CROSS-DISCIPLINARY INTEGRATION:
THROUGH ARGUMENTATION AND FOR SUSTAINABILITY

By

Bethany Laursen

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ABSTRACT

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Today's sustainability problems require wisdom that can only come by integrating different ways of knowing for each situation. When academic researchers undertake sustainability work, many of these ways of knowing come from different disciplines. However, years of cross-disciplinary research and practice have yielded only metaphorical or abstract understandings of what researchers actually do to integrate disciplinary contributions. Without a clear understanding of the actions researchers take to accomplish integration, we have been left with confusion, inconsistent proxy measures, or lengthy learning by trial and error. This has left sustainability and other wicked problems either in the hands of veterans with decades of experience or subject to unreliable integrative attempts by newer investigators. To aid practice through clearer understanding, I open the black box of cross-disciplinary integration, explicating one the main processes that investigators use to integrate disciplinary contributions into cross-disciplinary insights: reasoning together.

Through three articles, the dissertation shows that (1) as a field, argumentation studies provides valuable, actionable insights into cross-disciplinary integration, (2) one of the main processes of cross-disciplinary integration is reasoning together, and (3) the details of cross-disciplinary reasoning specify and clarify two existing, more abstract models of cross-disciplinary integration. Thus, overall, the dissertation clarifies what has been an urgent but confusing process in sustainability investigations, and, in doing so, it points the way to practical improvements in sustainability research policies, norms, and education.

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PREFACE

The questions driving this dissertation came with me into this world, lying latent as magma below the surface yet fueling fascinating choices throughout my life. I've been captivated by ecology, forests, science education, wilderness travel, group facilitation, landscape governance, and evaluation, always pursuing the next most interesting question—until I realized that they were all erupting from my simmering, essential joy in asking questions no single discipline could answer. At the bottom of it all, I enjoyed the learning process itself more than the content. The mental and physical flexibility required to learn from multiple sources exhilarated me more than the breadth and depth I could reach with this flexibility. Thus, I realized the only question I had that was big enough to carry a dissertation and a scholarly career was a question about how I and others make sense of multiple ways of knowing. I confess, perhaps along with many others, my dissertation is a selfish attempt to quiet my internal roilings.

But I don't feel too guilty for this pursuit, because I am not the only one who wants and needs to know how to integrate diverse knowledges. This wider need became starkly apparent to me as I conducted independent research and evaluation on complex environmental issues. While I had native talent in cross-disciplinary integration, I still needed training in how to do it well when the textbooks no longer applied. It turns out many others desire such training, too. We feel the pressure to conduct excellent, practical, and timely inquiries to aid our urgent socio-environmental problems. This is the external motivation behind the work you are about to read. If either of these stories resonate with you—an intrinsic drive to ask interstitial questions or an extrinsic need to act in a broken world—I hope you find something useful and inspiring as you turn the pages.

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CHAPTER 1: INTRODUCTION

While the world has always been interconnected, humans have driven those interconnections since the Anthropocene began, arguably around 1610 (S. L. Lewis & Maslin, 2015; Norton, 2012). Since the "Great Acceleration" began around 1950, complex, socio-environmental dynamics have sent Anthropocene ripple effects ever farther and faster (Steffen, Crutzen, & McNeill, 2007). Moreover, ripples that began decades and centuries ago—such as the widespread use of fossil fuels—are gathering into tsunamis—such as global climate change—that threaten to overwhelm the ways of life we have come to love and expect (Lenton et al., 2008; Rockström et al., 2009). In such a world, we feel deeply alarmed and compelled to adapt quickly if we are to maintain any hope of mutual human-environmental flourishing. We now call this the quest for "sustainability."[1]

Knowledge Integration in Sustainability Investigations

Moving toward sustainability requires asking wise questions and offering wise solutions—in a word, sustainability requires wise *inquiry*. It is so fundamental to sustainability that *inquiry* is an important frame I use throughout the chapters of this dissertation. Inquiry, in the pragmatist sense of the word, refers to any effort aimed to settle our feelings of doubt or uncertainty (Dewey, 1938; Peirce, 1877). Inquiry therefore encompasses research, which is a label for projects that aim at transferable knowledge, as well as queries that aim to solve local problems alone. Inquiries can be more or less formal, and here I will call more formal inquiries *investigations.* Investigations are formal to the extent that they use methods *explicitly* and *systematically*. Explicit use consciously follows a procedure and documents any changes to that procedure. Systematic use applies that

[1] While Paul Thompson (2013) persuasively argues that "sustainability" has come to mean either (1) resource sufficiency, or (2) functional integrity, I argue both of these meanings refer to mechanisms for reaching mutual human-environmental flourishing. That is, "sustainability" is multivocal (Buzzanell, 2017), referring both to the desired state and to the paths for reaching it. But even if one rejects this multivocal understanding of "sustainability," it is clear that the word has become a rallying cry to motivate socio-environmental improvement.

procedure and its adaptations consistently and thoroughly to the entire sample. These two features often require investigations to involve chartered projects, external funding, declared questions and conclusions, and other organized processes and artifacts.

Take, for example, two sustainability inquiries that seek to answer the question, "What does my city need to become more sustainable?" In an informal inquiry, I might simply list the things I heard around town. This is informal because I do not consciously apply a procedure consistently to all of my sources of evidence; I couldn't tell you where or when I heard everything or from whom, and I certainly didn't specify "around town" and listen the same way in every part of town. A formal inquiry would create a systematic search strategy and stick with it, perhaps circulating a survey or reviewing all city reports from the last five years.

While both formal and informal inquiries are important for sustainability, in this dissertation I focus on formal inquiries because they are more likely to overcome two core challenges to sustainability than informal inquiries are. First, sustainability is a global quest. At that scale, it is more likely to succeed using formal methods rather than informal ones. For instance, Xu et al. (2020) could provide a global status report only by using formal methods. Second, sustainable systems are complex and adaptive. Informal inquiries into such systems are likely to go astray by succumbing to psychological biases (such as confirmation and familiarity biases) and powerful interests. Formal inquiries limit the impact of these biases and interests—or at least make them available for scrutiny and repair—by enforcing an explicit, systematic procedure (Kahneman, 2011, pp.222-233 and throughout; Fitzpatrick, Sanders, and Worthen, 2012, pp.5-6; Jones, 1998, pp.xi-xvi).[2]

[2] Yet complete formality is not always desirable. Fitzpatrick et al (2012) caution that investigations like formal evaluations should be "a form of assisted sense-making" that finds a "middle ground" between too much method and too much intuition (p. 6). Specifically, Kahneman (2011) writes, "Intuition adds value [to selecting employees]…but only after a disciplined collection of objective information and disciplined scoring of separate traits" (pp.231-232).

Professional and citizen investigators increasingly join the quest for sustainability in the hope that they can contribute to powerful paths for action. There is strong, well-founded consensus that sustainability insights will illuminate *more* powerful paths for action if they integrate diverse knowledges (De Grandis & Efstathiou, 2016; Guerrero et al., 2018; Miller & Muñoz-Erickson, 2011; Miller et al., 2008; Palmer, Kramer, Boyd, & Hawthorne, 2016).[3] Such integration is important because sustainability problems are not only complex, they are *wicked* (Brown, Harris, & Russell, 2010; Rittel & Webber, 1973). In a wicked problem, there are multiple stakeholders who each understand and experience the problem differently; they each have different epistemic, metaphysical, and moral claims at stake. No one comprehends the problem completely nor can anyone predict all consequences of any attempt to solve it. This means it is not only difficult but impossible to solve sustainability problems once and for all; there are too many systemic interactions, uncertainties, and competing values to command and control the situation with optimum benefits for all. The best we can do when investigating wicked problems is to be as just, accurate, and effective as possible in our studies. The only hope for accomplishing this is to include many perspectives in the investigation.

Multiple ways of knowing could help communities ameliorate wicked problems because they introduce many different concepts, methods, and tools. When integrated effectively, these together shed more and more insightful light on the dynamics of the problem and therefore also on

[3] Some disagree that integration is the goal. Instead, they argue the goal should be constant critique of perspectives through dialogue lest we take our perspectives for granted. See, for example, Bryan Norton (2012). Constant critique centers analysis—the deconstruction of a whole into its parts to examine its workings and implications. This deconstructive view is compatible with the integrative view if we adopt the Cognitive Flexibility Theory that Spiro and colleagues offer (Spiro 2015; I will speak more of this in chapter 5). In that theory, when trying to understand a problem with no single correct template, case-specific assembly and re-assembly of multiple problem perspectives is required but only possible with cycles of *both* deconstruction and integration. Constant critique can fulfill the necessary function of deconstruction in such cycles but only if the critique aims "to consider possibilities" for change (Norton, 2012, p.457), not just to find fault with existing perspectives. Norton's main point offers guidance for how to proceed: these cycles of deconstruction and integration should occur in public, deliberative spaces designed to fit each case (Norton, 2012, p.463). This is one way of practicing the reflexivity others have noted is essential for sustainability wisdom (Popa, Guillermin, & Dedeurwaerdere, 2015).

pathways for improvement (Hagstrom, 1964; J. M. Lewis, Ross, & Holden, 2012; National Research Council, 2005). Moreover, given the ethical dimensions of wicked problems, justice during the investigation and in its outcomes is crucial. Involving multiple perspectives increases the justice of the investigation by legitimizing it and making it more likely it will treat all involved parties equitably (Adger et al., 2003; Heron & Reason, 2001). Ignoring the perspectives of those involved in the problem will only cause more problems.

I summarize this need to integrate multiple world views under the general term *knowledge integration*. As a form of inquiry, investigations ultimately aim to answer questions; investigating wicked problems is thus ultimately an epistemic task and the integration needed is ultimately knowledge integration. However, this epistemic task is constrained by ontological and ethical concerns, and so ontological and ethical commitments will also constrain the integration process. The knowledges involved will not be reducible to declarative statements but will also involve embodied ways of doing life, non-verbal expressions of truth, and the ways of generating these knowledges. Given the multifaceted nature of knowledge, I use a variety of terms when discussing it: "world views," "perspectives," "paradigms," "ways of knowing," and "knowledges" interchangeably refer to the epistemic resources stakeholders bring to be integrated in a sustainability investigation. The diversity within and among the knowledges involved makes integrating them difficult and sometimes impossible. Going beyond mere integration to just, actionable, and effective insights into wicked problems is even harder.

Nurturing Knowledge Integration

Recognizing the importance and difficulty of knowledge integration, administrators, funders, and educators have implemented many new programs to nurture it. These new programs spend enormous amounts of human, physical, and financial resources expecting that these investments will not only produce net resource gains but also transformative outcomes. A

prominent example of such a program is the new "Growing Convergence Research" Big Idea from the National Science Foundation.[4] The funder characterizes 'convergence research' as follows:

> Convergence research is a means for solving vexing research problems, in particular, complex problems focusing on societal needs. It entails integrating knowledge, methods, and expertise from different disciplines and forming novel frameworks to catalyze scientific discovery and innovation. (NSF Program Solicitation 19-551)[5]

Knowledge integration is the central goal of the convergence initiative at NSF, given the conviction that it is crucial to social and scientific progress and the recognition that such integration is difficult. Given the magnitude of the convergence challenge, NSF has funded several multi-million-dollar programs supporting convergence research. Growing Convergence Research has earmarked $12 million for its awards in 2020. The Convergence Accelerator program has devoted up to $90 million for its first cohort. There many similar funding programs across the world (e.g., Horizon 2020 in the European Union,[6] the Leading Integrated Research Agenda 2030 in Africa[7]), and they are accompanied by institutional initiatives such as research centers (e.g., http://c4i.msu.edu), community engagement training (e.g., Doberneck et al 2017), and RPT (reappointment, promotion, and tenure) policies that aim to support integrative, problem-focused research (Klein & Falk-Krzesinski, 2018). Beyond the academy, governmental units, non-profits, and citizen activists are organizing their own investigations in response to particular sustainability problems (e.g., The

[4] https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505637

[5] https://www.nsf.gov/pubs/2019/nsf19551/nsf19551.htm

[6] https://ec.europa.eu/programmes/horizon2020/en

[7] https://council.science/what-we-do/funding-programmes/leading-integrated-research-for-agenda-2030-in-africa/

Nature Conservancy's Center for Sustainability Science[8]; Vital Signs by Worldwatch[9]; LeeAnne Walters in Flint's water crisis[10]; and the US EPA's research into PFAS chemicals[11]).

Programs such as those associated with the NSF Convergence Big Idea can succeed only if their participating investigators reliably, incisively, and efficiently integrate knowledges arising from many perspectives on the target problem. Occasional, lackluster, and tardy integration is not sufficient. Yet—despite decades of practice and meta-research into research integration—program administrators, participants, and researchers of this process still do not know what makes these knowledge integration processes reliable, incisive, and efficient. In fact, we even lack clear, widely adopted methods for determining when integration has been achieved at all (Wagner et al., 2011). Thus, we are not sure if our investments in inquiry are worthwhile or wasteful, nor do we know how to improve our programs when they prove wanting. This is unacceptable.

To design effective sustainability programs and methods for evaluating them, we first need to understand exactly how knowledge integration happens in investigations. Specifically, we need to understand the tangible, improvable actions that investigators take when integrating different knowledges. This is our baseline knowledge gap. Once we understand these specific actions, we can study how researchers learn to conduct these actions reliably, incisively, and efficiently. Then, we can design programs with higher likelihoods of success and evaluation methods that report on these successes. These, in turn, will accelerate our quest for sustainability. Therefore, to begin this sequence of improvements, this dissertation focuses on addressing the baseline knowledge gap: articulating a main process by which sustainability investigators can integrate different ways of knowing. This search for a detailed, primary process and the next steps the search enables—for

[8] https://www.nature.org/en-us/about-us/who-we-are/our-science/center-for-sustainability-science/

[9] http://vitalsigns.worldwatch.org/

[10] https://www.goldmanprize.org/recipient/leeanne-walters/

[11] https://www.epa.gov/chemical-research/research-and-polyfluoroalkyl-substances-pfas

program improvement, evaluation, and eventually sustainability efforts—will be through-lines connecting all parts of the dissertation.

