficult to articulate because they are not processed

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[4] On an organizational level, tacit knowledge would include relationships among people and with technology which constitutes their capacity to do work.

in the same part of the brain that handles language and are therefore difficult to access and express. In other words, the ability to turn knowledge into action or the explicit, "know-what" into the tacit, "know-how" is a constant and exceedingly complex challenge (Cook and Brown 1999).

It remains unclear how thoroughly technical experience can be communicated through language. This has direct implications for the extent expertise can be gained through knowledge without experience and therefore how much knowledge can be transferred from expert to non-expert. Collins (2007) has argued[5] expertise can be transferred without experience. Others disagree as to the extent this is possible. (Selinger, Dreyfus et al. 2007) Schilhab (2007) has recently proposed an alternate explanation for tacit knowledge transfer. Her data suggests that observation of an activity stimulates neuron patterns similar to those generated during the actual activity, thereby facilitating tacit knowledge transfer without the use of language. This is important because it suggests a second-hand experience may transfer more tacit knowledge than previously thought. These "mirror neuron" responses, or neurological responses in the watcher form a parallel image of the doer and were more prominent in individuals who had previous experience with the action they were observing. An observer unfamiliar with the activity would not experience as much mirror neuron activity as one with some prior knowledge of it.

Another way of approaching knowledge transfer is to look more closely at the process of knowledge creation:

> Knowledge creation can be understood as a continuous process through which one overcomes the individual boundaries and constraints imposed by information and past learning by acquiring a new context, a new view of the world and new knowledge. … By interacting and sharing tacit and

[5] To some extent this contradicts Hildreth's contention about the transfer of tacit knowledge, but only partially because although tacit knowledge is a key component of expertise, they are not identical..

> explicit knowledge with others, the individual *enhances the capacity* to define a situation or problem, and apply his or her knowledge so as to act and specifically solve the problem. (Nonaka, von Krogh et al. 2006), p.1182)

These observations highlight the transformational potential of knowledge in a social context. Knowledge capacity is both limited and enhanced through relationships between people and information. Latour (2005) has described the multiple relationships through which we access the world and accomplish work as networks of association. It is through these ties that experience and information are given meaning and new knowledge is generated. Knowledge is therefore intimately contextual. This is not to say that knowledge is bound simply by local experience. Rather, creation and application are contextual phenomena and extraction and generalization of many forms of knowledge are challenging and limiting. Further, knowledge is transferred through relationships in the form of language or symbols that are representations of actual things or phenomena that only partially capture the full complexity of knowledge, especially tacit knowledge. Social justification of these representations is a fragile process that relies on leveraging multiple relationships. (Nonaka, von Krogh et al. 2006) Sharing or transferring tacit knowledge through these relationships is a complex challenge, as Hildreth and Kimble have explained:

> Although under certain circumstances tacit knowledge can become explicit, it is perhaps more accurate to say that even then only part of what is tacit is made explicit. This is because even what we normally think of as explicit knowledge has a whole history of culture, conventions of language and cross-referencing of thought that are never made explicit. There is always more that is embedded, implied, assumed and presupposed than can ever be externalised and made explicit. In practice, the tacit and explicit dimensions to knowledge are inexorably and inextricably interwoven. (2002, para. 28)

This integrated duality of knowledge exposes a limitation of external aspects of knowledge creation, since much of what is known is tacit knowledge and is therefore difficult to express or transfer, and remains with individuals. Cognitive skills are tied to technology and social processes that are often hidden or normalized (Latour 2005). Latour has suggested social phenomena, normally hidden, become visible during technological or social[6] disruptions. It is only when a computer stops working or relationships are disrupted that access to the know-how or tacit knowledge embedded in those ties or sociotechnic systems becomes apparent, or in Latour's words, these "networks of association" become visible.

A simple example is when a computer hard drive crashes. The usefulness of the machine becomes painfully apparent when the information stored within it is no longer accessible. At the same time, processes supported by the computer become difficult, if not impossible. Even turning to another machine is only a partial solution since an individual's computer system evolves over time to support daily routines. Email addresses, gone; shortcuts on desktop, gone; customized application and programs, gone. As Clark has observed, when a hard drive crashes it feels a bit like a mild form of brain damage. (2003, p. 4) Cognitive capacities embedded in a computer system (expanded exponentially through the Internet) are overlooked on a day-to-day basis, but become apparent during a disturbance. This is also true of people in organizations. Tacit and explicit knowledge are accessed and generated through relationships with key individuals. If an individual is no longer available, the extent to which they were relied on to accomplish work becomes very visible. Disruptions expose daily routines and capacities that normally hum along quietly in the background. However, exposing these quotidian processes can be a double-edged sword. Specifically in the context of knowledge production, exposing tensions or challenging norms can lead to conflict, but it may also lead to innovation. (Stokols 2006) In one sense, a group becomes more self-aware when these

[6] Social is a loaded term for Latour. See Latour (2005) for his in-depth argument.

knowledge creation processes are revealed and can then be adapted to the concerns or problem at hand. However, these knowledge systems or networks must be enacted continuously and relationships must be maintained, if a system is to persist. (Latour 2005)

Actor-network theory and trading zones constituted the core of my theoretical framework. Together they contributed to a better understanding of knowledge, knowing and the relationship between knowledge and knowing. But I wanted to investigate knowledge production in the CI Group, so I needed a research methodology with which to study the group that allowed me to gather data concerning it in a systematic way.

Chapter 5

Methods

Qualitative Research

This study focused on CI Group members as they generate, evaluate, and integrate knowledge and meaning. Put another way, like Galison (1997), I was interested in how unit members coordinated action and belief. But Galison analyzed subcultures of physics as a historical case study and I used qualitative methods to examine disciplinary knowledge and values barriers encountered by CI Group members. My goal was to understand better the means by which unit participants sought to coordinate action and belief, given the diversity of perspectives represented within it. Further, I looked for evidence the CI Group had developed a transdisciplinary shared conceptual framework and applied insights from trading zone theory to understand better the nature of what was shared and how it facilitated the team's communication and research practice.

Qualitative methods provided a useful framework for my research. Such approaches guide researchers in the collection and analysis of data in an attempt to situate the investigator in the world. (Denzin and Lincoln 2005) Ultimately, I, much like Denzin and Lincoln, see qualitative methods as a set of processes by which researchers seek to reveal the human experience. In this case, I sought to document the experiences of researchers in the CI Group. I aimed to investigate the ways they share and integrate knowledge in a milieu of diverse data, facts, ways of knowing, research goals, and value claims. CI Group investigators were constantly pushed and pulled in numerous directions as they conducted day-to-day research activities within the Institute, university, and scientific community writ large. Balancing such diverse claims was as much a measure of imaginative capacity as it was of intellectual aptitude. Success in addressing the challenges implicit in such efforts called for a blending of art and science (Somerville and Rapport 2000).

It is difficult to distill the diverse collection of qualitative research strategies into one clear compact definition. A complex array of ideas falls under the heading of qualitative research, techniques, axiologies, epistemologies, and ontologies that unfortunately elude clean taxonomic classifications. (Morse and Richards 2002; Denzin and Lincoln 2005; Bailey 2007) Paradigmatic perspectives heavily influence research practices. However, methods do not cleanly fall into one paradigm or another. One common characteristic among qualitative researchers is a focus on epistemology. (Hesse-Biber and Leavy 2004) In other words, qualitative methodologists view alternate ways of constructing knowledge as possible and legitimate and the process of knowledge creation as open to interrogation and questioning. That fact makes such methods especially relevant to my research interests.

My study focused primarily on relationships between and among people, but I was equally interested in relationships that individuals form and maintain with ideas, organizations, institutions, social norms and physical environments. I most closely align with the interpretive paradigm as described by Denzin and Lincoln (2005), or as Bailey has suggested, "research undertaken with an interpretive paradigm in mind focuses on social relationships, as well as the mechanisms and processes through which members in a setting navigate and create their social worlds". (2007, p. 53)

Nicolescu) has defined reality as both ontological and pragmatic, that which "resists our experiences, representations, descriptions, images, or mathematical formulations". (2002, p. 20) He argues that reality is a social construction, but that it also displays a trans-subjective dimension, in the sense that it goes beyond subjective existence and is affected by the physical qualities of matter. As he has observed, "Empirical evidence can ruin the most beautiful scientific theory". (2002, p. 21) Following this reasoning, my research was also predicated on constructivist and pragmatic strategies. I relied heavily on interpretations gathered through interviews and observations. I began working at VBI in the fall of 2007 doing research on transdisciplinary science and advising projects about the TDR approach. However, my observations were not formally captured through field notes or journaling. I sporadically participated in CI Group meetings and social events for two years before formally conducting interviews from November 2009 through January 2010. These experiences, while not formally framed, shaped my understanding of the CI Group and directly influenced my relationships with interviewees while also informing the questions I asked them.

Strategy of Inquiry

I undertook to conduct a basic interpretive study using qualitative methods, as Merriam (2009) has recommended, since my focus was constructed meaning and social relationships. To provide contrast, a basic interpretive study is not phenomenology, ethnography, case study, grounded theory, or ethnomethodology, even though these strategies of inquiry have common research techniques such as interviews, observations, or document analysis. My choice of a basic interpretive study was based on my interest in the way CI Group members addressed knowledge integration and competing values claims in the context of a heterogeneous research group.

This study was retrospective rather than longitudinal. All interviews were conducted after members had worked together for many years. The chief virtue of this approach was that participants could use their developed understanding of their group's dynamics to evaluate the evolution and current status of their team. What this approach did not capture was member perceptual data over time as group members experience change. A longitudinal study that followed the group from its inception would have provided more data points to trace the evolution of group dynamics. However, the group members would have lacked the shared understanding and concrete language they possessed by the time of the 2009-2010 interviews to express and situate those experiences fully.

My interview questions were primarily based on the literature and to a lesser degree field observations, but also a limited amount of document analysis of CI Group communications, web pages and publications, as per Denzin and Lincoln's advice "qualitative researchers deploy a wide range of interconnected interpretive practices, hoping always to get a better understanding of the subject matter at hand. It is understood, however, that each practice makes the world visible in a different way. Hence there is frequently a commitment to using more than one interpretive practice in any study". (2005, p. 4) Restated, I used observational data, document analysis, and interview questions as a form of triangulation to gain a more comprehensive understanding of the concerns I was studying.

Using the concept of trading zones, I focused on evidence of coordination between action and belief in the space where ideas, information, and technology move among groups of individuals (Galison, 1997). Jargon, pidgins and creoles are evidence of a trading zone as described above. Therefore, I looked for evidence of common language, metaphors, and analogies used by multiple members of the CI Group as indicators of the emergence of a trading zone. However, as Collins, Evans, and Gorman have argued, a common language does not constitute shared meaning or understanding and trade can occur without the construction of shared meaning and values. What distinguishes a "trading zone" from "trade" is the active negotiation of meaning and values. (Collins, Evans, and Gorman, 2007) More specifically, and for the same reason, I searched for evidence in the CI Group of boundary objects, interactional expertise, interlanguage or metalanguage as members negotiated shared meaning within projects. Further, I used the concepts of trading zones and a shared conceptual framework to explore the possibility of whether a transdisciplinary trading zone had emerged in the CI Group. In this way, theory was transformed from a guide for collecting data to a new understanding of trading zones and their relationship to an important dimension of transdisciplinarity.