Knowledge Integration Through Argumentation

I eventually conclude that one of the main sets of actions sustainability investigators can take to integrate various ways of knowing in sustainability research is *cross-disciplinary reasoning*. This term labels a generic process consisting of several reasoning mechanisms that differ by context, e.g., who is conducting the investigation for what purpose. One of the specific and widely used mechanisms of cross-disciplinary reasoning is argumentation, in which existing knowledge claims are asserted, evaluated, and exchanged to create new knowledge claims, which, in turn, provide guidance for action. Since there are many ways to argue, argumentative reasoning is actually a family of mechanisms that deserves further study beyond this dissertation. The current task is to establish that cross-disciplinary reasoning through argumentation is an observable process that can and does result in knowledge integration.

As stated above, the key to insightful study of wicked problems is integration of the different perspectives or ways of knowing involved. Given the formality required of sustainability investigations, they often involve investigators trained in academia. Thus, much of the knowledge they bring is disciplinary knowledge. For the purposes of this dissertation, I restrict "discipline" to an interacting set of concepts and practices (a repertoire; Ankeny & Leonelli, 2016) supported by social infrastructures that exist, at least partly, in higher education institutions and related social structures (e.g., journals, departments, societies)—in short, academic disciplines.[12] This category includes professions such as medicine and architecture that train within the academy but mostly

[12] Compare my working definition to Karin Knorr Cetina's understanding of an epistemic culture as "those sets of practices, arrangements and mechanisms bound together by necessity, affinity and historical coincidence which, in a given area of professional expertise, make up how we know what we know" (Knorr Cetina, 2007, p. 363).

practice beyond it.[13] It does not, however, encompass every way of knowing that should be integrated for sustainability; for example, it excludes professional trades and cultural world views (also legitimate ways of knowing) that do not have representation in the academy.

Cross-Disciplinarity

While there are many aspects to disciplinary integration, scholars and research administrators have paid much attention to how *deeply* or extensively disciplines can be integrated. Decades of discourse have yielded a scale of disciplinary integration terms that has now been widely accepted.[14] Ranging from barely any integration to complete integration, these terms are (Klein, 2017; O'Rourke, Crowley, Laursen, Robinson, & Vasko, 2019):

- Multidisciplinarity[15]—juxtaposing multiple disciplinary contributions
- Interdisciplinarity—interacting disciplinary contributions
- Transdisciplinarity—transcending disciplinary contributions, either within or beyond the academy[16]

The practices and products referenced by each term can be quite different from each other, but what they all have in common is some level of integration. I will therefore refer to all three modes

[13] Depending on what one is trying to do with the word, "disciplines" can be large and loose (e.g., entire branches of study, such as the natural sciences and humanities) (Palmer et al., 2016), small and tight (e.g., specific fields, such as adaptive governance of marine natural resources) (Benda et al., 2002), or somewhere in between (e.g., a formalized community, such as sociology) (Weingart, 2010).

[14] While these terms have been widely adopted, other "disciplinarity" terms remain contested. Many of these, such as "antidisciplinarity" (Ito, 2019; Jiwani, 2011), seek to focus attention on aspects of disciplinary integration that have been overlooked. Given more discussion, we may see other lists of widely accepted "disciplinarities" such as those discussed by Klein (2017).

[15] Many prominent scholars declare that multidisciplinarity completely lacks any conceptual integration (Klein, 2017; Repko, Szostak, & Buchberger, 2019). However, I agree with O'Rourke et al. (2016), who argue that even the mere juxtaposition of multiple disciplines is a form of integration, albeit quite shallow.

[16] *Transdisciplinarity* has a diverse history as described by Klein (2017, pp.29-30). Two main meanings have emerged: transgression of (1) disciplinary and (2) academic boundaries. These meanings are most often used on different continents: the first in North America and the second in Europe, Australia & New Zealand. Yet recently the latter meaning is gaining ascendency even in North America as globalization increases exchange between continental discourse communities (e.g., the newly-formed ITD Alliance; http://www.itd-alliance.org/).

with the umbrella term "cross-disciplinarity." What I say about cross-disciplinarity will apply to all three, with the level of integration understood to vary by mode. Similarly, what I say about any one mode will apply to the others by adjusting the level of integration being considered. Beyond the level of integration, I also account for other aspects of integration, including the nature and number of contributions being integrated and the purpose driving their integration (O'Rourke et al, 2016).

In their quest for wisdom, sustainability researchers and meta-researchers have focused on the necessity and difficulty of cross-disciplinary integration in their work. Cross-disciplinary integration (CDI) has been researched for at least 50 years and practiced for much, much longer (Klein, 1990). It has been studied in cases such as multifunctional landscape governance (Fry, 2001), phylogenetics (O'Malley, 2013), general education (Klein & Newell, 1997), and science as a whole (Porter & Rafols, 2009), to name a few. From these cases and from general principles, cross-disciplinary theorists have developed several unifying frames to explain what CDI is and how it happens in research and/or education settings. The most widely discussed frames include:

1. Bibliometrics (Leydesdorff, Wagner, & Bornmann, 2019)—for any research setting
2. Input-Process-Output (O'Rourke et al., 2016)—for any setting
3. Learning (Boix Mansilla, 2017)—for any education setting
4. Socio-linguistic interaction (Klein, 2012)—for any research setting.

I will briefly describe each frame and its potential for identifying observable, tangible actions for integration in order to justify my use of a socio-linguistic frame for the current project.

Cross-Disciplinary Integration Evinced by Bibliometrics

Bibliometrics is a quantitative approach to the study of knowledge that focuses on knowledge products: "counting books, articles, publications, citations, in general any statistically significant manifestation of recorded information" (De Bellis, 2009). Bibliometric studies have analyzed cross-disciplinarity in many ways, including the cross-disciplinarity of an institution's faculty profile based on its faculty members' departmental affiliations (Godley, Sharkey, & Weiss,

2013), the cross-disciplinarity of an entire journal's corpus using natural language processing (Norder, Emich, & Sawhney, 2018), and the disciplinary diversity of teams and their projects (Aydinoglu, Allard, & Mitchell, 2015). However, the most common bibliometric studies of cross-disciplinarity use variations of citation analysis (Allen, 2018). Citation analysis draws inferences about cross-disciplinary processes by observing citation features, such as the disciplinary categories of the journals referenced (Youngblood & Lahti, 2018). Bibliometric studies are good at discovering large-scale, text-based patterns contributing to or resulting from cross-disciplinary integration. However, these discoveries arise from quantifiable inputs to and outputs of CDI; they do not observe CDI processes directly. And, in general, the quantitative approaches used can only detect the juxtaposition of disciplines, not their integration. Indeed, citation analysis is so far downstream from the actual integrative act it is an unreliable indicator of what happened during the integration. Thus, the bibliometrics approach cannot describe the tangible, improvable integration behaviors of cross-disciplinary investigators.

Cross-Disciplinary Integration as an Input-Output Process

The IPO model of integration is a second frame for CDI, and it has gained significant discussion since its recent publication (O'Rourke et al., 2016). Michael O'Rourke and colleagues offered an input-process-output (IPO) model of integration as a synthesis of existing work on cross-disciplinary integration. Previous work had identified many quantitative and qualitative features of CDI that seemed hard to reconcile. The model absorbs these specific features as parameters in a universal IPO model that applies to any setting, even beyond CDI. (See Chapter 4 of this dissertation for a diagram of the model and further discussion). As a general, universal frame, the IPO model clearly applies to my current purpose but cannot—on its own—specify the tangible, observable, improvable actions investigators need to take to integrate diverse knowledge inputs.

Cross-Disciplinary Integration as Learning

The literature on cross-disciplinary learning is older and more diverse than the bibliometrics approach to CDI. Much of this literature arises from efforts to integrate undergraduate learning across academic disciplines. Such studies focus on artifacts from the formal education system, including classroom activities (Dreyfuss, 2011; Edelbroek, Mijnders, & Post, 2018), assignments (Augsburg & Chitewere, 2013), grading (Boix Mansilla, Duraisingh, Wolfe, & Haynes, 2009; Wolfe & Haynes, 2003), curricula (Carmichael & LaPierre, 2014; de Greef, Post, Wenting, & Vink, 2017), textbooks (Augsburg, 2016; Repko et al., 2019; Repko & Szostak, 2020; Repko, Newell, & Szostak, 2012), and educational philosophies (Vars, 2002). Obviously, one shortcoming of this literature for my current purpose is that most sustainability investigations do not occur in classrooms; thus, the frame is not sufficiently general. I could work to generalize it as Veronica Boix-Mansilla has (Boix Mansilla, 2017), but another shortcoming is that the cross-disciplinary learning literature is strictly normative. That is, it proposes various ideal integration processes for students and then designs activities to accomplish these processes. This top-down approach provides helpful standards for good integration, but it does not explore what investigators do in practice to integrate diverse disciplinary paradigms. Moreover, classroom ideals may be inappropriate or unrealistic for investigations outside of coursework.

Lastly, the learning literature almost never describes how embodied student activities cause integrative insights. Instead, like the bibliometrics literature, the learning literature proposes either inputs or outputs of integrative processes: either the activities alone without the mechanism by which those activities affect knowledge integration, e.g., “Debate” (Edelbroek et al., 2018) “Writing,” (Augsburg & Chitewere, 2013), and “Listening” (Dreyfuss, 2011); or only the outcomes or functions of these activities, e.g., “Explores conflicting ideas” (Carmichael & LaPierre, 2014), “Recognizing patterns” (Spooner, 2004), and “Use interpretive tools” (Ivanitskaya, Clark, Montgomery, & Primeau, 2002). While the learning literature parses integration further than the

bibliometrics literature, it still falls short of identifying causal mechanisms connecting tangible inquiry actions to integration outcomes.

Cross-Disciplinary Integration as Socio-Linguistic Interaction

The socio-linguistic view of CDI, however, does specify such actions. These actions include, among others, developing a shared language for the project (Galison, 1997; J. L. Thompson, 2009), compiling shared repositories of tools and data (Bammer, 2013; Leonelli & Ankeny, 2015), gaining interactional expertise (Boix Mansilla, Lamont, & Sato, 2015; H. Collins, Evans, & Gorman, 2007), restricting the scope of the project (O'Malley, 2013), and using an integrative metaphor or boundary object as an interaction platform (Klein, 2012; Piso, O'Rourke, & Weathers, 2016; Wolfe & Haynes, 2003). In a socio-linguistic frame, CDI is both a social and epistemic phenomenon that occurs through language (Bracken & Oughton, 2006; Klein, 1996; 2012; 2014; Nikitina, 2005; Piso, 2015; J. L. Thompson, 2009). While I deny that language is necessary or sufficient for all CDI, language is certainly part of many of our integrative actions, especially when academics are involved. The socio-linguistic frame therefore promises actionable insights for many of our sustainability practices. Chapter 4 includes an extensive discussion of this frame and how it relates to the IPO model and the main mechanism for CDI that I propose.

Cross-disciplinarians, of course, use language to do many different social things with their inquiry partners: perform, inform, persuade, build trust, coordinate actions, and more. Wittgenstein (1958) calls these "language games," because, like any game, they have rules, goals, and players, but unlike every game, these games are played through language. Therefore, when describing how CDI works from a socio-linguistic perspective, theorists need to decide which language games they are trying to explain. Some CDI scholars ultimately want to focus on how cross-disciplinarians use language to coordinate their actions, leading them to develop theories of CDI as collaboration (Bennett, Gadlin, & Marchand, 2018; Hall, Vogel, & Croyle, 2019). Other scholars want to explain how cross-disciplinarians develop shared understanding, leading them to theories of CDI as

communication (Holbrook, 2013; Morse, 2014; Olabisi, Blythe, & Ligmann-Zielinska, 2014; J. L. Thompson, 2009). Still others assert that cross-disciplinarians use language as social performances, which evokes CDI as discourse (Choi & Richards, 2017; Osbeck & Nersessian, 2010). Of course, there are many points of overlap between these views, so they often engage each other's questions. I see merit in all of these socio-linguistic proposals, and I borrow from all of them, but something is missing. In terms of the IPO model of integration, these proposals provide excellent descriptions of the inputs and outputs of these language games, but they are fuzzy on the actual processes of integration.

If integration is occurring in cross-disciplinary language games, then according to the IPO model, the action is in the process box. Existing views had left this box hermetically sealed to my understanding; I could not observe the moment distinct inputs became integrated into fewer ouputs. However, viewing cross-disciplinary language games as attempts to *reason together* opened that box, because it showed how an observable behavior—communication—directly influenced the outcome—knowledge integration. Indeed, Nikitina (2005) wondered if "there exists a central cognitive process expressive of the dialogical tendency of our mind, which manifests itself in interdisciplinary and other kinds of thinking" (p.414). I propose reasoning is at least one important "underlying mechanism at work in all" kinds of communication (p.415). The field of argumentation studies—a field using socio-linguistic approaches—describes what happens when people reason alone and together, especially across diverse perspectives. The process box, according to these scholars, is the process of argumentation, and we actually know quite a lot about that now. Thus, where existing theories of CDI had left me stumped, I found argumentation studies a promising road to understanding the integrative act.

Research Questions

Thus, this dissertation explores a road less taken in hopes of finding a more understandable and actionable explanation of CDI. Along this road, CDI is framed as argumentation. With three articles, I seek to answer the following research questions:

1. How can argumentation be used to understand interdisciplinary inquiry?
2. According to neo-Pragmatist argumentation studies, how do collaborative, interdisciplinary research teams integrate disciplinary contributions?
3. How does collaborative, interdisciplinary reasoning (CIR) relate to our best theories of interdisciplinary integration?