Data collection

My primary source of data was semi-structured interviews with CI Group members. Semi-structured interviews consist of a set of questions grouped by topics or issues, but not necessarily asked in a predetermined order. (Bailey 2007) The goal is to use the flow of the interview as a guide, to allow flexibility and to encourage participants to construct meaning; more like a conversation than a survey. (Merriam, 2009) Interview questions were designed to elicit responses about the knowledge integration and transdisciplinary characteristics. I conducted one primary interview with each CIG member that lasted approximately 45 to 90 minutes.

I conducted conversations with unit members in a professional, yet informal, manner. An interview consent form summarized and explained my research goals and interests. Consent forms were emailed to interviewees prior to our meeting to allow participants time to read them and to ask any questions before the question-answer session took place. I interviewed a total of 10 CI Group members. Those not interviewed did not respond to repeated attempts at contact. However, during interviews with other members it became clear that many of those who did not respond were not part of the core group. One possible interviewee was only loosely associated with the group, doing much work independently. One lab had only recently joined the CI group so its members were not included. Attempts to talk with the last few possible Group participants were abandoned after interview data became redundant.

Data Analysis

All interviews were digitally recorded, backed-up and stored in a secure location. I took minimal notes during each session to provide my full attention to the interviewee. Immediately after each meeting, however, I took time to debrief and record my thoughts and impressions as the first step in data analysis. I transcribed all interviews for data analysis and coding. Interviews were transcribed verbatim. However, conversational fillers, false starts and redundant words, such as "ah", "um", "you know" and "and, and …" are left out for the benefit of the reader because they did not reflect substantive data for this study.

As Bailey (2007) has noted, data analysis begins from the conception of a research project through the writing of the final manuscript. By starting with the first interview and constantly relating data back to the research questions and framework, interviews were refined throughout the study to gain a better sense of the phenomena under examination. (Merriam 2009) My research frame guided analysis as I connected what was said in interviews, and what I observed, to my research questions and back to my theoretical framework. I analyzed each interview to construct a more complete understanding of the social processes I investigated.

I used coding to organize my data and assist with analysis. (Neuman 2002; Denzin and Lincoln 2005) Coding is a useful way to start making sense of raw data as it is collected. I followed Neuman's advice as I placed my interview information into categories based on "themes, concepts, or similar features," which were developed into new concepts and refined and compared using theory. (2002, p. 460) This is sometimes referred to as axial or focused coding where data, initially clustered as narrow and literal categories, is moved into broader, more conceptual, groupings. (Bailey 2007) Merriam has described the process well: "devising categories is largely an intuitive process, but it is also systematic and informed by the study's purpose, the investigator's orientation and knowledge, and the meanings made explicit by the participants themselves". (2009, p.183) I transcribed and coded a total of 10 interviews ranging from 45 to 90 minutes in length. Each discussion was broken into smaller sections organized according to primary, secondary, and tertiary themes. As my findings became sharper, themes were refined and organized to better reflect my understanding of the phenomena under study. Data analysis and theory development constituted a recursive and reflective process in which each informed the other.

Another important aspect of my analysis was immersion in the data from the beginning of the project. Writing and discussing thoughts and interpretations of my data helped refine my understanding. Bailey (2007) has suggested that along with memo writing, brainstorming with colleagues can help clarify thoughts and facilitate insights. Memo writing and keeping notebooks also served as a useful aspect of data collection and analysis for me. (Neuman 2002) Memo writing is to qualitative methods what running statistical analysis is to quantitative methods. During data collection, I used my personal observations and notes to begin considering my interview data, turning it over, comparing it, pushing and pulling it to see whether and how the empirical evidence matched my theoretical frame.

Quality

In choosing qualitative research methods I was careful to address issues of reliability and validity. Some qualitative researchers argue these concepts are inappropriate for qualitative methods as they were developed for use with quantitative techniques. These analysts propose the use of credibility, dependability, confirmability, and transferability instead. (Lincoln and Guba 1985) This tension is a useful one as it brings to the fore the issue of quality in qualitative research. In the end, the quality of my research will be judged by others. I can promise that I have sought to be reflective and self-conscious about my methods so as to ensure my findings are as valid, reliable, and credible as possible.

To provide a starting point for my study, I relied on the following definitions. I share Neuman's assertion that reliability refers to precision or consistency and Maxwell's definition of validity: "I use validity in a fairly straightforward, common sense way to refer to the correctness or credibility of a description, conclusion, explanation, interpretation, or other sort of account". (2002, p. 106) Validity in these terms is not a measure of "absolute truth." It is, rather, a promise from the researcher (me) that data has been collected and analyzed with systematic and reflexive scrutiny. In other words, the most closely fit interpretation will be sought in respect to all that is known to me. Here are some of the ways in which I sought to secure validity:

- Intensive, long-term involvement—I have been involved with VBI for two and a half years
- "Rich" data—I conducted interviews, observations and gathered documents that sought to capture the complexity of the process(es) I studied
- Triangulation—I used multiple sources of data (and information from multiple sources) to increase the likelihood of producing a reasonable/judicious interpretation of the phenomena under investigation. (Maxwell 2005)

Ethical considerations

I sought assiduously to ensure that all participants in this research were treated with respect and dignity. As a researcher I have an obligation to interviewees to ensure they suffer no harm as a result of their participation in my research. (Fowler 2002) This included, in this case, keeping all recorded information as confidential as possible. All research participants were informed in writing (see appendix) and through verbal communication repeatedly that they were under no obligation to answer any questions. Also, they were free to stop or withdraw from their interview at any time. Communicating this freedom was an ongoing process through all stages of data collection. Interview questions and consent forms were approved by the Virginia Tech Institutional Review Board. All digital data was stored in a password-protected data file accessible only to me. Hard copies were kept in a locked file cabinet only accessible to my committee chair and me.

Given the circumstances of my research, it was not practical to guarantee my respondents anonymity or complete confidentiality, but I sought to be as discreet as possible. I used pseudonyms toward this end. However, due to the small size of the CI Group I was concerned that even pseudonyms used to identify multiple quotations from a single source might be decipherable by CI Group and other VBI employees. Some individuals voiced concerns during their interviews about the security of their employment and I felt obligated as a result to seek to protect their identities beyond the use of pseudonyms when possible. Therefore, most quotations are identified generically as personal interviews followed by the year when the interview was conducted, for example. (Personal interview 2009) Overall, I attempted to balance my interviewees' stated desire for confidentiality while also ensuring the integrity of my research. I used pseudonyms extensively in Chapter 7 both because interviewees used names of other members during their interviews and because without pseudonyms it would have been difficult to make distinctions about the specific set of relationships under discussion. Although each interviewee signed a consent form regarding confidentiality (see Appendix), I sought to do still more than originally promised and believe I found a balanced approach that retained the integrity of the research while protecting the identity of participants, to the maximum extent feasible.

Chapter 6

Boundary Objects and Interactional Expertise

Borders

Where would we be without walls? If life had somehow, however inconceivably, managed to evolve without walls it would look nothing like what currently inhabits the earth. The second most fundamental biological unit of life is a wall, second only to the code of life itself, DNA and RNA. There are many layers of walls in the human body beginning with the structure that surrounds the nucleus of cells moving all the way out to the skin. Walls are everywhere. But what is it about walls that make these structures so ubiquitous? The primary function of a wall could be viewed as a defensive one. Walls protect important things like DNA, families, community, and society. What differentiates one wall from another depends largely on porosity. Some walls are hard and difficult to penetrate while others barely keep anything out at all. But it is the movement from one side of a wall to another that reveals the true marvel of life. Without walls there would be no way for organisms to produce and store energy. Without energy there would be no life. What gets in and what gets out is regulated by walls. Through their many forms, walls also differentiate space and create diversity.

Walls or boundaries are as ubiquitous in society as they are in nature. Individuals, groups, organizations, communities, and nations are all differentiated, protected, and sustained by conceptual and physical walls or boundaries. The duality of these walls enables life to exist; they are necessary for keeping things out as much as letting things in. It is the action of crossing borders that generates life and livelihoods. What gets in and what stays out is partly a factor of recognition of things as harmful, helpful or benign, coupled with an appropriate response. Biological and social gatekeepers are as diverse as they are numerous constituting the complex, ongoing struggle for existence itself. Living organisms attempt to bring in useful resources and keep out or excrete harmful ones. The wonder is that life exists, given the difficulty and complexity of this challenge.

As beneficial as many walls and boundaries are, walls and gatekeepers create restrictions about what and who gets to cross. People struggle every day to break down walls, and not just physical barriers. Borders regarding race and gender are often relatively impervious categories that place some people together and others apart; although these walls are generally temporal manifestations of ideas[7], they can be extremely difficult to cross and surprisingly durable.

I personally dislike building walls and putting things in conceptual categories or boxes. As soon as I put something in a container and try to close the lid I see some part that does not exactly fit and I want to open it and take everything out and start again. Drawing solid lines around people, things, or ideas makes me uneasy. But to express the messiness of the world in a coherent manner requires making some choices and distinctions and even constructing some boxes. I just wish to submit as a caveat that the lines I draw below to

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[7] For a more thorough investigation of the durability and embeddedness of ideas in physical structures and technology see Foucault (1995), Latour (2005), or Law (1992).

distinguish one thing, person, or idea from another are to some extent porous and these things, once placed inside, still tend to flow outward towards each other. It is important to remember that some "conceptual prisoners" will metaphorically want to escape, no matter how strong I make the containers into which I place them, because I cannot fully remove them from their complex, ever changing situation without destroying them. Further, what I describe is only a snapshot in time, a frozen representation of a world in flux. My categories may not last as time passes, and at some point I may need to throw away the boxes and set their contents free, find more appropriate living quarters, or maybe just borrow a more appropriate lens through which to observe them. This is a reminder the heuristics I create to facilitate understanding and highlight some relationships over others are just that, heuristics and an always imperfect reflection of the reality I seek to capture.

Instead of creating analytical categories right away, I sought to allow CI Group members to describe what they took to be their own conceptual boxes. They described two main borders to communication and collaboration. One interviewee characterized the most prominent one this way:

> Since you have people who come from what are different sort of communities of practice, their motivations and rewards, this historical canonical cultural reward structures are different. For example, and since I'm both an engineer and a scientist, and I can live with that duality well, people who are typically trained as Ph.D style scientists, their motivation tends to be very focused on their own achievements and their own standing in the community, that's how they are trained, that's nothing abnormal. That's kind of the selective pressures we as a community put on them, so there tends to be in general, sort of a selection for people who are quite individualistic, high achievers, very motivated, but also not typically well trained or well experienced in working in teams, the second part of that in the sciences, people are usually rewarded for creativity, so the idea is always, I can always do better than anybody else, so a notion of leveraging and reusing somebody else's work is a little foreign, even if there is something of value that somebody else has done, the tendency is to want to do it better, rather than take advantage of what was done and

> build on it even though of course that does happen in science. If you take another slice and say you know, an engineer's culture so to speak is one of really developing good products that function well and that have a large amount of market share or so to speak, a lot of adoption, there tends to be, in general, a much more acceptance of working in teams and groups. And so I think that you see those differences throughout the group, I think that over time there are people who have actually changed substantially and other people have been more rigid. (Personal interview 2009)

The main distinction identified in this passage was one between members from academia and those from engineering. Most CI Group members described these two groups as the "Academics" and the "Industry Folk". Another CIG member described a core distinction among members as research versus engineering. But instead of taking these categories at face value, it is important to look closer and separate the causes of these distinctions from their outcomes, with which I deal later. The main divide described in the above quotation is one of values and this border surfaced over and over again throughout my interviews. The principal difference between academically oriented members and those with experience in industry related primarily to research goals linked to how team participants valued learning and knowledge. Interviewees described academics or the "Ph.D.s" as they were often referred to by "industry folk", as independent and focused on their own research goals and publications, and not as willing to share or collaborate. As this member pointed out:

> Yeah, yeah, I definitely see a difference there. People who have industry background expect to share their work or be part of a team and there's not that kind of holding their cards to their chest like academics do a lot of the time, yes, there's a big divide there. … I would almost say that the industry people are more willing to say hey I found this article and pass around an email saying check it out. Some of the academics, because they might think it gives me an edge in this area, 'I've seen it and you haven't and I'll be that much further ahead if you continue not to see it'. Again it's a deplorable attitude but true to some extent. Yeah, there are a lot of things like that that I can tell you about. (Personal interview 2009)

Sharing information within an organization is generally encouraged and rewarded in industry, but not as much in the academy. As important as this border is within the group, these categories described by CI Group members are not as simple as Ph.D's and biologists on one side and industry folk and engineers on the other side. Some of the academics in the group have years of experience in industry and most of the industry folk have at least a Master's degree, if not a doctorate. Although this may complicate determining who is on which side of the border based solely on experience, it does not change the structure of the wall itself, a division about values:

> So there may be group discussion of goals but there's not group decision-making on goals, so then if your own goals are not part of the group's goals you just have to keep them private. (Personal interview 2010)

On one side of the value divide are those who hold an academic mindset where knowledge is valued for its own sake and publishing in the scientific literature and conducting novel research are the main goals. On the other side are those who represent an industry perspective which values utility of knowledge and has as its central goal making products or performing services. CI Group members also described the tension between industry and academic perspectives in terms of timelines, producing deliverables, and shipping the product on one side, versus scholarship, publications, and original research on the other. Individuals had to balance their own values and goals with other group members' potentially competing values in the context of project objectives. This border arose as a result of the diversity of members as well as the hybrid structure of the group. Ultimately, these tensions were most evident at the project scale. As one CI Group member remarked on arriving in the group from industry:

> …when I got here I remember just saying this over and over again. <laughing> They would be writing this software, doing this software, and I just kept asking, who's the customer, who's the user, who's the user, every meeting and they would just look at me to say who's the user, why

> are you doing this? And it was absolutely, we were writing software to be writing software. (Personal interview 2009)

Although many members expressed frustrations and focused on the negative aspects of this tension, others highlighted its potential to enhance, rather than impede their work:

> I had no part in my previous job with any kind of papers or publications. So the notion that you not only need to build something that has high utility, but if you're going to publish it has to be unique, and provide some unique capability that wasn't there before or some unique observation. And so it's a real challenge that it is unique but it also is robust. So your trying to push the envelope on both edges, you know, you gotta build something that is very stable and will continue to work and work for lots of [users], but I also need to be doing something different than the other things that are out there. I guess it's broadened my thinking, probably. (Personal interview 2009)

The other main division identified by group members was the disciplinary or knowledge border. The multiple disciplines or communities of knowing represented in the group create tensions. That diversity of epistemological orientations only increases when one includes the numerous external collaborators[8] involved with the group. The knowledge borders encountered by CI unit members were numerous, but not impermeable:[9]

> I think the biggest challenges, and this is something at the beginning, when we started working in this field, interacting with people from different disciplines where they have their own terminology their own jargons and sometimes people are very sensitive about how you talk about it. So, usually, if you are coming from a different background then you try to generalize things or sort of abstract it so that you can understand it in your terms, but when you try to explain the same thing you know in your language to speak to a biologist they may get offended

[8] For the purpose of this research I did not explore interactions with outside collaborators.

[9] As noted above, Galison (1997) explored similar borders evident in the instrumental, experimental and theoretical subcultures of physics and found that although these knowledge boundaries were significant barriers to communication, they were not insurmountable.

> sometimes, it's the work of their life and you are sort of generalizing everything and trying to present it in a very naïve way. (Personal interview 2009)

The main issue at this knowledge border is communication between cultures possessing different systems of representation, validation, and interpretation. Not only is the knowledge to be traded interpreted differently, but the methods for creating it and the means of interpreting it also vary markedly. Trading across this border is complex and requires a specific set of member capabilities. The next chapter explores these challenges in greater detail and provides examples of how CI Group members sought to cross both knowledge and values borders.

Border Crossings: Boundary Objects

Boundary objects and interactional expertise can be used to bridge knowledge borders. Chapter 4 distinguished between these two concepts as different types of trading zones and as alternate methods of trading ideas and concepts across knowledge boundaries. This chapter examines evidence from the CI Group to see if boundary objects and interactional expertise were present in member interactions and, if so, in what forms.

Collins, Evans and Gorman have defined trading zones as "locations in which communities with a deep problem of communication manage to communicate." (2007, p. 658) The authors explore other means to overcome communication issues beyond an inter-language. As outlined in Chapter 4, they constructed a general model of trading zones where the fractionated trading zone described heterogeneous collaborative localities.

Considering the CI Group as a trading zone seems worthwhile for several reasons. Galison (1997) argued that the trading zone, "forms around the description of the phenomenological world of particle physics". (Galison 1997 p. 835) The CI Group trading zone has formed around the phenomenological world of genomics. The trading zone described by Galison constituted the common ground upon which sub-cultures of physics met to trade knowledge and produce technology. The CI Group confronted a similar situation, but the common ground has been molecular biology, as this group member described:

> Genes, RNA, protein, metabolic pathways, that is the common ground that we all have some hook on those mental constructs. That's where we all meet, somebody's talking about how a gene is regulated, everybody in the group has a mental model of what this DNA looks like and what happens when transcription starts, enough so we can follow what's going on and then, you know, if you veer off into a topic like you're talking about the data that lead you to believe there's this particular reaction that's going on then you might start losing people. (Personal interview 2009)

Boundary Objects and methods standardization were one way the CI Group dealt with their knowledge borders. Interactional expertise was another. In theory, these are two different concepts. Collins, Evans and Gorman (2007) have argued the difference between boundary objects and interactional expertise trading zones is the way in which boundary objects in one zone and interactional expertise in the other develop to overcome communication barriers. In a boundary object trading zone, communication is accomplished without a shared common language. Trade in interactional expertise trading zones is undertaken without the shared material component that boundary objects represent. However, in practice and over time, people relying on a boundary object may gain linguistic competency that allows them to develop interactional expertise or an inter-language. The boundary object may no longer be labeled such, but there is no clear way to determine where the boundary object stops and interactional expertise begins. To complicate matters, groups may use boundary objects and interactional expertise concurrently, as I will argue was the case for the CI Group. The more diverse the team, the more opportunities there are for members to develop and use expertise from multiple domains. In the case of the CI Group it was clear that every member gained at least some proficiency in biology. One group participant made this comment about learning biology:

> You can't just say that's just data. It's particular data and the people who use it are particular people and I think some of the, even on the most hard-core industry people, have picked up the biology to some extent. Otherwise you sit in these meetings and you have no idea what they're talking about. 'We need to display the genome and the GC content and the genes and the pseudo genes', it's all biology terms and you have to understand it. (Personal interview, 2009)

As argued in Chapter 4, boundary objects and interactional expertise eventually can lead to development of an inter-language or shared mental model trading zone. Boundary objects and interactional expertise can be viewed much like Galison's jargon, pidgin, and creole as stages and components of an inter-language; jargon fades to pidgin and pidgin into creole, but each component does not completely disappear, at least not immediately. Rather, they blend and combine with new components or capacities into something new. In the case of the CI Group, I saw evidence of each component and a progression moving the group from reliance on boundary objects to interactional expertise and eventually to shared understanding and mental models. As I discussed in Chapter 4 this path is strikingly similar conceptually to the process necessary for movement from a multidisciplinary to an interdisciplinary to a transdisciplinary approach to research.

Before I present more evidence from the CI Group concerning knowledge borders, I want to underscore the complex multi-project nature of the group. Members come and go, they learn and change, and manage multiple complex relationships crossing multiple borders. The main evidence of boundary objects, interactional expertise and shared understanding comes from one subgroup within CI who all worked on the PATRIC project. I focused my analysis on the PATRIC project for several reasons. First, the effort was the main contract within the CI Group and therefore required a good portion of the members' attention and resources. It also appears to be the Group's most successful project and I believe that was in no small part due to the creation of a shared understanding of its aims among group members coupled with the development of an integrated research and development process. The exception to my focus on the PATRIC project relates to communication difficulties in other projects. CI Group member accounts of difficulties did not identify specific projects, but they were efforts that occurred before the PATRIC project began. However, it appears that lessons learned from those difficulties were applied to the PATRIC project. As one CI Group member related:

> I think we get a lot of cases where it hasn't happened right or something fell apart along the way, communication problems. There were lots of communication problems and lots of not checking in to see how things were going. I'm trying to think of a good success story for this. I just don't know that we've had good successes. (Personal interview, 2009)

A unit participant who had not worked much on the PATRIC project offered this particular statement. The rest of the interview cited just above included details about a miscommunication between a bioinformatician trying to describe to the software engineers specifically what type of tool he needed so they could build it. After one long meeting the bioinformatician and the software engineers had little contact until the tool was finished. When the engineers handed the tool back to the bioinformatician, it was nothing like what he had expected, and it was not useful. I use this example as a starting point because it shows an instance where communication was not effective and no boundary object, interactional expertise, or shared understanding seemed to emerge. Here are some of the reasons one interviewee offered for that failure:

> Ok so we want to show you this new viewer and the bioinformatician says, so why did you do that? Why would you do this thing, like as though the first conversation had never happened. So we said well, this is what you asked for and we went back over the notes and you said this and you said that, and he said I meant something totally different. And the fact that this person and the developer hadn't gotten together at all during those two months. We hadn't had any verification. It was sort of a process thing for us to learn. OK, let's not go that far without checking back without being more sure. It was a particularly bad case. Just total wasted effort and, plus he still didn't have what he wanted and, and that, that event rippled forward to where we never worked well again. … We had a lot of failed efforts and false starts. It was part of the lack of communication between the people who knew what the software should be doing and the people who knew how to make software. There was a lack of experience in the software development team. Very young and fresh out of school, people who knew how to do class projects very well didn't really know how to do industry software and even at the management level. The manager was a professor in a past life and the processes weren't in place, we did too much too fast, not careful enough, not checking back with the other side and so there was, there was communication problems and there was also just a poor execution of the programming side and I was guilty as anyone else at being new at it, I never took computer science class and it was a lot of the failures that got me to look more into that industry software world and read some of the books and talk with some of the people. When we hired in someone who had been at IBM, tried to spend some time hopefully learning from this person. Putting in better processes. So we've gotten better at that. We don't have the same kind of problems that we did have. We're not totally there. (Personal interview 2009)

Several concerns treated in this story merit attention. The team was new, so interpersonal relationships had not had much time to develop and no procedures had been established to facilitate or encourage communication. The unit lacked experience and a shared goal of producing industry-level software. Instead, they had experience in academia and academic software that does not necessarily focus on the usefulness of products. A quotation offered above made this point concerning software produced early on in the CI Group, "they were making software to be making software". But most importantly, this experience led to change and improved processes to facilitate communication (or at least this same problem wasn't experienced again by this member). I also want here to point out a particular section of this story as significant, but then tuck the point away for later development. The statement about a "lack of communication between the people who knew what the software should be doing and the people who knew how to make software" was repeated in several different forms, but the message was always the same. The biologists provide the "know what" and the software engineers the "know how", but in this instance, the group lacked a means of translating what into how. However, at some point in the group's evolution, communication across this biology "know what" and engineering "know how" divide began to improve.

As described previously, shared methods and boundary objects are one way that intersectional work can be coordinated more effectively through improved communication. Star and Gressimer have offered this description of boundary objects:

> In natural history work, boundary objects are produced when sponsors, theorists and amateurs collaborate to produce representations of nature. Among these objects are specimens, field notes, museums and maps of particular territories. Their boundary nature is reflected by the fact that they are simultaneously concrete and abstract, specific and general, conventionalized and customized. They are often internally heterogeneous. (1989, p. 408)

In the case of CI Group, boundary objects can result when bioinformaticians, biologists, computer scientists, software engineers, usability engineers, and computational biologists practice infectious disease research. Their objects, following Star and Gressimer, are genomes, computer software, web-based tools and cyberinfrastructure. Multiple group members share these constructs, but they are sufficiently plastic that meanings can be different across the knowledge and values border. For instance, the web-based applications designed for the

PATRIC project have different value depending on which side of a values border one views them. On the academic side, they have value in answering interesting research questions for publication. On the industry side, meanwhile, they are useful tools or products the team built to fulfill a contract and possibly get a new or larger grant or contract.

Across the knowledge border biologists are interested in understanding the genomes accessible through the web interface to understand cellular processes or metabolic pathways better. The bioinformatician might see an efficient way to access large amounts of data to test a new algorithm. The computer software engineer might see the ways code affects the functionality of a website. What they have in common is the object, the website, they built together. It may not have the same meaning for all of them and they may value it for different reasons, but it is a common representation through which they can do work and communicate.

Another less tangible example of a boundary object that begins to stretch into interactional expertise is the shared concept of molecular biology, or the "central dogma" of biology. One CI Group member described it this way:

> I think everything hangs off that [central dogma of molecular biology] cause we can think of experiment data like that, we can think about our gene sequence data like that we can talk like Chris does these things called genomic islands. OK, something causes a new sequence to be sliced this way into an existing sequence. What does that mean, but then when you get into 'this is how I use this information to build genomic trees' the farther you go the more people you lose. (Personal interview 2009)

The central dogma of molecular biology is actually a visual representation of the most fundamental biological processes by which DNA code is translated into the building blocks of life, amino acids and proteins. Computer scientists may understand this process differently than biologists, but its details can be analytically extracted and generalized to the point that non-biologists or non-molecular biologists can gain a rudimentary understanding of its character and complexities. I point this out as an example of a CI Group boundary object that has facilitated inter-group communication. At some point the non-biologists in the group may gain enough understanding of the biology domain to permit their interpreted meaning of this concept to align more closely with the way a biologist thinks about it. Many such concepts or representations maintain analogous forms between different disciplines. Sometimes their origins are similar and sometimes they evolve concurrently. Over time, ideas brought within disciplinary walls evolve into entirely new concepts. I do not intend here to provide a detailed explanation of the evolution of analogous ideas across disciplines. I merely wish to mention that, although I have focused on their differences to this point, biology and computer science have some overlapping concepts, ideas, methods and ontology. These overlaps play an important role in the realization of developing interactional expertise. The higher the degree of overlap, the more quickly such expertise can be attained.

Interactional Expertise

Interactional expertise as developed by Collins and Evans (Collins and Evans 2002; Collins and Evans 2007) and adapted to trading zones (Collins, Evans and Gorman 2007) describes the process of gaining proficiency in more than one domain of knowledge. Eventually, expertise can progress to the point where contributions can be made in the new field. (Collins and Evans 2007) Shrager (2007) has provided a first-hand account of his experience with interactional expertise and the BioBike web-based genomics tool. BioBike was created by a collaborative effort between software engineers and biologists and it performed similar functions to the web-based tools developed by the PATRIC team:

> As the BioBike project progresses, an explicit set of new shared concepts is being developed upon which the interaction is focused. These concepts are computer programs (BioBike functions) and are at the same time boundary objects and form the dictionary of the collaborative communication. (Shrager 2007, P. 648)

Although the BioBike and PATRIC website served similar functions as boundary objects, the Shrager collaboration was completely mediated through the Internet. The biologist and software engineers working on BioBike lacked any personal connection or organizational continuity. Shrager himself is a co-creator of BioBike and self-proclaimed interactional expert. This entry from his "cognitive diary" recording his experience of moving from computer scientist into the domain of biology is insightful:

> Nearly at the moment at which -LZ- explained to me about the two vectors, something much larger clicked into place for me. I don't know quite how this happened, but somehow I had all the pieces of the puzzle (well, this local puzzle anyhow) in hand and identified, but hadn't put them into the frame. When -LZ- showed me the picture in the manual of the two vectors, with their various restriction sites, that was the frame for the whole procedure, and all the pieces fell right into it, and I very suddenly—literally in a matter of a few seconds—" saw" what I had been doing for the past day: I could see why we were cutting the vector and amplifying the gene, and ligating them together and why I had to use EcoRI. And then I understood, all in that same perceptual unit, how to figure out what to expect from the gel. Maybe this was just the first time I had actually had time to think, as opposed to feverishly cooking and being lost, but it doesn't feel like that. I think that I've been trying to think all the way along, but there just wasn't enough material to think with, or there were crucial pieces missing, or the frame was missing, or something. (Shrager 2007, p. 643)

This excerpt is useful for several reasons. First and foremost it captures the essence of a frame shift necessary to move into a new knowledge domain. It is almost as if Shrager put on special glasses and the world suddenly looked completely different. What he did not describe was whether he could take the glasses off once they are on. Did this new understanding exist separately from the old one, or was it a hybrid of the old and new? Either way, his account highlighted the embedded nature of knowledge as well as its tacit and explicit duality. Shrager's frame shift happened at that moment concerning that particular concept in that specific lab with that lab mate, based on that diagram. But it also represented a general shared quality or understanding that other biologists experience or "know" and from which they work. As Collins, Evans and Gorman have suggested, interactional expertise is very "tacit knowledge laden and context specific." (2007, p.61) This passage echoed a description that one CI Group member provided concerning the difference between the way biologists and computer scientists see the world:

> The biologist and the computer scientist were asked a question, a bicyclist is going from point A to point B. Over different time periods he increases the speed and decreases the speed and so on, and how much time does it take to reach from point a to point b or what is the distance from point a to point b and the same question was given to a computer scientist and biologist. Biologist thinks in a different way, he's more visualization. OK let's think about the scenario here and then let's just visualize that picture and come up with the solution there and so on. The computer scientist, on the other hand, is not visualization. It's just the formulas and so on. … So it's a good thing but now we have just taught them different languages and [they] come back and talk, even though it's English, now the way that it's being interpreted is entirely different. (Personal interview 2009)

Interactional expertise provides the possibility of translating among different ways of knowing. Gaining experience in the domain of biology improves communication between software engineers and biologists in the CI Group. The extent to which the communication and understanding can reduce the knowledge border partially depends on the degree to which either or both individuals achieve mastery of the other's language. And this competence does not extend simply to domain language, but also to the symbolic representations created and used by the disciplines each individual represents. Here is how a CI Group member described his experience with interactional expertise:

> I have found that trying to develop that understanding where, number one I think to some extent you start speaking the same language in the same terms even if, at the end, it's not like I become a biologist, but so that I should be able to communicate comfortably with a biologist and communicate whatever I want to communicate in a way that is acceptable to that community. Over the period developing that understanding, trying to understand what they are trying to say, what's their expectation and at the same time trying also to communicate a little bit from your side how software works or your jargons or your terminologies so that after some period you should be able to speak the same language and understand each other. (Personal interview 2009)

Expertise in a new domain is gained through a step-by-step process. The greater the capability, the more fluent the translation between bodies of knowledge can be. But in this case, the movement was dominantly towards biology, the research domain of the group. There were exceptions, but for the most part, everyone was described as having some level of expertise in biology, irrespective of their previous experience. When biologists and programmers are engaged in intersectional work in biocomputing the movement across the knowledge border is more in the direction of biology and not so much the other way. (Shrager 2007) This is also what I found in the CI Group where biologists typically determine what needs to happen and engineers figure out how to do it. As one CI Group member explained:

> Usually we have a biologist that's trying to solve a problem and deal with lots of data and turn it into something meaningful, and so the best approach we've found is [to] let them sorta do their thing for a while, assemble data in the way they would, and then sit down with a software engineer and a bioinformatician who will see ways to do that in a much more expedient manner through software engineering or tools, and that kind of stuff, and then they'll go prototype something and then bring it back and sit down with the biologist again and they see what else can be done and they keep refining, sort of, in this back and forth kind of thing,

> that's been the most productive tool we've had come out of that kind of interaction. So it's having the person that understands the domain problem the best leading the way, at least, trying to stake the problem and then working with the team to flush it out. (Personal interview 2009)

Interactional expertise existed on many different levels in the CI Group, from understanding basic terminology to being fluent in two domains, such as programming and biology. I previously suggested that the higher the level of interactional expertise, the easier communication becomes across the knowledge border. But I also mentioned the possibility that at some point interactional expertise in two domains branches off into a new discipline. Galison (1997) and Collins, Evans and Gorman (2007) use biochemistry as an example where scientists became fluent enough in biology and chemistry that they began speaking their own language and understanding biochemical reactions through a new perspective, distinct from biology and chemistry.