These questions reflect my approach to the study of integration. First, I examine the value of a road less taken. Second, finding value down that road, I propose my own contribution to CDI inquiry—Collaborative Interdisciplinary Reasoning, or CIR—based on what I find on that journey. Third, traveling back up that road to the intersection with previous paths, I compare what I found to existing proposals. In a way, the movement mimics part of a spiritual retreat in which one chooses a learning space, retreats to immerse herself in that space, and then returns to discuss her insights with others at the retreat.

Limitations

I see three main limitations to my approach. First, CDI, in the confines I have placed it here, only features in sustainability inquiries that involve academics or professionals trained in the academy. However, just as there are many perspectives beyond academic disciplines, there are many sustainability inquiries beyond the academy. Examples of these non-academic inquiries include neighborhood association strategic plans, cultural resistance movements, forced migration responses, farm labor contracts, Indigenous actions toward climate change, and more. From my own experience and that of others, I know that non-academic knowledge integration proceeds differently from its academic counterpart. Thus, what I learn about cross-disciplinary integration

should be interpreted as applying only to academic sustainability inquiries. Future work will need to expand my work by investigating non-academic cases of sustainability integration.

The second limitation is that argumentation studies have traditionally understood reasoning in terms of propositional knowledge. That is, most of the conceptual resources in argumentation studies describe reasoning only in terms of declarative sentences. However, there are at least three other kinds of knowledge that likely figure into CDI besides propositional knowledge: (1) experiential knowledge, (2) presentational knowledge, and (3) pragmatic knowledge (Heron & Reason, 2008). It is not clear if or how argumentation concepts apply to these other three forms of knowledge, although work is proceeding on visual argumentation (Alcolea-Banegas, 2009). Thus, relying upon argumentation studies builds in a bias toward propositional knowledge, although this bias may not persist as argumentation studies expands its scope.

Thirdly, there do seem to be ways to integrate disciplinary contributions that do not involve reasoning at all. One can think of integrating data sources through algorithms as some models do (Bergmann et al., 2012, pp. 95-105), which isn't obviously a form of argumentative reasoning. In non-disciplinary settings, we often observe families engaging in integrative behavior, such as when a child and parent feel a close bond as a parent tucks their child into bed at night. It is not clear that argumentation has anything to say about these sorts of integration. Thus, relying upon argumentation as the primary frame for a new understanding of CDI risks a lopsided understanding of CDI by neglecting non-propositional knowledges and relational interactions. At the least, an argumentation framing should speak tentatively, perhaps even admitting ignorance, of these other pathways to CDI.

Dissertation Contents & Contributions

Despite these limitations, this dissertation explains huge swaths of cross-disciplinary activity that do use declarative sentences, which had previously shrouded integration in mystery. I use three articles and two book-end chapters to develop a theory explaining how integration—

specifically, cross-disciplinary integration—often occurs through *argumentation* in sustainability inquiries. My account of CDI draws mainly from other theories (e.g., neo-Pragmatist theories of reasoning and the IPO model of integration), but empirical data also provide support. This first chapter introduces the project by explaining the need for it, setting its scope, briefly reviewing the literature, and stating the specific research questions the articles address.

Chapter two was first published in *Issues in Interdisciplinary Studies*, and it justifies argumentation as a useful way to understand cross-disciplinary integration. It uses theories (one from argumentation, one from interdisciplinarity) to analyze two case studies (one disciplinary, one interdisciplinary). The analysis shows argumentation and interdisciplinarity are complementary frames. Specifically, when trying to understand cross-disciplinary inferences to the best explanation for a data pattern, argumentation reveals socio-linguistic challenges while interdisciplinarity reveals socio-material challenges. Ultimately, the chapter illustrates that CDI is often accomplished through reasoning in particular contexts and is worth theorizing further.

Chapter three was previously published in *Informing Science* as part of a special issue on transdisciplinary communication. This chapter defines a particular kind of cross-disciplinary reasoning—collaborative, interdisciplinary reasoning (CIR)—based on argumentation theory by neo-Pragmatist philosophers Jürgen Habermas, Larry Wright, Dale Turner, and Christian Campolo. It shows by example that the definition is useful for understanding CDI by applying the definition to sustainability team talk from a Toolbox Dialogue Initiative workshop (O'Rourke & Crowley, 2013). This application is accomplished through a new form of discourse analysis I call "argumentative discourse analysis." This chapter also presents a novel way to visualize integration through argumentation as a Sankey diagram. This diagram shows that integration occurs at two points in CIR: (1) when disciplinary contributions support an overarching premise, and (2) when all premises support an inference to the conclusion.

Chapter four, co-authored with Michael O'Rourke and also published in *Issues in Interdisciplinary Studies*, further justifies the definition proposed in chapter three by showing how it compares with two established theories of integration authored by Julie Thompson Klein (the socio-linguistic model) and O'Rourke and colleagues (the IPO model). CIR instantiates both the socio-linguistic and IPO models of integration by specifying the inputs, processes, and outputs when integration is achieved through the socio-linguistic process of reasoning together. The three explanations of CDI are progressively specific in their scopes, with the IPO model being the most general and CIR the most specific. Together, they shed amplifying light on CDI, which benefits both theorists and practitioners.

Chapter five concludes the dissertation by summarizing the answers to the research questions proposed in the introduction and how they contribute to the literature, and by discussing both further research on and practical uses of CDI as argumentation. Further research will address the limitations of the dissertation described above, how cross-disciplinary reasoning interfaces with other kinds of CDI, such as social integration, and what prerequisites enable cross-disciplinary reasoning. Practical uses of the dissertation's findings will include action research into which cross-disciplinary reasoning tools work best in which situations and what kinds of education build cross-disciplinary reasoning capacity for practitioners and team facilitators. Together, these future research and practical findings should improve how research policies, norms, and educational programs facilitate cross-disciplinarity in wicked problems like sustainability.

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CHAPTER 2: ON THE INTERSECTION OF ARGUMENTATION STUDIES AND INTERDISCIPLINARY STUDIES: THE CASE OF INFERENCE TO THE BEST EXPLANATION

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Laursen, B. K. (2018). On the intersection of interdisciplinary studies and argumentation studies: The case of inference to the best explanation. *Issues in Interdisciplinary Studies*, *36*(1), 93–125.

Abstract

This article aims to convince readers of the value of intersecting the scholarship of interdisciplinarity with the field of argumentation studies. The interdisciplinarity literature has not much engaged with the vehicle that carries interdisciplinary learning, languages, and locutions: the argument. On the argumentation studies side, despite the diverse interests of these scholars, not many have studied how reasoning proceeds in interdisciplinary inquiries. To aid bridge-building from both sides, I use the example of interdisciplinary abductive reasoning to show how the two fields can benefit from each other. The article proceeds as thin, comparative case studies thickened by theory. By analyzing two extended cases of inquiry cast in Douglas Walton's argumentation terms, I argue Walton's model is necessary but not sufficient for understanding and dealing with the unique challenges of interdisciplinary abduction. I propose, instead, we add the PEPR model (Pattern Recognition, Explanation Imagination, Pattern Matching, and Reporting) to help us focus on the data to be explained while we lean on Walton's model to understand the people doing the explaining. I conclude argumentation studies and interdisciplinary theory can be mutually enlightening.

Keywords: abduction, causal reasoning, field integration, imagination, inference to the best explanation, interdisciplinary argumentation, pattern recognition, pattern matching, reporting

Introduction

This article aims to convince readers of the value of intersecting the scholarship of interdisciplinarity with the field of argumentation studies. Itself an interdisciplinary field, argumentation studies has roots in philosophy, cognitive psychology, computer science, rhetoric, and sociology. The focus of the field is the nature and use of arguments in natural settings, i.e., the world beyond symbolic logic. This "world beyond" includes interdisciplinary inquiries, yet both argumentation theorists and scholars of interdisciplinarity have generally overlooked what argumentation might have to say about interdisciplinarity, and conversely, what interdisciplinarity might have to say about argumentation. I make my case for the value of bringing these fields together by showing what argumentation has to say about a particular kind of reasoning often found in interdisciplinary inquiries: inference to the best explanation, also known as abductive reasoning or abduction.[17] I then show that a prominent existing model of abduction from the argumentation field needs to be augmented in order to identify and deal with difficulties in abduction highlighted by interdisciplinary reasoning. I conclude that when we understand interdisciplinary inquiry as reasoning through arguments, we then have many new resources for describing how integration (so key to interdisciplinarity) works *and* for improving models of argumentation.

[17] Abduction is a third major kind of reasoning first so-named by C. S. Peirce (1878). Deduction makes inferences about how a particular member participates in a general set. Such inferences are certain so long as the premises are true. Induction makes general inferences about a set based on observing a number of its members. Such inferences are probabilistic, so long as the observed are actually members of the target set. Abduction, however, makes inferences about how the general and member observations are related. Such inferences are plausible – based on presumed causal mechanisms. Peirce's examples help distinguish the three: (1) "Deduction: All the beans from this bag are white. These beans are from that bag. Therefore, these beans are white." (2) "Induction: The beans are from this bag. These beans are white. Therefore, [it is probable] all the beans from this bag are white." (3) "Abduction: All beans from this bag are white. These beans are white. Therefore, [it is plausible] these beans are from this bag." Notice the conclusion of this abductive argument is an explanation for why the beans are white; hence many scholars call abduction "inference to the best explanation" (Douven, 2017).

Definitions

"Interdisciplinary." For the purposes of this article, I adopt the following definitions of "interdisciplinary" and "inquiry." Firstly, I lean heavily on the 2005 National Academies of Science report, *Facilitating Interdisciplinary Research* (National Research Council, 2005). According to this view—a view that accords with the well-known Klein & Newell (1997) definition—interdisciplinary work integrates disciplinary contributions, often to answer complex questions.

What counts as a "disciplinary" contribution is contested, of course. A discipline can be understood mainly either as a socio-institutional structure or an epistemic culture (Knorr Cetina, 2009, pp. 2-3).[18] Here I intend the latter because I am emphasizing an epistemic activity – inquiry. Therefore, the participants in inquiry that I will discuss here represent different epistemic paradigms; they may or may not have jobs in the same departments, publish in the same journals, or hold the same degrees.[19]

"Inquiry." Secondly, by "inquiry," here, I mean any systematic process of answering a well-formed question.[20] This includes but goes beyond research to include formal evaluations and other investigations. Leedy and Ormrod (2005, p. 2) state, "*Research* is a systematic process of collecting, analyzing, and interpreting information (data) in order to increase our *understanding* of the phenomenon about which we are interested or concerned" (emphasis added). However, people use interdisciplinary arguments to answer questions for other purposes than simply to increase understanding. For instance, interdisciplinary evaluations use systematic processes to answer

[18] When emphasizing the "socio-institutional" definition, we see that in some disciplines, such as economics, differences in perspectives within the socio-institutional discipline may be quite small, while in others, such as philosophy, the differences may be huge.

[19] Not sharing these socio-institutional contexts often – but not always – makes interdisciplinary reasoning more difficult, but I will leave these complications for future discussions.

[20] In this article I do not need to restrict my definition of inquiry to that proposed by John Dewey, although his definition does work here: "Inquiry is the controlled or directed transformation of an indeterminate situation into one that is so determinate in its constituent distinctions and relations as to convert the elements of the original situation into a unified 'Whole' " (Dewey, 1938, pp. 110-111).

questions about the "merit, worth, and value" of something or someone (Scriven, 1991, p. 1), questions which require not only understanding but also evaluative judgment. Another example of interdisciplinary inquiry is crime investigations, which do not try to understand general phenomena but rather specific instances of them; nevertheless, law enforcers rely upon systematic collection of evidence interpreted through many disciplines, such as physiology, physics, psychology, and sociology. In short, we engage in interdisciplinary arguments for reasons including and exceeding mere understanding. Thus, I use the term "inquiry" rather than "research" to emphasize this broader scope.

"Interdisciplinary investigators." Interdisciplinary investigators are knowledge workers engaged in formal interdisciplinary inquiry. They might be academic researchers, professional evaluators, program staff, law enforcement officers, or others, and they may work alone or in groups. Regardless of their differences, many interdisciplinarians share the common goal of generating good explanations for how and why certain problems arise and continue. By understanding root causes and linkages, these practitioners may be able to generate effective solutions. They pursue solutions by approaching their respective problems from various disciplinary perspectives, insights from which they then attempt to integrate to answer the question driving their inquiry.

The Gap in Interdisciplinary Theory

To date, interdisciplinary inquiry has rarely been framed as a "reasoning" or "argumentation" task, leaving core issues related to reasoning relatively under-theorized. This is not to say no one has done any work about how interdisciplinarians think, but they have not framed it as argumentative reasoning and have therefore not drawn on the resources from this other field. As discussed above, interdisciplinary inquiry is unique among other kinds of inquiry in aiming for answers that integrate insights from multiple disciplines. Scholars of interdisciplinarity have described this epistemic goal in various ways related to but not directly labeled reasoning or

argumentation. Examples include knowledge synthesis (Bammer, 2013; Boix Mansilla, 2010), knowledge integration (Holland, 2013; Klein, 2011; Repko, Szostak, & Buchberger, 2016), interdisciplinary cognition (Derry, Schunn, & Gernsbacher, 2013; Nikitina, 2005), interdisciplinary learning (Augsburg & Chitewere, 2013), integrative learning (Leonard, 2012), integrative thinking (Abbott, 2012), interdisciplinary thinking (Dreyfuss, 2011), and multicultural discourse (Holbrook, 2013). The explanations of each yield slightly different sets of insights and recommendations for the proper conduct of interdisciplinary inquiry. Some focus on the abstract, epistemological structure of disciplinary knowledges (e.g., knowledge synthesis) while others emphasize their concrete communication practices (e.g., multicultural discourse). These are all real, important processes at work in interdisciplinary inquiries. However, I believe we have not been quite as explicit as we need to be about *why* interdisciplinarians use the tools of integrative thinking, learning, and discourse to achieve integrated, synthesized knowledge. We need to talk about the goal of understanding.