One of my principal interests while interviewing CI Group members was whether the bioinformaticians would act as translators between the biologists and the programmers in the CI Group. I expected they would possess interactional expertise and could converse with biologists and computer scientists on a high enough level to facilitate trade across knowledge borders. However, what I found is that although the bioinformaticians in the group seemed to posses this ability due to their duality of expertise, they tended not to act in this capacity as often as would be expected. In fact, they were more likely to occupy different ground more to the side, so to speak, than in the middle between biology and engineering. As a result, to get there, biologists, for example, needed to learn bioinformatics terminology and concepts. As I explained previously, however, there are still overlapping concepts and this new discipline and the barrier between biology and bioinformatics is not as strong as the border between computer science and biology. Nonetheless it is a new boundary and CI Group members had to address it. As one group member explained the matter:

> There should be a goal to make a continuous gradient between biologist and computer biologist and mathematician biologist and physicist, biologist and chemist because these are all the disciplines that need to come together in the near future. But we're creating somebody in between and that is becoming a field in its own so that's an issue in bioinformatics. Bioinformatics has grown into a discipline on its own. Now there are, instead of two disciplines that we need to deal with biology and computer science, we need to deal with a third discipline, bioinformatics. So somebody has to be careful, there are bioinformaticians within the group who really would like to code and do the analysis, and keep on doing things, they neither go to the biology nor the computer science, now they created, 'you come to me to understand what I'm trying to do now' it becomes third discipline. (Personal interview, 2009)

The bioinformaticians may in general represent an emerging discipline, but individually, they still fall somewhere on a continuum between biology and programming. This continuum may be curving towards a new point that represents bioinformatics, but the CI Group bioinformaticians are not all there yet and I think this is representative of the field as a whole. Many interviewees voiced a frustration that bioinformaticians had the potential ability to act as translators between computer science and biology, but more often than not they chose to "go it alone", rather than utilize their interactional expertise to facilitate communication. Here is the issue as it was described by three CI group members:

> Oh, the bioinformaticians. Yes they could [translate] if they would just scale back on being my way or the highway kind of stuff. I think they could, yes they certainly could. (Personal interview 2009)

> [Do bioinformatician act as mediators in the group?] I think that that was the goal, but I think that in the end they're more of a loner than everybody else and they're not actually facilitating. That's my opinion. (Personal interview 2009)

> The bioinformaticians are this group of 'I know how to write code and I don't need to use anybody else's code. I don't need you to provide that I'm just going to go script it. I'm just going to go through a unix shell'. (Personal interview 2009)

One bioinformatician admitted a tendency to work alone, but also suggested he was working as a translator between biology and computer science or software engineering:

> Unfortunately I do that [work alone because I can], I mean I know that there's not quite a spectrum like biology over there and real hard core computer over there. But if you imagine it that way I know that I'm occupying some area in between and there are people here that know way more both ways and there are cases where I have to be deferring to other people but I think I can at least almost be a translator at times or an interpreter and I think I'm seen that way sometimes. (Personal interview 2009)

And this computer scientist described in detail the quality of bioinformatician's interactional expertise:

> In terms of technical bridging, bioinformaticians are pretty good at that because they do write a fair amount of code, they do understand software languages and basic software constructs, but they also understand the biology, actually usually quite well, especially in particular domains, so they understand not only the data they're seeing but where it came from and you know if it was computed how and what are the uncertainties in that data and what's the statistical significance of that data and all those kinds of things too, and they can usually do the translation there. Especially when it comes down to trying to make tough technical decisions or look at different approaches to a particular problem, evaluating which one's going to make the most sense. (Personal interview 2009)

These quotations highlight the complexity of the bioinformatician's role as translator in the group. The bioinformaticians in the unit are perceived as having interactional expertise or technical ability in two domains; biology and programming. That fact notwithstanding, other group members did not view them as commonly using this ability to collaborate with or translate between team participants. One explanation is simple—their level of expertise is no longer interactional, but expertise in a third discipline, bioinformatics. I think this was true to some extent, but did not represent the whole story. There is an interpersonal dimension to all of these relationships among group members I did not have the capacity to explore fully in this study, although it was clear that some individuals' interpersonal skills were not as conducive to collaborative work as others. Individuals perceived as less collaborative also tended to have trouble crossing the values border. In other words some of their research goals conflicted with project objectives or contract obligations. This was more often the case on the academic side than the industry side of the values border, as described in Chapter 6 where personal attributes AND their professional acculturation were problems.

My study focused on the knowledge and values borders in the CI Group. However, individuals must develop relationships that require time and energy to establish and maintain to assure effective intra-group communication. Alternatively, that time and energy could be spent working alone and potentially getting more work done—depending on what sort of work is valued and for what purposes. I have already discussed many of the communication issues when crossing knowledge and values borders, and noted the CI Group had plenty of both. Despite these challenges many unit members did manage to work together across multiple disciplines and even establish very productive partnerships within the unit. One surprising finding about the CIG was there were a few key partnerships between members who were particularly effective at crossing the knowledge and values border, but neither individual in them was a bioinformatician. However, bioinformaticians did develop and contribute to the shared mental models of the PATRIC project I describe in the next chapter.

Chapter 7

Transdisciplinarity and Trading Zones: An Integrated Approach

Trading zone theory offers expertise, common objects, or common language modalities to facilitate communication across knowledge and practice borders. But before exploring boundary objects, interactional expertise, and inter-languages from trading zone theory to determine their implications for transdisciplinary practice, it is important to compare and contrast what interested scholars have described as a transdisciplinary metalanguage, or a shared conceptual framework, with that of the inter-languages, boundary objects and interactional expertise of trading zone theory.

A shared-conceptual framework is commonly suggested to be a sine qua non of transdisciplinary work. (Stokols, Fuqua et al. 2003; Parkes, Bienen et al. 2005; Abrams 2006) The different ways of knowledge trading through interactional expertise, boundary objects, and interlanguage generation in trading zones provide a means to unpack the "black box" of processes by which a shared conceptual framework may be achieved by individuals, partnerships and a group. A transdisciplinary research team could be described as a fractionated, or heterogeneously collaborative trading zone that relies on interactional expertise and/or boundary objects, and the development of shared representations to secure knowledge integration in order to move toward a shared mental-model. Meanwhile, Galison's (1997) definition of a trading zone clearly covers most, if not all, transdisciplinary research endeavors based on the broad, but widely agreed upon, definition of transdisciplinarity as a process and intention of knowledge integration from multiple perspectives. (Sage 2000; Pohl, Kerkhoff et al. 2008) Participants must cross knowledge and values borders that exist between the multiple systems of representation to achieve transdisciplinary outcomes. Magill and Evans have explained it this way:

> A unique benefit is that the research emerging from a transdisciplinary approach reflects a true integration and synthesis of knowledge from each discipline rather than a mere compilation of knowledge from each discipline. The transdisciplinary approach encourages the cross-fertilization of knowledge and ideas and debate about theories, resulting in truly new perspectives that are more than the sum of the parts. (2002), p. 226)

A focus on local coordination despite global disagreement also rings true to transdisciplinarians who suggest that problem-centered research can overcome disciplinary boundaries, resulting in more multidimensional understandings. (Pohl and Hadorn 2007; Hadorn, Hoffmann et al. 2008)

The trading zone bridges local coordination and global shared conceptions in a way that dovetails well with my research focus. But further study is needed to develop this idea in relation to the shared understanding and conceptual framework described by transdisciplinary scholars and practitioners. Researchers involved in transdisciplinary projects attempt to share knowledge and reach some measure of common understanding on research goals and practices. However, the tighter the focus on the details, the more likely global agreement about goals and practice will resist alignment. (Collins, Evans and Gorman, 2007) In other words, as concentration on actually doing research intensifies, differences tend to become more pronounced, possibly causing friction as researchers expose potentially disparate beliefs and values embedded in their systems of symbol recognition and interpretation. Even if a group of individuals share common experiences or conceptions, the ways in which they construct meaning and the meanings they construct could well be, and often are, contradictory.

Agreement about ideas or values that lack macro-scale precision can, in effect, create a bridge among diverse participants in the context of local practice. (Kellogg, Orlikowski et al. 2006) Put another way, a particular group of researchers, through a focus on a common problem, even if not understood the same way, can co-create meaning and understanding. How this co-creation is achieved was of particular interest to me as the investigators I studied sought to work amongst a diversity of knowledge producers. Can a balance between local coordination and global agreement be achieved, if only for a brief period, before a new set of agreements must be developed? Failure to balance goals and competing knowledge claims may result in domination by one perspective and lack of integration, or the complete inability of the group to work together and project failure. A focus on project details versus general agreement may also change through time as conditions change. In this sense, common principles can be shared, but cooperation and coordination may break down over how details are interpreted. Kellogg, Orlikowski et al. (2006) offer templates or genres as one example that can create global agreement because they require minimal communication in contrast to more detailed plans. Templates and genres may serve as boundary objects.

I propose the metalanguage of transdisciplinarity is a combination of interactional expertise and the inter-language of trading zones. The metalanguage, or shared conceptual framework, serves as a meta-frame that combines a shared inter-language with a superordinate goal created in the context of common research problems facilitated by high levels of interactional expertise. This metalanguage is a transdisciplinary concept, but augmented with elements of trading zones drawn from empirical evidence provided by the CI Group. A more comprehensive understanding of how knowledge and values borders are crossed in the CI Group is attained by using the more developed trading zone theory that addresses communication barriers in cross-disciplinary work in combination with the shared conceptual framework ascribed to TDR. This understanding contributes to a more practical understanding of trading zones and a more robust theory that informs transdisciplinary research efforts.

Trust

So far I have distinguished transdisciplinarity as primarily a research principle and guide for an investigative approach, but have not yet offered any detailed means to address knowledge borders that bound disciplinary knowledge and knowing. Effectively, I have described trading zones as the site where communication between divergent disciplines is accomplished through the development of an inter-language. But how did the CI Group's shared conceptual framework form and merge with boundary objects and interactional expertise into a metalanguage?

Interpersonal relationships are an important part of communication in any team. Several CI Group participants experienced an increase in the quality of interpersonal relationships with other members while working in the unit. Why some members developed successful relationships across disciplines while others did not was not always clear. What was apparent was the members who were described as less collaborative by co-workers lacked strong interpersonal relationships with other group members and more importantly, did not experience the high-level of shared understanding team members with strong interpersonal relationships reported.

Trust is an important component of interpersonal relationships extensively documented from psychological and organizational behavior perspectives. (Lewis and Weigert 1985; Fukuyama 1995; Mayer and Davis 1995) That being said, I want to focus specifically on one dimension of trust necessary for transdisciplinary inquiry. Evaluation of knowledge across disciplinary borders requires trust between members about the integrity of knowledge created through unknown or unfamiliar disciplinary methods and practice. Cross-disciplinary research depends upon communication and requires interactions between collaborators from different disciplines. Trusting other collaborators and their knowledge facilitates sharing across disciplinary borders.

Cross-disciplinary research presented an evaluative challenge for CI Group members. Trust was one means by which group members addressed this core imperative. One CI Group member described the importance of relationships and trust in this way:

> I don't see too many mediators as I do certain combinations of people have worked well together doing these things, they have certain chemistry or communication together that allows them to move things forward very quickly and their comfortable enough from the trust level and the communication level, they don't understand something on one side, they'll let that person go and then they can come back together and reconcile or whatever else they need to do to keep moving forward… when I said trust I meant trust that part that I'm not explaining to you, you understand, it's more not like you're going to steal my idea kind of thing, it's like I have enough confidence in the way that you do things that I'm okay with what you did behind the scenes on that. (Personal interview 2009)

In the absence of interactional expertise, evaluation of knowledge across disciplines was a constant challenge for the CI Group, but trust provided an alternative to cross-disciplinary knowledge verification. In the CI Group, biologists generally lacked the expertise to evaluate the quality of computer science research. I have already discussed interactional expertise as one way to break down knowledge barriers. Trust was another component that increased CI

Group members' capacity to "diffuse" knowledge across borders. Almost as if carrying a passport, knowledge was allowed to pass from one side of the border to the other while retaining its value and status. Upon arrival, dual citizenship was metaphorically granted the received knowledge either by an individual or the sub-group receiving it and was then incorporated into the broader "production" process. Without trust, knowledge presented across disciplines encountered a strict interrogation at the border. Group members pointed to one relationship in particular between a biologist and a software engineer as evidencing elevated levels of cross-border trust and understanding.

Tyler and Morgan

Tyler and Morgan achieved a particularly successful cross-disciplinary partnership. They proved especially adept at dissolving knowledge barriers, in effect communicating the "what" from the biology side to the "how" of the computer side. Many in the Group noted that these two people in particular worked very well together. Their rapport was an example of how transdisciplinary knowledge integration begins to form within the context of a trading zone and the possible reach of that process. What I found was that boundary objects and interactional expertise both contributed to the capacity of the CI Group to practice cross border communication and knowledge production. But how exactly was that achieved? I have already discussed the presence of boundary objects and interactional expertise and both of these were components in creating shared group mental models. Tyler and Morgan demonstrate the extent to which shared understanding can develop and integration can be achieved through a combination of expertise and boundary objects.

Morgan is a biologist and Tyler a software engineer. They have been working together in the CI Group for a few years now, like most of the other members. The difference is that Tyler and Morgan have developed so strong professional relationship that they managed to work across disciplines to build something together that neither individual could have created alone. Morgan had few software coding skills and expressed no desire to gain any. Tyler had achieved some level of expertise in the biology domain, like many of the other software engineers in CI Group, but possessed little academic training as a biologist when he began working in the CI Group. Here is how Tyler explained the importance of communication across disciplines:

> There is some initial barrier; once you cross then it becomes really producing, otherwise it takes a lot of time to translate it from one discipline, if the requirement are coming from a biologist, going from there to software requirement if there is no one-to-one communication and that developed understanding, then you have to go through several long channels before you can convert it to a software product and I think over the period if you can speak the same language, if you can understand each other very well, then I think you can shorten the channel and then it can be very productive. (Personal interview 2009)

Translation was accomplished through the work itself as a boundary object, and Tyler's interactional expertise, the alignment of goals with Morgan and a personal relationship that facilitated communication and understanding. Each of these components was important and each contributed to development of a more complete metalanguage between these two individuals. Another way to describe better the success of this relationship is to compare Morgan's relationships with other software engineers in the group. Here is how Morgan described the difference:

> What they'll [Tyler and Jenson] do, actually come in, they are the only two software people who will come in and watch how I do things. And see exactly what I'm doing. [The others] aren't like that and we've had some problems with that. They're more thinking from a computer science thing. We should do this and this and this will be so cool. But those two people, Jenson and Tyler, are interested in seeing how I do it and what the endpoint is, and because they are watching me they know what my endpoint is, and they're sitting there watching and asking questions and

> it's very frustrating for someone who's an expert at computers watch a novice do things. Jenson would have this expression like Ohhh, Madison <laugh> and Tyler does something like he says 'tell me, why are you doing this?' It is just so frustrating for him to watch, but then they see what my endpoint is, kind of how I'm getting there and that helps them know exactly what's needed. That's an important thing that those two people really, became aware of and have pushed development a lot faster than the people who just, 'oh I can do this' without seeing … how someone manipulates the data and what their goal is. So it wasn't hard at all. Tyler, the first thing is trying to, well, it wasn't hard because I had done all the homework and I had done the whole spreadsheet. I had my own spreadsheet I had worked on. You know, it wasn't as pretty as this stuff but it was colored and you can see the patterns and he can see it and then I can do this, and they get so frustrated watching me do it so slowly, here we can help you with this, this, this and this. Tyler is actually a genius at that kind of stuff at figuring out the connections. So it wasn't hard. (Personal interview 2009)

There was an obvious difference between those who watched the process and aligned their software tools with Morgan's goals and methods, and the other computer scientists who did not observe the process and went off after only brief contact to apply "computer science" to the perceived problem. There are several layers of meaning to analyze here. Tyler managed to achieve a degree of shared understanding with Morgan other computer scientists did not. One factor was the time and effort Tyler invested to understand what Morgan was trying to accomplish. That time lead to a shared experience and the potential for knowledge co-production, rather than just transfer. But the other computer scientists Morgan mentioned did not seem to accomplish the transfer, or at least not to the extent that Morgan had hoped. Tyler managed to "shorten the channel," as he called it, and increase the porosity of the knowledge border through the creation of shared goals.

However, in one sense, Morgan and the computer scientists share common values. They all sit on the academic side of the values border, but instead of aligning values they wound up representing competing interests. The computer scientist was working on a Ph.D. project that developed software solutions to Morgan's biology problem in a way that was more publishable and interesting than it was useful to Morgan. Tyler, on the other hand, was interested in creating software that would do exactly what Morgan was doing manually to create a useful product. In some ways Tyler and Morgan did together what many bioinformaticians commonly attempt alone. That is they created software tools that locate interesting patterns in biological data. Here's how Tyler viewed the situation:

> Personally my end goal was always to have a product that is useable. That means that not thinking strictly in terms of software or strictly in terms of the problem, but I think trying to come up with an optimal solution. So I think in that sense I always found that it helps me personally to know more about the problems or domain that I am working on, and then thinking about how we can apply whatever tools or techniques are available in the software or solve that problem. So I mean that's probably one of the reasons I am always on the line trying to communicate with both groups, going back and forth. (Personal interview 2009)

Ultimately, the tools Tyler created for Morgan were useful and also led to a publication. (Personal interview 2009) In this instance, goal alignment was not a matter of sharing the same aim or values, but generating shared understanding of what needed to be done to accomplish the two separate aspirations of a useful product and a scientific publication. In effect, Tyler used interactional expertise to translate the 'what" outlined by the biologist into the "how" of software engineering. In the less successful example, the computer scientist may have achieved the goal of publishable research, but produced a less useful tool for users, in that case, another member of the Group, Madison. I turn next to analyze shared understanding as an aggregate of the larger team that worked on the PATRIC project and the possibility that it represents a stage 3 trading zone and/or a transdisciplinary research approach.

Transformation

The CI Group spent many years developing shared understanding and an integrated research process. The PATRIC project itself was a five year grant and most of the group members interviewed were involved for the majority of that time with the shortest participation being two years. In the beginning they looked much more like Gorman's stage 1 trading zone than anything else, where "experts throw parts of the solution over a wall to one another without really sharing knowledge". (2008, p. 92) The intention to work as a transdisciplinary team was infused in the organizational structure and directives of VBI and the CI Group, but the relationships were still new and team members lacked the experience to cross knowledge borders effectively. As Tyler described the transition:

> Initially as I said, it was pretty much sort of a unidirectional flow of information. Biologists they are sitting in a room having their meeting, generating a set of requirement bioinformaticians might be helping them, at the end you have this five page or 10 page document that describes everything. Pass it to a software developer and he's supposed to implement exactly the way it's sort of written. You may have some questions but I remember hearing answers like 'this is biology you know nothing about it just do what you're asked to do', something like that. (Personal interview 2009)

The CI Group began much like a multi-disciplinary team or stage 1 trading zone, where knowledge was developed separately within the confines of each subgroup and was then passed along to the next subgroup. Each subgroup staked out its turf and actively patrolled the borders of that territory. The biologists excluded the software engineers from challenging things they considered the province of "biology", thereby creating a unidirectional flow of information. At the same time biologists were subordinating the role of software engineers to that of “technician”. Through time the group developed a more integrated approach, as Tyler observed:

> I think from there we as a group evolved a lot where now we are in a state where each team or meeting that we are having or discussion that we are having, even for the requirement part or exploratory project, it always involves the composition where you have some biologists, bioinformaticians, usability person and software developer. So we have moved away from one person is responsible for writing requirement and one person is implanting it to sort of this shared model where rather than going though this long loop maybe spending a few weeks or a month generating the requirements passing it through usability, and they provide this user interface design, and then going to the software development where software developers say this is not possible with the current infrastructure that we are using, and then it goes back. Instead of that we have evolved into these small teams where everybody’s in contact. And the goal is not [that the] software person will pretty much question each and everything that’s being discussed from the biology side, but to remind people about the software issues that we need to think about especially when you have a large resource on a project like this, especially when your data is pretty much developing every year, reminding people of issues of scalability and performance and portability and, all those things basically. (Personal interview 2009)

Eventually the group, particularly the PATRIC project members, began to resemble (or re-assemble as) a transdisciplinary team, where perspectives were integrated from problem identification through implementation. A shared process and understanding developed because territory was less guarded and knowledge borders were crossed more freely. The porosity of the knowledge borders was increased through development of a shared practice and understanding of goals along with interactional expertise.