If interdisciplinary inquiry is to generate understanding, it requires investigators to know why the final inference is reasonable. That is, these inquiries require epistemic justification. The structure of epistemic justification is captured in arguments, and arguments are constructed through reasoning. Reasoning, in turn, is accomplished through many psychological and social processes, such as the thinking, learning, and discourse processes mentioned above. Therefore, if we want to explain how interdisciplinarians come to understand their synthesized knowledge, we must not only explore how they think, learn, and hold discourse; we must also explore how these processes support reasoning and, in turn, the arguments underwriting justified belief in interdisciplinary knowledge. To study reasoning and argumentation, we need theories from reasoning and argumentation studies, yet these resources have been largely absent from the interdisciplinary literature. At the same time, interdisciplinarity has not often been studied by

argumentation theorists. Those working in each field stand to benefit from those working in the other.

Argumentation and Reasoning Studies

Overview. Of course, humans have been thinking about thinking for millennia. Argumentation and reasoning studies as an academic field, however, is relatively new. It emerged in Western universities in the 1970s. Many teaching philosophers realized the traditional Western university approach to teaching critical thinking was not very successful in preparing students to make rational decisions in daily life. This is because the traditional approach forced students to memorize deductive systems using symbols in proofs: It was formal logic. To make critical thinking more accessible and relevant to the average student, these teaching philosophers developed an alternative: informal logic. Informal logic is concerned with arguments and reasoning as they live in their natural habitats beyond the symbolic logic textbook (Johnson, 2014).

Soon, scholars from non-philosophy fields such as artificial intelligence, human and animal psychology, and rhetoric joined their ongoing studies of reasoning to this informal logic movement (Groarke, 1996). This brought informal logic and argumentation studies together in a heterogeneous academic field called argumentation and reasoning studies, a field that has begun to institutionalize the ancient quest to understand real-life reasoning. Because these scholars study reasoning in many different settings, there are many different approaches, theories, and frameworks involved. They would all agree, however, that they are trying to understand the processes of making inferences in naturalistic settings. But not many have studied how reasoning proceeds in interdisciplinary inquiries.[21]

[21] Unfortunately, the argumentation and reasoning studies field mainly cites Western (occidental) scholarship. There are many non-Western theories of reasoning that would benefit this field and ought to be included. But whether the field becomes more pluralized or not, it will provide great value to those doing interdisciplinary work.

The Gap in Argumentation Theory. Most theories and case studies in the argumentation literature have focused on disciplinary settings, such as law (Bench-Capon & Prakken, 2010), advertising (Wierda & Visser, 2012), medicine (Pilgram, 2012), and archaeology (Shelley, 1996), or they have focused on everyday, common-sense logic (Johnson, 2014). The resources that have been developed in these disciplinary settings may not apply to interdisciplinary argumentation. Interdisciplinarity offers a reasoning context that argumentation theories ought to be able to illuminate if they are comprehensive theories of argumentation. However, it is not yet clear that argumentation theories apply to interdisciplinarity because interdisciplinary inquiries have been relatively unstudied by most of those in the argumentation field.

There are two exceptions to this gap between interdisciplinarity and argumentation research. First, Michael Hoffmann (2011) has studied interdisciplinary argumentation using argument mapping software, demonstrating that the software aids in argument reconstruction and evaluation in this context. Second, Louise Cummings (2012) has argued that fallacy analysis would be useful in the interdisciplinary field of public health. However, neither study addresses particular *kinds* of interdisciplinary reasoning, such as interdisciplinary abduction. While novel and useful, these two studies are merely two pillars in the potential bridge of research spanning the gap between interdisciplinarity and argumentation studies. To aid bridge-building from both sides, I use the example of abductive reasoning to show how each field can benefit from the other.

The Example of Abduction. In this article, I complement Douglas Walton's (2004, pp. 240-242) dialogical model of abduction with a new model abbreviated PEPR, which stands for Pattern Recognition, Explanation Imagination, Pattern Matching, and Report Publication. Walton's model lends itself to use in interdisciplinary contexts because interdisciplinarity can be understood as a dialogue between and among disciplines (Holbrook, 2013). In fact, even when single investigators engage in interdisciplinary inquiry on their own they are bringing various disciplinary contributions into conversation with each other.

In Walton's model there are two main conversational roles: the respondent, who is seeking the explanation in answer to the inquiry, and the proponent, who offers candidate explanations for consideration. In interdisciplinary abduction, these two roles are played by various disciplinary representatives, and their contributions may be expressed in print, in the internal thoughts of a single investigator, or in the verbalizations of multiple collaborators. As the dialogue progresses, the sequence of exchanges may cause the respondent's and proponent's perspectives to evolve, e.g., to shift, integrate, or otherwise transform. For example, a sociologist may add agricultural causes to her explanation of landscape governance so her perspective becomes something more like rural sociology. Then the proponent becomes rural sociology. This is the nature of interdisciplinary inquiry: We begin with disciplinary inputs and, through progressive exchanges, end with interdisciplinary outputs (O'Rourke, Crowley, & Gonnerman, 2016). Walton's model emphasizes the dialogical nature of this synthesis as it unfolds in a conversation.

I want to emphasize that Walton designed his model for collaborative contexts, and I am expanding its use to inquiries conducted in the mind of a single individual as well. I believe this expansion is justified because even when alone, we engage in discourse; it is impossible to remove ourselves from distributed networks of knowing, because our own thoughts upcycle the thoughts of others through the artifacts they create (Bakhtin, 1981; Fenwick, 2010). Individual investigators dialogue with other perspectives by reasoning with themselves. We ask questions, play devil's advocate, and challenge our own conclusions. This is necessary for conducting an inquiry systematically. In the absence of a real-time participant, we provide that role by taking others' perspectives, and our own may also evolve. In interdisciplinary inquiry, these different views belong to different epistemic communities, sometimes represented by real-time participants and sometimes by artifacts such as books. Dialogue with representatives of other perspectives is required throughout the interdisciplinary process – whether the dialogue involves real-time others or not – and therefore Walton's dialogical model is appropriate for interdisciplinary contexts

regardless of the number of participants. However, to make Walton's model work well, for both individual and collaborative interdisciplinary contexts, we need to adapt it using insights from interdisciplinary theory about the nature of disciplinary data.

Walton's dialogic model proposes four phases of abductive conversation: (1) Dialogue Setting, (2) Formation of Explanation Attempts in Dialogue, (3) Evaluation of Explanations, and (4) Dialogue Closure. The first phase of Dialogue Setting establishes what others have called the "common ground" of the inquiry (Beers, Boshuizen, Kirschner, & Gijselaers, 2006; Campolo, 2005; Davidson, 2002; Repko, 2011). Contents of this common ground include (a) the type of dialogue (e.g., legal abductive? scientific abductive?), (b) the presumed data and shared understanding of the data, (c) defining the initial perspectives that will fill the roles of respondent and proponent, and (d) articulating which speech acts and commitments the contributing perspectives/participants are permitted to make (e.g., Are universal claims allowed? Stories? Only peer-reviewed literature?). According to Walton's model, the respondent then begins the second phase, Formation of Explanation Attempts in Dialogue, with (a) an initial request for explanation to which (b) the proponent gives an initial reply. This alternating sequence continues until terminated when the participants exhaust either the logical or practical possibilities, resulting in (c) a set of candidate explanations. In the third phase, Evaluation of Explanations, each candidate explanation is evaluated for (a) its own plausibility and (b) its plausibility compared to the other candidates. A single candidate is then chosen as the "best explanation," perhaps for further study. In the fourth and final phase of Dialogue Closure, the participants review their work: How complete has the inquiry been? Are we really ready to close the dialogue now? If so, how much trust can we place in our knowledge? Are we willing to be wrong if contradicting evidence comes forward?

The Gap this Paper Seeks to Fill

Here I ask, *What are the unique challenges of interdisciplinary abduction?* Answering this question will help us develop abduction and interdisciplinary theories directly. Indirectly,

answering this question will also illustrate the benefit of integrating the two fields of interdisciplinary and argumentation studies.

I train my scope on the abductive process itself, which can be viewed as an input-process-output (IPO) process. On such a view, the inputs to abduction are the phenomenon under study, the study tools available, and the inquiry participants, who each come with their own perspectives. Then begins the process of abduction proper, which Walton says begins with defining the inquiry's question (Dialogue Setting) and ends with reviewing the answer (Dialogue Closure). The answer then defines the inquiry's output, which may be more understanding, evaluative judgment, or some other product. My focus in this article is noting how features of the inputs, process, and outputs make interdisciplinary abduction uniquely challenging. This focus combines the perspectives of argumentation and reasoning studies with interdisciplinary theory; the former names the input, process, and output entities while the latter describes the unique features of these entities in interdisciplinary settings.

By analyzing two extended cases cast in Walton's terms, I argue Walton's model is necessary but not sufficient for understanding and dealing with the unique challenges of interdisciplinary abduction. I propose that we also use the PEPR model to help us focus on the objects to be explained while we lean on Walton's model to understand the subjects doing the explaining. Such a stereoscopic view will identify more of the difficulties and opportunities facing interdisciplinary investigators and therefore – like three-dimensional magnetic resonance imaging in cancer treatment – allow us to target more effective interventions to support interdisciplinary inquiry.

Disciplinary vs. Interdisciplinary Abduction

To give a sense of the differences between disciplinary and interdisciplinary abduction, I'll apply Walton's model first to a disciplinary, then to an interdisciplinary case of inquiry.

A Disciplinary Example

Phase 1. Dialogue Setting. In 2010, I began a research project in forest hydrology, a single discipline with clear ontology, methodology, and axiology. The data had already been collected, and my task was to answer this research question: What fraction of forest precipitation escaped every year through evaporation versus transpiration (i.e., when trees exhale water vapor)? When I ran the calculations, the answer came up positive. Positive numbers indicated an increase in certain isotopes that mark evaporation – as if there was no loss of evaporated water as had been hypothesized, but rather a gain. Naturally, I abandoned my original "what" question to pursue a "why" question: Why did I get a positive answer where I expected a negative one?

Phase 2. Formation of Explanations. I looked for a plausible explanation: Were my data or calculations incorrect? Were my assumptions wrong? Was my reasoning fallacious? Could there, in fact, have been an addition of evaporated water? If so, how? Why? I returned to the basic theory of isotopes and discovered a possible mechanism that had never been reported in this type of forest, so no one had ever bothered to look for it. This temperate forest seemed to be recycling water vapor.

Phase 3. Evaluation of Explanations. I checked for calculation errors: None. My assumptions were all confirmed by direct data or similar studies. I checked my inferences; they were solid. Finally, my collaborators and I ran calculations and thought experiments on the last explanation that revealed the implications of the new mechanism. Our tests reproduced the observed positive answer *and* other patterns in the larger dataset.

Phase 4. Dialogue Closure. The article was published in a disciplinary journal (Green, Laursen, Campbell, McGuire, and Kelsey, 2016). But, of course, it only reported on a case study, and we weren't able to specify exactly what parts of the forest were doing the water recycling. Case studies generalize only if theoretical assumptions actually obtain, and colleagues haven't determined that yet. Therefore, although my study closed my particular argument, the larger

dialogue about the mechanism is still open—as is the original descriptive dialogue I abandoned about evaporation and transpiration.

A Contrasting, Interdisciplinary Example

Now, I'll apply Walton's dialogic model to an interdisciplinary case of inquiry and show the model does not capture key differences between this case and its disciplinary counterpart.

Phase 1. Dialogue Setting. In 2011, I started a single-investigator, interdisciplinary project studying social-environmental systems. My original research question was given to me: What are the characteristics of the bioenergy information networks in this county? I value treating my subjects as agents rather than sources, providing actionable and resilient answers, and finding those answers by integrating insights from multiple perspectives. I rejected the original research question as against these values, but then struggled to find a new question that supported them. Every theoretical perspective I examined, of course, prompted me to ask a different question. Finally, after a year, I decided on this: What is the adaptive, collaborative management (ACM) capacity of the local resource experts, and what might explain that level of capacity?

My source theories included evaluation, forestry, social network analysis (SNA), governance, and resilience. Thus, I next collected social network data about the information patterns of the experts in the networks, observations of their interactions in meetings, interviews about their management roles, and observations of the physical landscape. These were very different kinds of data; they included relational matrices, field notes, interview notes and transcriptions, and photos, each collected and/or analyzed from a different disciplinary perspective with different tools. Each dataset contained its own patterns, and these combined to form many more patterns among all of the datasets. I was quite lost with my multiple source theories acting separately. After another six months, I managed to integrate them into a new theory that told me I should look at one particular pattern to assess ACM capacity. At this point, my interdisciplinary

project looked very similar to my disciplinary project: In both I had amassed piles of patterns but selected only one to explain.[22]

Phase 2. Formation of Explanations. The pattern I selected in my interdisciplinary project evinced a rigid division of information and work between forestry and agriculture experts. That is, they were not interacting so as to affect each other's management decisions. There were many viable ways to explain this pattern: Certain network measures predicted others; the landscape topography lent itself to this division; some experts had been involved longer than others; the governing committees played power games; and a historic policy event had initiated a series of events that interacted with these other factors.

Phase 3. Evaluation of Explanations. How was I to infer the *best* explanation among these? Again, as an interdisciplinary scholar, I prioritize explanations that integrate multiple chains of reasoning from different disciplines. I assumed the best explanation would integrate many of the candidate explanations. Therefore, I decided not to choose only one among the many viable explanations because this would have reverted to a disciplinary approach; each of the viable explanations required a different discipline to justify it, and I knew each disciplinary explanation was only partial. As an engaged scholar, I also prioritize explanations that are useful to local people, but some explanations provide no useful insights for local change. For example, in this case, we had no local officials who could understand the algorithms behind the social network analysis (SNA) measures that predicted each other, and some of the variables in the algorithms were not actionable. Thus, an explanation based purely upon SNA was not the best explanation.

I developed an argument I presented as a story that combined most of these explanations in such a way that they could all be true and understandable. The story showed how each of these key

[22] Both of my examples in this article are confirmatory studies; that is, which patterns were worth observing were determined based on theory prior to data collection. Exploratory studies may also seek inferences to the best explanation, but such studies would work differently than confirmatory studies. Exploratory studies would have an extra step at the beginning for determining which patterns were important to observe.

explanations – sometimes singly, sometimes together – caused various plot twists and in the end yielded the observed division between forestry and agriculture, which suggested an explanation for their merely moderate capacity for governing their multifunctional landscape. This is not, of course, the only story one could weave from my findings, so it may not in fact be "the absolute best" explanation. Nevertheless, it was satisfactory; it was the best given the constraints of the project.

Phase 4. Dialogue Closure. A report on the work was published, and my community stakeholders found new ways to think about their self-governance (Laursen, 2013a; Laursen, 2013b). As with my disciplinary example, the local dialogue was closed with this study, but the larger dialogue continues about the extent to which the story I identified may be playing out similarly in other times and places.

Summary of Examples

Walton's four-phase model worked well in capturing the major turning points in both the above examples of abduction. There were definite phases of Dialogue Setting, Formation of Explanations, Evaluation of Explanations, and Dialogue Closure. However, the two cases differed in their details within each of these phases, and Walton's model is not specific enough to distinguish these details. As these examples show, then, Walton's model doesn't quite give us the conceptual resources we need to understand and enhance interdisciplinary abduction.

Table 1: Challenges to abductive reasoning in disciplinary and interdisciplinary cases

	Disciplinary Cases	**Interdisciplinary Cases**
1. Dialogue Setting	**Short & easy**	**Long & arduous**
Type of dialogue	*Likely agreement*	*Possible disagreement*
Proponent(s)	Colleagues using one perspective	Colleagues using multiple perspectives
Respondent(s)	Investigator(s) using same perspective as proponent(s)	Investigator(s) using different perspective from proponent(s)
Common Starting Points	*Consensus on starting points achieved quickly & easily*	*Consensus on starting points achieved through extended struggle*
Question	Easily agree on question of interest	Perhaps strongly dispute question of interest

Table 1 (cont'd)

	Disciplinary Cases	**Interdisciplinary Cases**
1. Dialogue Setting	**Short & easy**	**Long & arduous**
Presumption	Easily agree on presumed data & salient patterns	Perhaps strongly disagree on presumed data & salient patterns
Common Understanding	*Large amount of common understanding*	*Small amount of common understanding*
Proponent's Understanding	Mostly the same as the respondent's; small gap	Mostly different from the respondent's; large gap
Respondent's Understanding	Mostly the same as the proponent's; small gap	Mostly different from the proponent's; large gap
Empathy	Much more	Much less
Shared Language	Much more	Much less
2. Formation of Explanations	**Well-structured search**	**Ill-structured search**
Initial Question	Immediately salient to proponent	Perhaps not immediately salient
Initial Answer	Immediately salient to respondent	Perhaps not immediately salient
Repeated Q&A Sequence	Likely to be linear with relatively small scope; well-structured	Likely to be complex with relatively large scope; ill-structured
Sequence Termination	Likely agreement supported by traditional epistemic values	Likely disagreement supported by competing epistemic values
3. Evaluation of Explanations	**Clear & closed-ended**	**Fuzzy & open-ended**
Baseline Plausibility	More easily determined due to fewer variables	Less easily determined due to more variables
Overall "Best" Explanation	Likely agreement supported by traditional epistemic norms; more tendency to aim for a global "best"	Likely disagreement supported by competing epistemic norms; more tendency to "satisfice"
4. Dialogue Closure	**Quicker, easier, & broader in scope**	**Slower, harder, & narrower in scope**
Judgment of Completeness	Much easier to determine completeness	Nearly impossible to determine completeness
Reconsideration of Closure	Less likely	Always likely
Knowledge Base Assessment	Likely consensus and higher certainty	Likely disagreement and lower certainty
Openness to Defeat	High, but constrainable so scope of findings is potentially broader	Very high, and hard to constrain so scope of findings is seen as limited

Challenges for Interdisciplinary Abduction that Complicate Walton's Model

Table 1, while long, is actually a shorthand and probably incomplete list of likely differences between disciplinary and interdisciplinary processes of inquiry in the four phases of abductive argumentation. It reflects hypotheses based on a combination of my personal experience and

theories of interdisciplinarity from the literature. They should be tested against empirical data, yet they serve well enough as the basis for further discussion here. The first column in Table 1 lists the important features of each phase as Walton identified them in his 2004 book. The second and third columns mention ways interdisciplinary abduction is likely more confusing, disputed, and ill-structured than its disciplinary counterpart. The contents of the table reveal a pattern of differences that Walton's model can't address. Below, I unfold these differences and show that they arise from what is arguably the defining feature of interdisciplinary projects: the diversity of the data they engage. To clarify these differences, I then introduce a complementary version of Walton's model that is phrased in terms of the objects to be explained – data patterns – rather than the subjects doing the explaining – the proponents and respondents, in Walton's terminology.

Phase 1: Dialogue Setting is Long and Arduous

Data patterns are the result of a long, arduous first phase I will eventually call Pattern Recognition. This phase begins simply with a phenomenon under study, some study tools, and some curious participants. With these inputs, participants agree upon a question to drive their inquiry, they collect data to answer that question, and they summarize the data into patterns that beg for an explanation. In interdisciplinary abduction, the (1) nature of the phenomenon under study and the diversity of (2) tools and (3) participant perspectives make this first phase perhaps the most difficult.

First, the nature of the phenomenon under study influences the tools and perspectives used to study it. The materiality of the phenomenon limits the tools we can use to collect data from it; after all, one cannot collect electron bubble tracks from a social network. Moreover, interdisciplinary inquiries often focus on complex phenomena. Here I use the term "complex" to refer to "components actively connected through predominantly nonlinear relationships" (Newell, 2001, p. 9). Complex phenomena are tricky to understand. When interdisciplinarians want to study them, their complexity adds many options for data to track and explain.

Second, disciplinary tools have a wide variety of formats made from many kinds of materials. These differences matter because they create data in many formats and materials. The material differences layer atop inquiry challenges due to the phenomenon itself. For example, due to the nature of both the phenomena and the tools used, GIS data have columns containing spatial coordinates, timeseries data have columns containing timestamps, and interview data have columns of verbatim text. It is not obvious how to integrate those datasets, especially when each has a different set of standards for how missing data, mistakes, and aggregation are handled.

Third, the deep differences in disciplinary perspectives create a large gap in shared understanding from the beginning of the phase Walton calls Dialogue Setting. Participants not only may not fully understand each other's languages; they may even disagree on what the original research question is; that is, they may disagree about the type of abductive dialogue they are having. For example, a network analyst might have framed the question central to my second study described above this way: What network variables predict collaboration outcomes? But a forester might have asked, Which ecosystem features are governed by which management policies? The network analyst wants to have a quantitative abductive dialogue appealing to network entities through statistical standards of evidence. The forester, however, thinks they should have a policy-based abductive dialogue that will appeal to policy entities through pragmatic standards of evidence. Based on their diverse training, researchers in interdisciplinary inquiries are likely to ask different research questions and therefore want to collect and analyze different data using different methodologies (Eigenbrode et al., 2007; Leedy & Ormrod, 2005; Norgaard, 1989; Palmer, Kramer, Boyd, & Hawthorne, 2016). Coming to consensus on which questions and data will be pursued can require extended dialogical struggle depending on how deep the differences in epistemologies, ontologies, and axiologies are (Laudan, 1986; Patterson & Williams, 2008). Choosing my interdisciplinary research question took an entire year. Indeed, similar lengthy time investments are common at the start of interdisciplinary projects (National Research Council 2005; 2015).

But even after a research question is chosen, a study is designed, and the dataset is collected, the abductive dialogue has not yet been fully determined. At this point, the investigators have a set of data points, and likely these data points are of different types (e.g., spatial, temporal, qualitative). Nevertheless, there is nothing to explain (in the next phase of the project) until those points have been summarized as forming one or several curious patterns. Investigators do not try to explain separate data points. Rather, they wonder why this data point looks different from the others or why these data points indicate a trend: In other words, they are looking for patterns. Here again, differences in research perspectives associated with different disciplines may inhibit shared understanding and consensus about which patterns are (a) real, (b) salient, and (c) worth investigating.

Granted, the research question will narrow the patterns of interest but often not enough for researchers to decide which patterns to explain. Other selection criteria must be worked out. Which pattern is eventually chosen for further study may depend upon negotiation of further cognitive, pragmatic, and social values each investigator brings to the project (Douglas, 2009; Eigenbrode et al., 2007; Elliott, 2017; Hall & O'Rourke, 2014). One values-based choice is choosing what standards of evidence to use when drawing conclusions about the reality of a pattern based on limited data; one may require more evidence if the risk of being wrong is very high, such as declaring a chemical to be safe when it's not (Douglas, 2009; Elliott, 2017). Another values-based choice is choosing which real patterns are worth further study; do you choose to develop the one more likely to get published, be understood by citizens, or match funder interests? In disciplinary inquiry, these epistemic and non-epistemic values are relatively well-defined, albeit implicitly (Eigenbrode et al., 2007). But in interdisciplinary cases, the relevant values may not only be implicit but may also differ across disciplinary lines. This often requires negotiation of values not only among types of values (e.g., pragmatic, social, epistemic) but also among types of investigators (e.g., sociologists,

physicists, philosophers), who each may hold different positions about these different types of values.

For example, both sociologists and physicists hold epistemic values about "interesting patterns" that they must balance with pragmatic concerns, such as timelines for publication. But in addition, a sociologist may believe an "interesting pattern" is epistemically complicated while a physicist may believe it is epistemically simple. An inappropriate, biased way of handling these different values would be to ostracize the sociologist and never consider complicated patterns to be real or worthy of study. An appropriate way to negotiate these values might include an attempt to come to consensus or compromise and to report the negotiated standards of pattern choice in a section of the write up entitled "Conceptual Framework." Declaring significance – what is worthy of note – within a discipline can be difficult, and it can be even more difficult in interdisciplinary contexts because there are many standards of evidence that might apply and they can be difficult to compare and compromise upon (Eigenbrode et al., 2007).

The above-mentioned differences (in phenomena, tools, and perspectives) are together manifest in the data presumed to ground the inquiry (Benda et al., 2002; Kuhn, 1970; O'Rourke, Crowley, Eigenbrode, & Wulfhorst, 2014; O'Rourke, Crowley, Laursen, Robinson, & Vasko, 2018). The data therefore become both instantiations of and proxies for all that is unique about interdisciplinary inquiry. Data differences go much deeper than the split between quantitative and qualitative approaches, both of which can express the same perspective (e.g., a structural view of social capital can be expressed in both a quantitative matrix and in a narrative). Interdisciplinary data collection can be like going to the supermarket, and data analysis can be like trying to compare apples and oranges. At the supermarket, the cashier uses the same scale to weigh all produce. Some tool like that is needed to interface different kinds of data in interdisciplinary inquiry. But unlike a scale, a mere mechanical transliteration (e.g., qualitative to quantitative) will not be enough; meanings must be negotiated and translated much as one interprets The Iliad in an attempt to

reconstruct the history of Troy. The interpretation process begins by identifying the shared features of the data types to be combined, but what they share may not be obvious without a perspective change. A perspective change reframes the data in a way that helps align meanings that once seemed incommensurable.

Phase 1 Difficulties Exemplified. Because interdisciplinary inquiry contains so much data complexity and diversity from the start, settling on the relevant data patterns may require layers of integration before explanations can even be considered in phase 2. In my interdisciplinary case I had four data types and innumerable data points and patterns. These arose from my initial question about adaptive capacity, which took a year to define based on the complex phenomenon I was studying and the diversity of tools and perspectives available. But adaptive capacity can be observed in many ways. To narrow down the patterns to consider, I took a step upstream and integrated my five source theories (representing five disciplines) into a single theory that indicated a single pattern to look for. However, that pattern would only be visible once it emerged from the integration of several kinds of data. So, I began integrating my datasets point by point. For example, I paired an interviewee's quote with an observation I jotted in my field notes at a committee meeting between the local politicians and the experts: "Theme: stick to the agenda. Do not offend." I reasoned that the employees' fear of retaliation from offending their supervisors squelched any non-authorized collaboration among the experts. But I also paired this data point from my notes with a photo I had taken of the landscape that showed hard edges between forests and croplands. Together with other points, these formed a pattern of divisive policies. There were many other such examples of data combination and resulting patterns. I couldn't explore them all; I had to choose one or a few patterns to attempt to explain.

In my work, I knew which pattern I was looking for, but this is not always the case. As different data sets are woven together, perhaps point by point, the number of possible patterns increases dramatically. Moreover, just as with comparing apples and oranges, the patterns one

notes depend on what one is looking for. Size? Weight? Appearance? Interdisciplinarity provides many different perspectives on a problem. Thus, for every possible combination of data, there is also a permutational set of ways to examine it for patterns. The total search space is vast, and each investigator can only see part of it, creating a huge logistical problem that can manifest in communication, epistemic, and cognitive errors as well as in insights.