Metalanguage

Possibly the most important aspect of a shared conceptual framework is the integration of disciplinary methods, perspectives and practice in situ. That is to say, each common knowledge frame is unique to the members assembled and the problem being addressed in a transdisciplinary effort. This does not rule out the possibility of multiple shared conceptual frameworks developing within subgroups of a broader transdisciplinary effort. In fact, I argue that CI Group achieved a metalanguage that represented the elusive shared conceptual framework of transdisciplinarity and a shared mental model of a type 3 trading zone that Gorman has argued is a collaborative and iterative model for the relationship among science, technology and society "in which participants jointly create a dynamic, evolving representation of the superordinate goal and the boundary system." (2008, p. 92)

As I have stated, the PATRIC project is the main component of a larger collaborative effort not fully represented by CI Group members. My study lacked the capacity to capture relationships amongst participants of the larger partnership. This limits my findings concerning what developed within the CI Group. Any shared conceptual framework or integration that happened at that broader level is beyond the scope of this study. However, I found evidence that amongst the CI Group members working on the PATRIC project, a shared understanding developed regarding methods, goals, and practices that resembled a transdisciplinary metalanguage. Here is another description offered by Ryan that depicts the adoption of a shared methodology in the PATRIC project linked to the formalization of the team's work practice:

> So we have this process, I guess I'm going to draw a picture. So, in software there's this notion of a spiral development process … you start off, by understanding what the problem is, designing for it and then building for it, and then what I call it, evaluation, and you kind of start

> here and in theory is kind of take baby steps and so that when you get back to the beginning, you have a small piece of software that's functioning, and over time you kind of grow this system. So the size of the spiral in a traditional system, or a traditional spiral development cycle is more indicative of the size of the system so as you go out you have a bigger application or website or whatever. Now take this thing and pull it out of the board and put time on this axis. At first our spirals were really big and then, we started getting them closer together, so we were able to iterate around this thing faster because over time it was like we had a mind meld. Over time we all had this shared common view, we had a list of thing we knew we needed to be working on and by the time we needed to start working on the fifth thing we hard already been talking about it, we already had kicked around some ideas over coffee about the types of things we wanted to do, and we really got to the point where a lot of the formalization of the usability engineering process, documentation became a lot more light weight, which just makes it faster. (Personal interview 2010)

Ryan's depiction contains several insights that deserve consideration. But first it is worth mentioning the spiral design process he described is very similar to the concept of "recursiveness" in TDR (Pohl and Hadorn 2007). One way to interpret Ryan's account is that the "usability engineering process" is only a frame Ryan used to understand the formalization of procedures within the group. However, I think this interpretation is limited because other group members also mentioned the usability engineering process as an integral component of their common vision and practice. At the same time the formalization of the usability engineering process is also a methodology for practicing research, and to some extent the group adopted this approach as part of the metalanguage that developed. Further, the introduction of the usability engineers into the PATRIC project was considered by many to represent a turning point in the evolution of the team toward a more effective and integrated collaboration. As this member described it:

> One interesting example I can think of was the way that the human computer interaction people [usability engineers] worked with the group, because they were familiar with the interface side with websites. They were not familiar with the domain and they may or may not have been

familiar with particular tools that computer people are using to implement the system. And they needed to understand what the goal was from the biological standpoint. What the end user was trying to achieve and then from kind of what I contributed, what [was] mechanistically under the hood to make the process go, and then they would look at that and say well, if you set up your webpage in a certain way that would get the user to supply the parameters that were needed and not confuse them and it would illicit the information from the user in the most efficient way so that then the computer people could go and implement the software to fill the requirement of all three groups. There wasn't one person or one faction that really facilitated the discussion. It was kind of a group, people. From the input of all four groups we all came to a better understanding of what the problem was. If you saw the first implementation of the webpage before the human interface got involved, it was very different from what they came up with afterwards. And you could really see the value of their input. (Personal interview 2009)

Ultimately, others incorporated a usability engineering perspective to the point the perspective was represented even if a usability engineer was not present. The incorporation of this viewpoint across disciplines in the context of the PATRIC project reflects the level of integration reached in the team. One usability engineer first described early experiences and then a transition towards a metalanguage:

> I would throw things over the preverbal fence and then software developers would have some web page they were wanting me to look at so they would throw it back over the fence to me. Whereas now, I would say not only am I asked for input or for my opinion, hey I'm building this webpage and it's to the point now you and I need to sit down together and look at the interface, I've got the basic functionality working we need to look at the interface. There's also a lot more and it's a two-way street right, the user interface components of what we're building are in the forefront of everybody's mind now, so even if I'm not in a meeting those interests will be represented, which is great. And it's because people have come to realize if the website is not successful then we're not successful. We can have all of the best data and tools in the world but if nobody comes to the site, or nobody stays at the site, it's all for [nothing]. (Personal interview 2010)

At first, the group exhibited a compartmentalized process where subgroups only interacted long enough to pass information over the fence. Research was carried out in stages, each contained within a different discipline, then transferred to another discipline to complete the next phase. Eventually information flowed more freely through increased communication. Knowledge was then co-created through an integrated process, rather than being produced separately in fragmented subgroups. This disjointed process resulted in co-production, but not co-creation since each sub-group worked on separate parts using distinct disciplinary methods and tools. Once the CI Group achieved shared understanding and increased communication in an integrated process, its members began to co-create knowledge. The shared understanding also developed around the value and importance of integration itself. The value of integration was enacted through the knowledge production process and expressed as the importance of gathering different perspectives at all stages of research and development. Each viewpoint was increasingly given equal consideration by a majority of sub-group members, thereby increasing the flow of information and trust of knowledge that moved across borders. Here is how one CI Group member described this process:

> There are different problem solving perspectives around each problem. And I think actually that's something that we have gotten better at. I think that in the beginning … there was always the natural tendency to decompose the problem, any problem into its disciplinary views or something quasi like that. And then to see it solution so to speak, or it's attack as a serial process where, the geneticist does this, then the statistician does that, then the software developer does that. We've become increasingly good and in particular over the last few months, of really, really, really starting to embody a notion that any problem… actually it's meritorious to have a number of different views involved in the problem. And most importantly it's very important that those different views be shared sort of on an equal playing field and discussed openly because there are all sorts of dependencies. So I think we've become a lot better at recognizing the most important thing we can do as a team is share the different perspectives on the problem and its potential solution, so to speak, and recognize that the capacity to integrate all that

> information into an execution strategy is probably the most important aspect of what we can do. (Personal interview 2009)

The team also reached an understanding about the different, but integral part each perspective represented in the process. Biologists no longer staked out their "biology" territory and actively excluded the software engineers. Interactional expertise was one reason for dissolution of this border as software engineers gained expertise in the biology domain. But not all members gained interactional expertise and biologists in particular were less likely to gain proficiency in engineering or computer science than were computer scientists to gain expertise in biology. When interactional expertise was lacking, the group also relied on boundary objects, such as the PATRIC website, and standardized methods, including the formalized usability engineering process. The work process itself also became more standardized as team members developed shared expectations about interactions among team members. As one PATRIC member expressed this point:

> I think there's a shared understanding of, at sort of a low level … of exactly what we're building at any moment in time and shared understanding of what level of interaction I am expected to have, and…what level of interaction we will not have. (Personal interview 2009)

Boundaries established around member interactions helped differentiate roles among team members that created a more efficient process. One part of this differentiation resulted from the realization that biologists possessed the domain knowledge necessary to define the problem the group needed to solve. The computer scientists and engineers knew how to build tools that could address the biologists' domain problems   The usability engineer brought an effective process and capacities that helped bridge the knowledge border between the biologists' "what the problem is" and the engineers' "how to solve the problem". One usability engineer also helped balance the value of scholarship with the value of a useful product. However, it was difficult to discern if this was due to the usability engineering perspective or just this particular usability engineer who valued both scholarship and useful products. I found the usability engineers were the effective boundary spanners, not the bioinformaticians.

I expected bioinformaticians to exemplify interactional expertise and actively facilitate among group members. As it turned out, they were more likely to proceed on their own because of their interactional expertise, rather than translate between group members embedded in different disciplinary knowledge systems.

Chapter 8

Conclusion

This dissertation explored group dynamics in the VBI Cyberinfrastructure Group where members with diverse disciplinary and professional backgrounds attempted to work together to co-produce tools and knowledge that address infectious disease problems. Over time, the PATRIC project members developed a shared understanding of research goals and procedures that crossed disciplinary boundaries and facilitated research and development of web-based genomic tools and applications used by infectious disease researchers around the world. These collaborative efforts also resulted from attempts to balance the goals of developing scientific products and at the same time generating scholarly publications within and across disciplinary fields.

The project group's accomplishments did not come easily and were built upon many false starts and failed attempts that provided valuable lessons about unproductive behaviors. The integrating process that evolved among team members took years to reach fruition through numerous stages. The most accomplished travelers across knowledge borders developed valuable personal relationships with other members. Collins, Evans et al. have offered a similar argument:

> … there is not just one best way of organizing inter-disciplinary collaborations and that, even within the same collaboration, different relationships will develop at different times. Secondly, and perhaps even

> more importantly, thinking about trading zones as places where cultures meet, languages are learned and tacit knowledge shared, emphasizes the difficult and time-consuming nature of the work. (2007, p. 665)

Group members who were not well suited for, or interested in, cross-disciplinary work either left the group or were pushed out at some point during the unit's evolution. Value alignment was an important aspect of maintaining productive relationships within the group. Some members found ways to balance the need to make useful things with the necessity to publish papers. Those who had not attained such a balance were most likely to express dissatisfaction in their collaborations with other members.

Although this study was not specifically designed to evaluate the effectiveness of the group, organizational support of, and structures based on, transdisciplinary principles seemed instrumental to the group's success. The CI Group was clearly doing something right given its growth and recent substantial grant award from NIAID. The award is especially relevant to this research because NAIAD is a component of the National Institutes of Health (NIH), which has stressed transdisciplinary scientific integration in its research guidelines in recent years. (Stokols 2008a)

Research goals revisited

This research was initiated to understand better the dynamics of the CI Group as its members sought to share and integrate knowledge across knowledge and values borders. My first research question was:

> *Did group members manage to co-produce knowledge across the disciplinary barriers inherent between separate systems of symbol representation and manipulation? If so, how?*

Some group members were successful in co-producing knowledge across knowledge borders. Some were not. The core members of the PATRIC project achieved the highest level of shared understanding leading to increased levels of communication and coordination. They accomplished this through several means including accretion and extension of trust among participants, creation of a shared conceptual framework, common use of boundary objects, development of interactional expertise and co-creation of a metalanguage to characterize group discourse.

One dimension of the team's communication across borders included gaining interactional expertise and working towards an alignment of disciplinary goals. Shrager has offered this observation based on his experience with designing web-based applications among computer scientists and biologists:

> But how do the software engineers know what functionality to add? There is, of course, no single nor simple answer to this question. In my case, I was both programmer and biologist; I understood what was needed. But, as described above, this is rare for present day biology. More commonly, biologists and programmers will be involved in a collaboration where the biologists set the goals and the programmers execute on them. In this case the programmers generally do not understand the biology at all—they are just manipulating strings or numbers at the behest of the biologists. (2007, p. 646)

However, what I found in the CI Group, in particular among the core PATRIC project members, was the evolution of an alignment process that included software engineers gaining some proficiency in the biology domain. They did not just manipulate numbers, but participated in a knowledge co-production process facilitated by interactional expertise, boundary objects, trust and shared mental models. There were also individuals in the CI Group with expertise in both biology and programming, as in Shrager's reported experience, but they were not as instrumental in bridging knowledge borders as expected. Instead, it was the usability engineers who facilitated communication of user needs to the software engineers and software limitations to biologists. One main difference between the CI Group and Shrager's BioBike project was the close proximity and personal interactions of the CI Group compared to BioBike's exclusively web-based communication. Long-term professional relationships built through repeated interactions and communication were a key element of constructing shared understanding and trust among the PATRIC project core members.