To proceed from what is found in this vast search space, investigators must choose one or a few patterns to try to explain in phase 2. Selection is necessary because (a) some patterns are spurious, and (b) project resources are limited. Interdisciplinary investigators might choose one pattern that has already integrated several disciplinary perspectives, or they might choose several disciplinary patterns to try to integrate through the explanation process in phase 2. In my interdisciplinary case, I chose a single interdisciplinary pattern, and I judged it was worth explaining based on several of my epistemic and non-epistemic values: theoretical coherence, utility of the findings to stakeholders, and ease of analysis; or, as my colleague put it, "whatever was most interesting and obvious." I chose the pattern showing lack of collaboration between forestry and agricultural experts. Not everyone would have chosen the same way; again, there are many ways to observe adaptive capacity. Looking back, I can see I didn't fully understand how my values were driving my theorizing, and I had a hard time choosing and defending my integrated theory because of this lack of clarity. Training to increase clarity about such selection is important; it can help interdisciplinarians understand what's at stake in each phase of abduction, even and maybe especially in this first phase.

Phase 1 Renamed: Pattern Recognition. In addition to "Dialogue Setting," this phase can also be understood as the Pattern Recognition phase. This name emphasizes that although the distal target is the phenomenon – we want to understand something in the world – the proximal objects to be explained are data patterns – what we've observed about the world – and therefore, the dialogue is subject to all of the challenges related to pattern recognition. These challenges

include interfacing different data types, identifying implicit biases, and misunderstanding what colleagues propose. Such re-framing and re-naming of this phase makes way for insights from cognitive psychology, rhetoric, computer science, and other fields that study human pattern recognition. With Walton's model alone, it is not clear that these apply.

Phase 2: Formation of Explanations is Ill-structured

Once a pattern has been recognized and selected for explanation, it is time to form candidate explanations. This phase of a project is also more difficult for interdisciplinarians compared to their disciplinary counterparts. Interdisciplinary investigators are likely to disagree on what counts as an explanation as well as what makes an explanation plausible (a) in itself and (b) compared to others. In fact, investigators may not even be able to know what determines plausibility in many of the complex problems tackled by interdisciplinary inquiry (Bammer, 2013, pp. 63-76). The ensuing brainstorm may therefore cover many domains and types of explanations. There are few logical restrictions on which disciplinary explanations might be true simultaneously and how they might be integrated into a coherent explanation. Any narrowing of scope that was achieved in phase 1 may again explode in phase 2 with the number of possible explanations, and this is due not only to the power of the human imagination but also to the math of permutational combination. There is no single "right" way to integrate disciplinary explanations; the imaginative process is often ill-structured in interdisciplinary inquiries.[23]

Phase 2 Difficulties Exemplified. My governance project exemplified this ill-structured proliferation of explanations. Even with some simplifying assumptions, the proliferation can be overwhelming. Suppose there were at least five different processes driving adaptive capacity, as revealed by the five different disciplines I used (viz., evaluation, forestry, social network analysis,

[23] See work by Rand Spiro and others on problems in ill-structured domains, such as socio-environmental issues (Feltovich, Coulson, Spiro, & Dawson-Saunders, 1992; Jacobson & Spiro, 1995; Kulinich, 2016; Miyashita, 2002; Spiro, Coulson, & Anderson, 1988).

governance, and resilience). Suppose also that these processes didn't overlap: no simultaneous processes. Suppose lastly that integration could mean a mere juxtaposition of processes (which is a *very* simplifying assumption). Order matters when assembling the pieces of a causal explanation because causality is unidirectional, so we are looking at permutations not combinations. These assumptions indicate there were (at least) ${}_5P_5$ choices for viable explanations of the forestry-agriculture divide. That's $5!/(5 - 5)! = 5! = 5x4x3x2x1 = 120$ different integrative explanations I should have evaluated to find the best explanation for my chosen data pattern.

It is more aligned with interdisciplinary theory, however, to say that integration requires more than mere juxtaposition but also something like multiple causation or simultaneity. If we continue this thought experiment, supposing processes can overlap in any number of layers (viz., 2, 3, or more simultaneous processes), the math approaches infinity because the permutation goes recursive; each possible permutation of layers adds to the number of possible layers, which adds to the possible permutations of these layers, ad infinitum. The first round of 120 was overwhelming enough, but infinity is impossible to explore. Yet, in principle, the quest for the best interdisciplinary explanation of a complex phenomenon should consider the entire search space to find the globally optimal explanation. What should interdisciplinarians do? While an exhaustive search isn't feasible, an investigator ought to conduct the search systematically to counteract cognitive and/or unjust biases, a process that will help ensure the best possible explanation is among those considered, even if this "best possible" is not the global but only a local optimum. At the same time that one must be systematic, one must also be creative. It takes wisdom and insight to focus one's limited resources on a promising section of the infinite, ill-structured explanation space.

But even with a wisely narrowed explanation space, it is still impossible to test the plausibility of every explanation imagined within that space. Rather, of the many explanations imagined, the few explanations that make it to phase 3 for plausibility testing are chosen, as with

Pattern Recognition, based on a variety of values that participants must negotiate. For instance, an investigator may favor the simplest process, or the one with the most external evidence, or the one that provides leverage points for action. Again, these values are often more similar among those who share disciplines than among those who don't, which makes interdisciplinary abduction harder than its disciplinary counterpart.

Phase 2 Renamed: Explanation Imagination. To emphasize the creativity involved in phase 2, the phase Walton calls Formation of Explanations, I prefer to call it Explanation Imagination. This label focuses our attention on the factors that influence our imaginations as well as what we think counts as an explanation. The main factor that is different between disciplinary and interdisciplinary Explanation Imagination is the diversity of data driving the imagination process in the latter case, which also changes the number and kind of relationships that can be imagined among these data (Bennett, 2011). Diversity of data also influences which explanations can feasibly be carried forward into plausibility testing in phase 3.

Phase 3: Evaluation of Explanations is Fuzzy and Open-ended

Because the explanations imagined in phase 2 of an interdisciplinary inquiry are likely very different from one another and possibly novel, it is not clear how to evaluate the plausibility of each or how to compare that plausibility to that of the other candidates. The evaluation procedure is fuzzy, and I mean this in both its colloquial and technical senses. Colloquially, it is simply unclear how to judge the adequacy of interdisciplinary explanations. Technically, such evaluation requires fuzzy logic – allowing infinite degrees of truth and group membership – to accommodate the inherent uncertainty and ambiguity of meaning invoked in interdisciplinary explanations. Steven Gray, Fikret Berkes, and others have used fuzzy logic to integrate interdisciplinary knowledge in several kinds of socio-environmental problems (F. Berkes & Berkes, 2009; S. A. Gray, Gray, Cox, & Henly-Shepard, 2012; Papageorgiou, 2014). Given both kinds of fuzziness, the evaluation of explanations is rather open ended. Moreover, interdisciplinary explanations often focus on complex

socio-environmental problems that have many interdependent variables, making it even harder to evaluate the plausibility of an explanation. That is, when there are so many things going on, it is hard to tell what causes what. This uncertainty contributes to the fuzzy and open-ended nature of the explanation selection process in interdisciplinary settings.

Therefore, as with Pattern Recognition, in phase 3 investigators who hope to be effective must navigate a range of cognitive, pragmatic, and social values when choosing which explanation is the best explanation for the pattern that has been recognized as most worth attention. These standards must be explicated and negotiated. Investigators must determine how good the explanation needs to be to warrant reporting, which requires consideration of funder expectations, journal conventions, stakeholder needs, paradigm diversity, and many other value-laden features of the inquiry context. However, by this point investigators may well be exhausted from all the sifting and winnowing they've already done, and they may be unlikely (as I was) to take the time to explicate these value choices.

Phase 3 Difficulties Exemplified. In my interdisciplinary case, with at least 120 different integrative explanations to consider, I couldn't give each equal consideration. Some were ruled out by logic, but most were not. Unfortunately, I had no systematic process for choosing among the remainder. My choosing was influenced by values from the five disciplines I was combining, along with values from funders, stakeholders, and me— a milieu of values so layered I couldn't explicate what was actually determining my choices. I did not have the time, expertise, or support to write more than one explanatory narrative. I'm sure that without a sorting tool, I succumbed to some biases in determining which of the 120+ explanations were viable. My result may have been satisfactory but sub-optimal.

Phase 3 Renamed: Pattern Matching. A helpful way to think about this phase of the abduction process is that it is aiming for a Pattern Match between the imagined explanations and the original data pattern (Marquart, 1990; Trochim, 1985; 1989). That is, the explanations

imagined in phase 2 are trying to re-create or match the pattern(s) recognized in phase 1. Sometimes this means running a real experiment and sometimes just a thought experiment. When investigators get the results of the experiment, they assess the degree to which those results match the original pattern we are trying to explain. Good explanations create strong pattern matches. A strong match has a high degree of similarity between what the explanation predicts and what we earlier observed. The stronger the correlation, the more confident we are that an explanation is real. We are even more convinced that the match did not happen by chance if the pattern we observed and matched is complicated. Interdisciplinary patterns are often complicated, so interdisciplinary explanations that predict or reproduce these patterns can warrant strong confidence, even if this pattern match is only accomplished through a thought experiment.

In my interdisciplinary case, the explanation I generated as a narrative predicted the same ending as the ending I actually had observed: a split between forestry and agricultural experts. It was a complicated narrative, so even though I couldn't re-create the situation in real life, my thought experiment gave me strong enough confidence in my explanation to move ahead with publishing the results of my work.

Phase 4: Dialogue Closure is Slow, Hard, and Narrow in Scope

Discussion of the first three phases of the abduction process has shown why uncertainty and disagreement are often more characteristic of interdisciplinary than disciplinary projects (Bammer, 2013). This uncertainty and disagreement mean phase 4, the one Walton calls Dialogue Closure, will likely be slow and difficult in an interdisciplinary project. In order to achieve closure, the investigators will need to restrict the scope of their dialogue to an explanation they have more certainty and agreement about, despite having explored a large cognitive terrain.

Phase 4 Difficulties Exemplified. In the case of my own interdisciplinary example, I felt confident stating my conclusions about what caused the split between forestry and agriculture, but I could not also explain another interesting pattern I had found: the high reliance on non-personal

information sources such as websites for some expertise areas (e.g., soils) but not others (e.g., dairies). None of my contributing disciplines had quite enough to say to predict that pattern of information sources. This uncertainty forced me to limit the scope of my conclusions, avoiding any conclusions about what caused the pattern of information sources, even though I desperately wanted to theorize about the cause. I also limited comments on the role of governance policies; while governance as a field would propose that all patterns can be explained in terms of policies, forestry as the science of silviculture would deny that, pushing back and reminding governance that the materiality of trees – how and where they grow – is also essential. In my view, the goal of interdisciplinary Dialogue Closure is to be convinced one has found an explanation that allows all of the disciplinary contributions to be true in some sense or scope.[24] Finding that sense or scope can take a long time and a lot of effort, and sometimes it may not happen.

Phase 4 Renamed: Report Publication. In systematic inquiries such as those discussed in this article, there is almost always some report made of the findings once the dialogue is closed. The report summarizes the individual or group's position on the final questions Walton suggests be asked: How complete has the inquiry been? Are we really ready to close the dialogue now? If so, how much trust can we place in our knowledge? Are we willing to admit we're wrong if contradicting evidence comes forward? The report represents an official statement of the best explanation that is then often used as "evidence" in "evidence-based practice," which is an

[24] The "they could all be true" test for integration differs from that endorsed by Newell: "Each discipline should contribute to that understanding, but no one disciplinary perspective should dominate it. The goal is to achieve a balance among disciplinary influences on the more comprehensive understanding" (Newell, 2007, p. 261). It is not clear that integration places limits on the relative proportions of the inputs. To use the familiar smoothie metaphor for integration (Nissani, 1995), I can have a fully blended strawberry-banana smoothie that nonetheless has many more bananas than strawberries. The "they could all be true" test allows such "unbalanced" instances to still count as integration—even good, desirable integration. There are at least two reasons to allow for such integration. Firstly, it is possible a phenomenon is driven mainly but not solely by one kind of driver and therefore its explanation would be dominated by one discipline. Secondly, explanations that emphasize a single driver or discipline may serve other communication goals for the research, such as getting uptake from policy makers or inspiring grassroots action.

immensely important yet controversial strategy for addressing wicked problems (Greenhalgh & Russell, 2009). By renaming this final phase of the abduction process, calling it Report Publication instead of Walton's label, Dialogue Closure, we emphasize again the data (and phenomena) to be explained rather than the mental attitudes of the investigators. By acknowledging that interdisciplinary abduction ends with Report Publication, we clarify how interdisciplinary reasoning connects with societal and policy change through lenses such as "evidence-based practice."

Summary of Unique Interdisciplinary Abduction Challenges

The above analysis shows there are unique challenges to interdisciplinary abduction we need to articulate: disagreement on the type of abduction and particular question under consideration, disagreement on what count as legitimate points and patterns in the dataset, an ill-structured and enormous range of possible explanations, and difficulty in reporting the strength and scope of a pattern match from each of the viable explanations. All of these challenges stem most directly from the unique diversity of data in interdisciplinary inquiries. Since data diversity, in turn, stems from the inputs to abduction – the complexity of phenomena and diversity of tools and participant perspectives – no phase of the inquiry is untouched by these difficulties.

A New Perspective: The PEPR Model Complements Walton's Model

While Walton's dialogic model notes the importance of data, it emphasizes the participants and leaves us with poor vocabulary for articulating these unique data-driven challenges. Without a way to describe these challenges in detail, we lack a way to describe how to meet these challenges. To address this need, I have attempted to show that there is another way to think about abduction that focuses on the proximal objects to be explained—the data—rather than the subjects doing the explaining – the participants. I propose additional names for each of the four phases that correspond to this shift in emphasis. Dialogue Setting is also Pattern Recognition; Formation of Explanations is also Explanation Imagination; Evaluation of Explanations is also Pattern Matching;

and Dialogue Closure is also Report Publication. This data-driven model of abductive dialogue can thus be abbreviated the PEPR model (Figure 1).

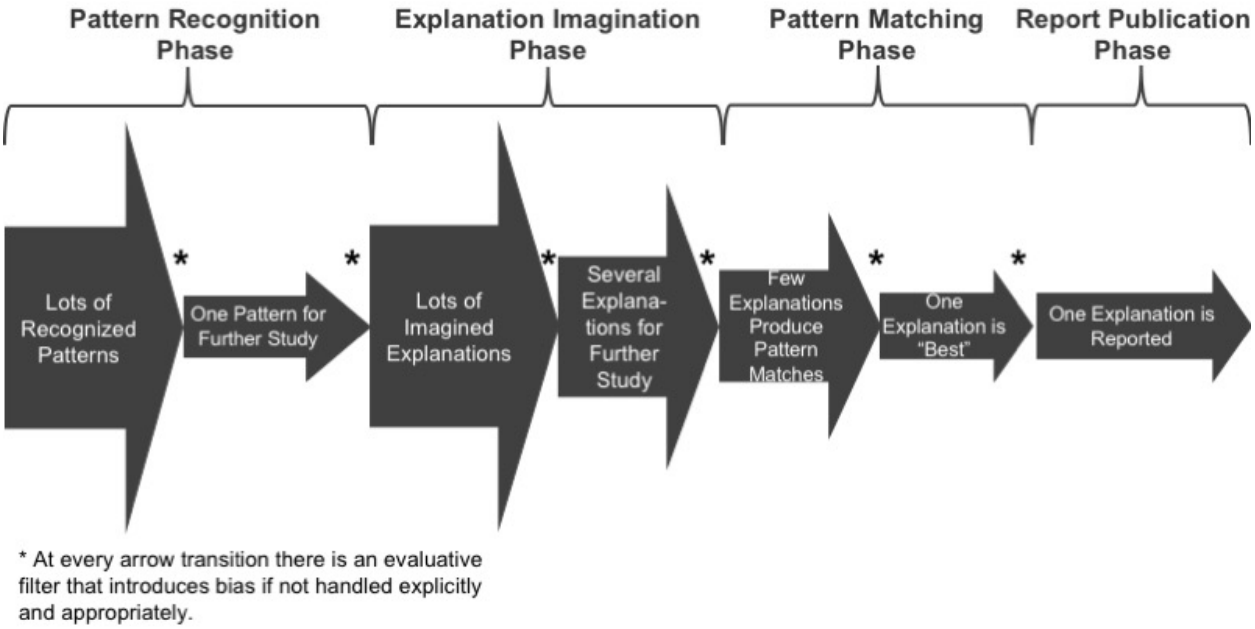

Figure 1: The "PEPR" Model of abduction, derived from the practice of disciplinary and interdisciplinary inquiry.

In our quest to understand interdisciplinary abduction, focusing on the data is helpful for several reasons. First, the tangible data embody the intangible differences in research worldviews, making it easier to talk about abduction with investigators who often prefer to remain data-driven rather than reflexively aware.[25] Second, the data bring additional, material constraints to the interdisciplinary synthesis process that are not captured when focusing on the subjects alone. That is, the material forms of the data circumscribe the number of possible explanations and how long it might take to integrate them (O'Malley 2013). Example constraints include merging spreadsheets with different columns and rows and interfacing qualitative and quantitative data. Third, by phrasing abduction in terms of data, we can bring to bear findings from cognitive science about the

[25] Indeed, in a Polanyian (Polanyi, 1962) or Meekian (Meek, 2011) theory of knowing, it is not possible to know something by constantly focusing on the means by which one knows it; one must eventually make the means of knowing subsidiary to the focal objects of knowing.

various cognitive processes involved – recognition, imagination, and matching – since these findings are also framed in terms of data. Fourth, the materiality of data invites material tools that could help address the unique challenges of interdisciplinary inquiry. These tools should address differences in data formats as well as meanings to maintain the stereoscopic focus on objects and subjects of interdisciplinary process. Such tools might include the Toolbox Dialogue Initiative (O'Rourke & Crowley, 2013), group concept mapping (Kane & Trochim, 2007), VisPorter (Chung, North, Self, Chu, & Quek, 2014), and even simple tools like rubrics (Better Evaluation, 2013). Given argumentation's under-emphasis on data-driven difficulties, these insights from interdisciplinarity can contribute to future work in this other field.

In the other direction, from argumentation to interdisciplinarity, interdisciplinary abduction via the Walton-PEPR stereoscope reveals interesting things about integration. First, when integration is used to produce an explanation, it seems to proceed through four phases of disciplinary dialogue. In each phase, the participants are exchanging claims, reasons, and evaluations of those claims and reasons. That is, integration is constructed through a social, fallible, embodied process of reasoning or argumentation (Laursen, 2018). Second, integrative explanations develop through a series of reasoning filters determined by the epistemic, cognitive, and pragmatic values of the participants. These filters show there are appropriate roles for values in interdisciplinary abduction. Third, since integrative, interdisciplinary explanations develop through the social exchange of reasons, interdisciplinary abduction—and likely all interdisciplinary inquiry—should be studied through discourse analysis (Choi & Richards, 2017). Discourse analysis can reveal conversational moves, discourse frames, rhetorical strategies, and other argumentative features inherent in human communication (Jaworski & Coupland, 2014).

In summary, Walton's model is extremely important for identifying the interpersonal necessities of interdisciplinary abduction, such as shared understanding, exchange of explanations, and conversational moves across disciplinary perspectives. But the model lacks clarity about the

necessary features of an integrated, shared, agreed-upon dataset – specifically, what it takes to recognize and match data patterns. Therefore, it will not do to adopt only Walton's model or only the PEPR model. We need both to understand the unique challenges of interdisciplinary abduction.

Here is an example of how we might fruitfully use the two models together. Say we want to understand how the Intergovernmental Panel on Climate Change (IPCC) concluded that humans are the primary cause of today's climate change (Intergovernmental Panel on Climate Change, 1990). Walton's model first asks us to identify who is asking what question based on what dataset. To do that, we need the PEPR model to remind us to look for a dataset made of patterns, not points, and to ask how different types of data were combined in that dataset. Walton's model next asks us to describe the candidate explanations; the PEPR model forces us to look closely at the imagination process that generated them. When Walton's model next prompts us to wonder how the IPCC chose the "humans are to blame" explanation among all the others, the PEPR model specifically asks how the IPCC came up with that pattern match. Finally, when we wonder how the IPCC decided they were ready to publish, Walton's model asks us to audit their concern for defeasibility and comprehensiveness, and the PEPR model focuses our attention on the framing and scope of their conclusions. The two models form a sort of stereoscope that allows us to see more dimensions to abduction. Walton points us to the who, why, and when features of an interdisciplinary abductive argument based on who is doing the explaining, but the PEPR model points us to the what, where, and how features based on the data to be explained.

This sort of stereoscope is exactly the kind of double integrative perspective desired by Angus McMurtry in his 2010 article, "Knowers and Phenomena: Two Different Approaches to Interdisciplinarity and Interprofessionalism." McMurtry describes such integrative perspectives as sociomaterial perspectives of knowing (Fenwick, 2010). Existing sociomaterial theories include communities of practice (Wenger, 1998), cultural-historical activity theory (Cole & Engeström, 1993), complexity theories (Mitchell, 2009), and actor-network theory (Crawford, 2004). The

PEPR-Walton stereoscope could indicate another sociomaterial theory of knowing based upon argumentative inferences. Such a theory would focus on the material and social reasons used to epistemically justify interdisciplinary conclusions.

Conclusion

In this article, I have taken us on a journey from the perspectives of both disciplinary and interdisciplinary inquiries that are trying to generate rigorous answers to causal questions. We saw that a key reasoning task in both kinds of inquiry is abductive inference to the best explanation, a process I first presented in terms of Douglas Walton's (2004) dialogic model of abduction. While both disciplinary and interdisciplinary inquiries can be understood through this model, sharing, as they do, some inquiry challenges, they also manifest different challenges based on the number and diversity of perspectives being integrated in the inquiry. The complex phenomena and diverse tools and perspectives in an interdisciplinary dialogue generate particularly diverse data formats and meanings. As explained above, such data diversity creates unique challenges for interdisciplinary abduction, including disagreement on the type of abduction and particular question under consideration, disagreement on what count as legitimate points and then patterns in the dataset, an ill-structured and enormous range of possible explanations, and difficulty in reporting the strength and scope of a pattern match from each of the viable explanations. These unique difficulties require considerations and vocabulary that complement Walton's, adopted in a model I named the PEPR model of abduction, abbreviating four phases of Pattern Recognition, Explanation Imagination, Pattern Matching, and Report Publication.

Given the unique challenges facing interdisciplinary investigators, future research can proceed on various fronts. First, is there a clear threshold for maximum disagreement before disciplinary perspectives and data become incommensurable? Second, how and how much must perspectives and data be integrated in order to count as an interdisciplinary inference to the best explanation? Third, how do different socio-institutional settings change the difficulties of

interdisciplinary abduction, if at all? Fourth, which tools aid interdisciplinary abduction in which settings? Fifth, what is the role of abduction versus other kinds of arguments in interdisciplinary inquiries? And are these other kinds of arguments also different from their disciplinary versions? Lastly, how does the Walton-PEPR combination compare to existing models of interdisciplinary integration, even if the latter do not address abduction specifically?

This deep dive into interdisciplinary abductive reasoning illustrates the potential fruitfulness of intersecting the scholarship of interdisciplinarity and that of the field of argumentation studies. On the one hand, interdisciplinarity reminds argumentation scholars to remain attentive to constraints imposed by interdisciplinary data, which are particularly diverse in formats and meanings due to the range of phenomena, tools, and participants generating them. On the other hand, argumentation reminds interdisciplinarity theorists that integration is a social reasoning process governed by participant values. I don't think either field has completely lost sight of data or socially-driven inferences, respectively, but they have emphasized one or the other so much that their accounts of interdisciplinary abduction would be quite lopsided on their own. Together, they provide language that maintains the necessary balance (or tension) between objective and subjective constraints (McMurtry, 2010), another example of a sociomaterial approach to integration (McMurtry, 2013).

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CHAPTER 3: WHAT IS COLLABORATIVE, INTERDISCIPLINARY REASONING? THE HEART OF INTERDISCIPLINARY TEAM RESEARCH

Laursen, B. K. (2018). What is collaborative, interdisciplinary reasoning? The heart of interdisciplinary team research. *Informing Science*, *21*, 75–106. http://doi.org/10.28945/4010

Abstract

Aim/Purpose	Collaborative, interdisciplinary research is growing rapidly, but we still have limited and fragmented understanding of what is arguably the heart of such research—collaborative, interdisciplinary reasoning (CIR).
Background	This article integrates neo-Pragmatist theories of reasoning with insights from literature on interdisciplinary research to develop a working definition of collaborative, interdisciplinary reasoning. The article then applies this definition to an empirical example to demonstrate its plausibility.
Methodology	The empirical example is an excerpt from a Toolbox workshop transcript. The article reconstructs a cogent, inductive, interdisciplinary argument from the excerpt to show how CIR can proceed in an actual team.
Contribution	The study contributes operational definitions of 'reasoning together' and 'collaborative, interdisciplinary reasoning' to existing literature. It also demonstrates empirical methods for operationalizing these definitions, with the argument reconstruction providing a brief case study in how teams reason together.
Findings	Collaborative, interdisciplinary reasoning is the attempted integration of disciplinary contributions to exchange, evaluate, and assert claims that enable shared understanding and eventually action in a local context. Pragma-dialectic argument reconstruction is a method for observing such reasoning from a transcript. The example team developed a strong inductive argument to integrate their disciplinary contributions about modeling.
Recommendations for Practitioners	Interdisciplinary work requires agreeing with teammates about what is assertible and why. To assert something together legitimately requires making a cogent, integrated argument.

Recommendation for Researchers	An argument is the basic unit of analysis for interdisciplinary integration. To assess the argument's cogency, it is helpful to reconstruct it using pragma-dialectic principles. To assess the argument's interdisciplinary integration, it is helpful to graph the flow of words as a Sankey chart from participant-disciplines to the argument conclusion.
Future Research	How does this definition of CIR relate to other interdisciplinary 'cognition' or 'learning' type theories? How can practitioners and theorists tell the difference between true intersubjectivity and superficial agreeableness in these dialogues? What makes an instance of CIR 'good' or 'bad'? How does collaborative, transdisciplinary reasoning differ from CIR, if at all?
Keywords	Argumentation, Discourse, Interdisciplinary, Integration, Intersubjectivity, Transdisciplinary, Toolbox

Introduction

Collaborative, interdisciplinary research has grown dramatically in recent decades—both in prevalence as well as promise (Van Noorden, 2015). The National Academies recently reported that 90% of scientific and engineering papers are now written by two or more authors (National Research Council, 2015, pp. 19-20), and many of these teams are interdisciplinary. Bibliometric measures of interdisciplinarity estimate that in six domains, papers from 2005 average 50% more disciplines than papers from 1975 (Porter & Rafols, 2009). The domains studied were (1) Biotechnology & Applied Microbiology; (2) Engineering, Electrical & Electronic; (3) Mathematics; (4) Medicine – Research & Experimental; (5) Neurosciences; and (6) Physics – Atomic, Molecular & Chemical). The trend towards interdisciplinary referencing practices—and by implication, interdisciplinary reasoning among author teams—has been especially marked since the mid-1980s (Lariviere & Gingras, 2014).