One advantage of using a retrospective methodology was that a concrete language regarding principles of transdisciplinary research had developed by the time group members were interviewed. They could talk about their experiences using a shared lexicon that had evolved concurrently with group projects and product development. Almost like a third dimension of expertise, group members became proficient in an integrating process of research and development that was expressed as a common language and embedded in technology and shared meanings.

Another dimension of communication and coordination issues was a tension between CI Group members with previous experience in academia and those with experience in industry. This division was a constant challenge for the group. In this regard, my second research question asked:

> *What did group members value and how did these values influence group goals and outcomes?*

I did not expect this boundary to be as pronounced and ubiquitous as it was. I thought the disciplinary boundaries would be more of an issue for the group and that the bioinformaticians would be the most adept at crossing boundaries and assisting others across them. My working hypothesis was that the bioinformaticians would be adept at boundary spanning based on their disciplinary location at the nexus of biology and computer science. While it was true that bioinformaticians were comfortable in both worlds, rather than working as a conduit between biologists and software engineers this duality resulted in isolation more often than not. Bioinformaticians were described by themselves and others commonly to "go it alone" whenever they could. Instead of an expected hard knowledge border, I found the values border created the most tension, and the usability engineers, rather than the bioinformaticians, turned out to be the more successful mediators of its crossing. Group members had to balance tensions concerning value placed on producing scholarship for publication and the usefulness of products that fulfilled research contracts.

Transdisciplinary Trading Zones

Transdisciplinary and trading zone frames were applied as means to understand better communication and coordination among a diversity of disciplinary collaborators yielding an interwoven cognitive structure that closely resembled a transdisciplinary trading zone. The group I studied developed an iterative process with common points of focus that coalesced as a shared metalanguage to allow members from different disciplines to work together despite cognitive and professional (experience-related) communication barriers. The two main boundaries explored were knowledge and values, using the concept of trading zones to understand group dynamics across disciplinary knowledge barriers and professional values. The metalanguage or shared mental model that developed among core PATRIC project group members had three main components: boundary objects, shared procedures and interactional expertise. As the group evolved, boundary objects, standardized procedures and interactional expertise developed in a way that facilitated integration of knowledge products and that ultimately constituted a metalanguage.

The concepts of transdisciplinarity and trading zones were crucial in identifying cross-disciplinary borders and describing how members achieved communication and knowledge integration. However, each construct had weaknesses. Transdisciplinarity needed more theoretical development and trading zones required more empirical evidence. In order to explain the shared understanding developed among PATRIC project members, including methods, goals, and metalanguage, I constructed a combined conception of a transdisciplinary trading zone. Trading zones provide a descriptive theoretical frame that complements the normative model of transdisciplinarity, which offers few details about intra-group formation of shared understanding and language. In turn, the concept of trading zones benefited from viewing the work of the group as a process of knowledge integration, and regarding the emergence of metalanguage as a shared conceptual framework. At the same time, the theory of trading zones lacked empirical evidence that examining CI Group knowledge sharing dynamics contributed.

Knowledge integration has not been fully addressed by research concerning trading zones and expertise has not been a focus of transdisciplinary scholarship. Although knowledge integration and expertise are similar phenomena, they present nuanced differences. An amalgamation of both yielded a more complete description of CI Group dynamics and evolution that either alone could provide. Ultimately, the shared practice and understanding of research goals along with interactional expertise and boundary objects within the CI Group reduced knowledge borders and facilitated value(s) alignment. However, even though this research provides an increased measure of clarity, the so-called "black box" issue of how diverse groups representing alternate ways of knowing develop mechanisms and processes to create common conceptual frameworks still needs more attention.

Future Work

Fractionated trading zones still require more empirical work to understand fully the range of communication barriers and forms of coordination that emerge to address them across disciplinary borders. Precisely how values alignment occurs within interdisciplinary group participants also remains understudied. This study focused on only one type of trading zone. The three other zones identified by Collins, Evans and Gorman were not addressed here represent potentially fertile avenues for future research into interdisciplinary knowledge integration dynamics. Inter-language, enforced and subversive zones could be explored and compared with the group dynamics in this fractionated trading zone, for example. Broader studies that focus on implementation of research are an important aspect of transdisciplinary work that deserves more consideration as well.

The relationship between organizational goals and structures was not a primary focus of this research, but it too deserves further attention. What was the effect of CIG adoption of transdisciplinary principles on research practice? Further analysis could produce a normative model of cross-disciplinary work building on the findings of this study. Over time, analyses of efforts to integrate and share knowledge amongst a diversity of participants should afford the capacity to offer practical recommendations concerning how shared frames are attained in small transdisciplinary groups. That knowledge in turn can inform both how such efforts are structured and the ways in which group members serving in them seek to address the complex problems with which they are typically charged.

More particularly, perhaps this group constituted a shared mental model zone, which shares many characteristics with a transdisciplinary research approach. Gorman (2008) has argued a superordinate goal is an expression of moral imagination, or the group's ability to share an ethical common vision of research that is sensitive to the needs of society. Funtowicz and Ravetz (1990; 1992) have offered a similar conceptualization, but one focused on consciously democratized efforts that address problems of society through an extended peer review process. Transdisciplinary research also focuses on the needs of society and a common vision among researchers that leads to a shared conceptual framework through which to conduct research. Unfortunately, neither the shared conceptual framework of transdisciplinarity nor Gorman's shared mental model trading zone provide a nuanced description of how these processes alleviate communication and value conflicts. The CI Group members provided evidence of shared goals and values, but rarely discussed the broader social impacts of their research. Future research is needed to expand the conception of a transdisciplinary trading zone into a broader context specifically focused on addressing socially sensitive research problems.

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Appendix A

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants in Research Projects Involving Human Subjects

Title of Project **Trading zones and transdisciplinarity: knowledge sharing and integration in a cognitive *heterogeneous milieu***

Investigator(s) Derren T. Rosbach, Doctoral Candidate; Max Stephenson Jr., Faculty Advisor

Purpose of this Interview:

You are being asked to participate in an interview regarding your experiences as a member of the Cyberinfrastructure group. The study, titled **Trading zones and transdisciplinarity: knowledge sharing and integration in a *heterogeneous cognitive milieu*** is being conducted to gather information to complete a doctoral dissertation.

The purpose of the research is to explore the ways that researchers from different disciplines work together on research projects. In particular we are interested in how individuals share information and generate knowledge amongst a diversity of participants. As a member of the CI group, you are being asked to participate in this interview. Overall, we hope to speak with all members of the CI group for this study. Interviews will take approximately 90 minutes.

Procedures

You are being contacted to conduct a personal or telephone interview with Derren Rosbach, a graduate student in the Planning Governance and Globalization program at Virginia Tech. The interview will be digitally recorded and transcripts will be made and used only for fact checking and verbatim quotations in research papers. Interview files will be kept confidential in a secured location and erased upon completion of the study.

Your participation is voluntary and will involve only one interview. If you have any questions regarding the procedures or the contents of this consent form, please do not hesitate to ask us. Our contact information is listed below.

Risks

We believe that the risks of harm to you from your participation in this study are very low. They are surely no greater than those you encounter in your daily life.

Benefits

We cannot guarantee a personal benefit to you for your participation, but we are grateful for your consideration. If you are interested in the results of this research, Mr. Rosbach will be happy to provide you with a copy of his final paper. Our contact information is provided below.

Confidentiality and Anonymity

We are seeking your ***written consent*** to allow the researcher to include your statements in the scholarship that will result from this effort. Rest assured that tapes and transcripts are accessible only to the interviewer and transcriber. You will have the option of sharing information "on the record" or "off the record" throughout our conversation. We will honor your specific requests for confidentiality or "off the record responses" when you ask us to do so. We will also be using pseudonyms in an attempt to protect your identity. However, we cannot guarantee that using pseudonyms will provide complete anonymity given the nature of the research and the size of the CI group.

It is possible that the Virginia Tech Institutional Review Board (IRB) may view this study's collected data for auditing purposes. The IRB is responsible for the oversight of the protection of human subjects involved in research. Their contact information is at the bottom of this page.

Compensation

We are unable to provide compensation for your participation.

Freedom to Withdraw

You are free to withdraw from this research at any time. You are also free NOT to answer any questions that you choose.

Your Responsibilities and Permission

I, ____________________________________, voluntarily agree to participate in this research on the work of the Cyberinfrastructure group. I am 18-years-old or older.

I have read and understand the purposes of this research and the contents of this Informed Consent form. I hereby acknowledge the above and give my voluntary consent:

____ ___________

Signature Date

Should I have any questions about this research or its conduct, or questions regarding my rights, I may contact:

Faculty Advisor:
Dr. Max O. Stephenson, Jr.
Virginia Tech Professor
540-231-7340 mstephen@vt.edu

Investigator:
Derren Rosbach
Doctoral Candidate
540-231-0965
derren@vt.edu

IMPORTANT:

If I should have any questions about the protection of human research participants regarding this study, you may contact Dr. David Moore, Chair Virginia Tech Institutional Review Board for the Protection of Human Subjects, telephone: (540) 231-4991; email: moored@vt.edu; address: Research Compliance Office, 1880 Pratt Drive, Suite 2006 (0497), Blacksburg, VA 24061.

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
Recruitment Letter

Title of Project **Trading zones and transdisciplinarity: knowledge sharing and integration in a *heterogeneous cognitive milieu***

Investigator(s) Derren T. Rosbach, Doctoral Candidate; Max Stephenson Jr., Faculty Advisor

Hello, my name is Derren Rosbach. I am a doctoral student at Virginia Tech working on a project to understand better the ways that researchers from different disciplines work together on research projects. In particular we are interested in how individuals share information and generate knowledge amongst an intellectually diverse group of participants. As a member of the CI group, you are being asked to participate in a personal interview aimed at understanding such dynamics more fully. Overall, we hope to speak with all members of the CI group for this study. Interviews will take approximately 60 to 90 minutes.

The results of this study will be submitted to academic research journals and Virginia Tech as part of the requirements for a doctoral degree. Any questions can be directed towards myself or my Faculty Advisor, Max Stephenson. Our contact information is listed below.

Thank you for your time and consideration,
Derren Rosbach

Faculty Advisor:	**Investigator**:
Dr. Max O. Stephenson, Jr.	Derren Rosbach
Virginia Tech Professor	Doctoral Candidate
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mstephen@vt.edu	derren@vt.edu