Rapid expansion in collaborative, interdisciplinary research has been justified by both the epistemic and instrumental promises of this mode of research (National Research Council, 2005). Epistemically, the claim is that many problems—especially so-called "grand challenges" (De Grandis & Efstathiou, 2016) or "wicked problems" (Rittel & Webber, 1973)—cannot be understood by a single discipline. Rather, insights are claimed to be more relevant and more incisive when knowledge is integrated across disciplinary boundaries and interstices (National Research Council, 2005, pp. 16-17). Instrumentally, it often 'takes a village' to access the material, human, temporal, and technical resources needed to research such wicked problems (Hagstrom 1964; Lewis, Ross, and Holden 2012).

However advantageous, this form of research poses its own challenges, which have in turn sparked meta-research on collaborative, interdisciplinary processes—a literature to which this study contributes (e.g., Frodeman, Klein, & Mitcham, 2010; Frodeman, Klein, & Pacheco, 2017). Meta-research and lessons learned in practice have together produced a plethora of tools,

frameworks, and constructs aimed to help us understand and address challenges inherent in cross-disciplinary teamwork (e.g., *i2insights.org*, http://i2insights.org; National Institutes of Health (NIH) National Cancer Institute, n.d.).

What has been underrated in this meta-research and practice, however, is a clear understanding of what could be considered the most basic task of these research teams: collaborative, interdisciplinary reasoning. By *reasoning*, here, I mean making inferences from what we understand to what we don't understand (Scriven, 1976, pp. 1-2). Making inferences entails exploring implications of a claim, using some claims to justify or cast doubt on other claims. That is, reasoning assesses the "warranted assertibility" (Dewey, 1938, p. 9) of a claim by evaluating the implications of other, more well-established claims.

Broadly speaking, we engage in reasoning when someone wants to assert an idea and others want to assess the right to assert it. These desires create different kinds of discourse settings in which assertions are made and defended. Sometimes, what is asserted is an answer to a question. These discourse settings constitute *inquiries*. Research is a type of inquiry, and therefore reasoning is essential to it. Failing to understand this most essential activity results in limited progress in improving theory and practice of collaborative, interdisciplinary research.

This investigation contributes to filling the related conceptual gap by first proposing a definition of *collaborative, interdisciplinary reasoning* (CIR) based on the neo-Pragmatist reasoning and argumentation literature. Next follows an in-depth example of CIR so understood to illustrate that this form of reasoning in interdisciplinary teams is plausible. The paper concludes by reflecting on areas for future research. The areas for future research include situations in which reasoning goes poorly. This paper presents the ideal for CIR as a goal for which to aim. However, an ideal—by definition—is never fully realized. A full, ethical, and useful treatment of CIR must therefore consider non-ideal situations, providing conceptual frameworks and practical suggestions for engaging the real world. This paper provides an orienting direction for such future work.

Collaborative, Interdisciplinary Reasoning Defined

Reasoning Together Defined

To reiterate, this article focuses upon reasoning that should occur among members of an interdisciplinary research project. *Research* here distinguishes inquiries that are planned and conducted systematically. More specifically, Leedy and Ormrod (2005), state, "Research is a systematic process of collecting, analyzing, and interpreting information (data) in order to increase our understanding of the phenomenon about which we are interested or concerned" (p. 2). Research, in other words, is a type of formal inquiry that seeks to increase understanding. In this conception, research occurs not only in academic settings but also in industrial and national laboratories, law enforcement offices, and non-profit organizations, to name a few places. Research projects might involve only one person, but the focus here is projects involving two or more collaborators.

CIR is a specific kind of the more general activity of reasoning together, requiring first an understanding of that more general concept. Communication is the vehicle for collaborative reasoning. J. Britt Holbrook (2013) helpfully identified three ways to understand communication, particularly as it applies to interdisciplinary research. One view is the Kuhn-MacIntyre thesis that reasoning across perspectives is not possible, because perspectives amount to incommensurable paradigms. Any collaborative reasoning that does occur requires one of the interlocutors to acquire "native fluency" in the relevant disciplinary languages, an accomplishment that is extremely difficult, rare, and in the end, not the integration of two paradigms. A second view, the Bataille-Lyotard thesis, holds that collaborative reasoning can proceed only by inventing a new language, built expressly for that discourse. Like the Kuhn-MacIntyre thesis, the Bataille-Lyotard thesis contends that different perspectives amount to incommensurable paradigms. However, unlike its Kuhn-MacIntyre counterpart, this thesis argues that commensurability is possible—but only through the invention of a custom-built language. A third major understanding of reasoning

together is the Habermas-Klein thesis, which holds that collaborative reasoning is possible through *integration* of perspectives. While Holbrook's article does not acknowledge this, other work from the Habermas-Klein perspective discusses many possible paths to integration (Klein, 1996; 2014a, pp. 20-22; O'Rourke, Crowley, & Gonnerman, 2016; Repko, Szostak, & Buchberger, 2016). Some paths may involve the creation of a new language but others may integrate existing languages. Moreover, although the Habermas-Klein thesis emphasizes integration as the ideal, the thesis acknowledges that in reality some perspectives are incommensurable (whether for inherent or contextual reasons is up for debate in each case). Thus, while Holbrook may disagree with me, I believe the Habermas-Klein thesis accommodates both the Bataille-Lyotard and Kuhn-MacIntyre theses while also affirming what most of us tend to believe: that reasoning together does happen across different perspectives.

Therefore, for the purposes of this project the Habermas-Klein thesis is most appropriate. I emphasize one strand of this thesis with a conception of 'reasoning together' found in works by Jürgen Habermas (1985), Larry Wright (1995; 2001), and Christian Campolo (Campolo, 2005; Campolo & Turner, 2002). This approach differs from perspectives of reasoning that have been more common in interdisciplinary literature, such as interdisciplinary learning (Augsburg & Chitewere, 2013), thinking (Dreyfuss, 2011), and cognition (Derry, Schunn, & Gernsbacher, 2013; Nikitina, 2005). The difference is that this neo-Pragmatist approach centers the social practice of giving reasons through discourse for the sake of coordinated action. It elevates the role of communication as a learning-for-doing tool while minimizing communication, learning, or doing treated separately: to neo-Pragmatists, collaborative reasoning is cognitive and communicative and contextually practical all at once. With such a focus, new facets of interdisciplinary communication come into the spotlight. As discussed and exemplified below, these new facets include types of discourse, standards for assertion, argument structures (including premises and conclusions), and conversational moves. The article attempts to show these are valuable insights.

Habermas's theory of 'reasoning together' unfolds several types of argumentation that differ based on differing goals of discourse (Habermas, 1985). Possible goals include finding truth ("theoretical discourse"), determining what is right action ("practical discourse"), establishing standards for value ("aesthetic criticism"), assessing authenticity of expression ("artistic critique"), and—as a meta-purpose—clarifying the appropriate forms of the above discourses ("explicative discourse") (Habermas, 1985, p. 23). Regarding the last goal, we need such meta-discourse because we always risk reasoning about different types of things in inappropriate ways, e.g., confusing the way things are (finding truth) with the way things should be (determining what is right action, or establishing standards of value). Explicative discourse is especially important in interdisciplinary contexts as disciplines disagree about the appropriate way(s) to discuss many topics (Eigenbrode et al., 2007); indeed the interdisciplinary example analyzed below illustrates explicative discourse.

Habermas emphasizes that rational discourse toward the above goals always involves argumentation because rational discourse depends upon one's ability to evaluate reasons and inferences against shared ("transsubjective") standards of adequacy (Habermas, 1985, p. 9). Such discourse can be understood as reasoning together, both because the claims and reasons are given in *social contexts* and because the standards by which those reasons are evaluated are *socially constructed*.

Intersubjective standards, as Wright and Campolo call them, are statements whose meaning is shared between interlocutors and is used to judge the acceptability of claims. For example, a common intersubjective standard in quantitative research is that statistical inferences must have a *p* value below 0.05 to be considered credible (Wasserstein & Lazar, 2016). Qualitative researchers, on the other hand, often require credible findings to be member checked (i.e., given approval by the respondents themselves) (Lincoln & Guba, 1985, p. 314). Both of these standards are socially constructed by epistemic communities. These standards can therefore change. Moreover, these standards can have different meanings, even to members within the same epistemic community or

the same person in two different contexts. For example, 0.05 is the threshold for which statistical test? With what kind of data? Similarly, member checking must include which members? And how should the check be performed? These questions identify key features of the *meaning* of each standard. Intersubjectivity of these standards requires participants agree upon the answers to such key questions. The best test we have of agreement is the ability to coordinate actions that depend upon the meaning. For example, if I ask for the data so I can test for significance, and if you give me the data in the form I expect, then I can be fairly confident you and I have the same test in mind and therefore a shared meaning of "statistical significance." Intersubjectivity, therefore, is best evidenced in localized social exchanges where actions serve as evidence of agreement across subjects.

It is important to note that Habermas's conception of rational discourse includes both "linguistic and non-linguistic actions," where non-linguistic expressions might include "delays, surgical interventions, [waging] of war, [and] repairs" (1985, p. 8). Both linguistic and non-linguistic expressions communicate, but only linguistic expressions use words to do so. What matters is that the expression effectively makes a claim addressing one of the purposes listed above, and that this claim can be evaluated against shared standards of reasoning.

For examples of the kinds of discourse Habermas discusses, consider the following pair of climate change discourses. To set context, imagine a city has adopted a climate change adaptation plan that involves spending $12 million to raise the elevation of causeways in and out of town. The action of causeway renovation is a non-linguistic claim approximately translated linguistically as, "We believe climate change is real and that this is a right way to deal with it." This statement prompts two different kinds of discourse in local meetings, coffee shops, and newspapers. First is the "theoretical" or truth-finding question, "Is climate change really real?" Second is the practical question, "If it is real, what is the right way to deal with it?" These two questions have different assertion goals and therefore require distinct forms of reasoning. What shapes those distinct forms

ought to take would be decided in an "explicative" discourse about each question that clarifies their appropriate form. In all cases, for these discourses to count as discourses, multiple parties must participate, and participation requires their ability to evaluate each other's claims. As Habermas observes, "[My] reflections point in the direction of basing the rationality of an expression on its being susceptible of criticism and grounding" (Habermas, 1985, p. 9).

Expanding on Habermas's insights, Wright (1995) and Campolo (2005) theorize that 'reasoning together' is the activity of establishing or repairing intersubjectivity about the implications of a claim for the sake of continuing a shared effort. Or, as Campolo puts it, "It is a way of restoring or initiating purposeful coordination to our several actions or behaviors" (2005, p. 38). Purposeful coordination is exactly what is at stake in collaborative projects; without it, a group is unlikely to accomplish its goals. Examples of coordinated action include meeting together, defining a research question, collecting and analyzing data, and submitting an article.

Here's how reasoning together supports such coordinated action. The initial result of a session of reasoning together is an assertion, which is a type of action ("communicative action," according to Habermas (1985)). This initial action then enables a chain of other actions: assertions enable understanding, understanding enables belief, and belief enables actions (see bottom half of Figure 2). This chain must occur for each of the innumerable decisions an interdisciplinary team must make. Moreover, the project itself is the first link in this chain as the understanding it generates should go onto influence beliefs and actions beyond the project.

Collaborative reasoning in research can be triggered by a disruption in any one of these links in the chain of action—originating either within or beyond the project. John Dewey called such a break "the feeling of a discrepancy, or difficulty" (1910, p. 73), and it is the first step in an inquiry. An example of disruption within the team might come when teammates do not agree on how to complete the data analysis, or when someone doesn't understand what someone else wrote in the manuscript so they can't approve its submission. Disruptions beyond the team might arise even

before the team assembles; these might be disruptions that start the team's entire project as an inquiry into an external disruption. For instance, when colleagues in a field no longer understand a phenomenon (i.e., the claims are controversial, incoherent, or absent), the coordinated action of understanding has been disrupted, and this event can manifest as a research question. In another instance, resource users might be at a loss about what to do because they are questioning some long-held beliefs (e.g., they question if climate is stable), and if researchers are listening to their needs, this disruption in daily life might prompt a research question. Research projects are attempts to restore disrupted chains of action in the world (including disrupted understanding, such as curiosity) by answering research questions, and this requires answering many other kinds of questions within the team's work. Answering questions *as a team* requires reasoning *together*.

Integrating the insights of Habermas, Wright, and Campolo, in the present project I understand *reasoning together* as follows:

> *Reasoning together is (linguistic or non-linguistic) discourse in which the participants exchange, evaluate, and assert claims that enable coordinated action in a local context.*

This proposition is worth unpacking. Recall that reasoning involves assessing one claim's dependence on other, more well-established claims. To evaluate these claims, participants must agree upon the standards by which they will evaluate them. The following questions arise: What counts as a "supportive" claim? How do we judge when one claim legitimately "depends on" another? What do we accept as "well-established"? If members of a team are not yet on the same page about these standards, they need to resolve their misunderstandings using a meta-, "explicative" discourse. Otherwise, they might go ahead and apply a shared or dominant standard in any of Habermas's four other forms of discourse.

Therefore, in order to exchange, evaluate, and assert claims together, participants need shared standards of what counts as good reasons and inferences. Well-supported, shared

inferences then enable coordinated action. An expanded definition of reasoning together, therefore, follows:

> *Reasoning together is the co-application and, perhaps, co-revision or even co-creation of intersubjective standards for what counts as a good reasons and inferences in a localized social exchange so that people can continue working together.*

The prefix "co-" specifies that these activities occur collaboratively, through conversation and other forms of communication. Co-application consists of applying existing standards of reasoning. For instance, a team may have already decided that 'good' claims in their project must be based at least partly on inferential statistics. They could then apply that standard to a questionable claim to see how good it is. Co-revision modifies an existing standard to restore shared understanding of it. Co-creation, however, is the synthesis of a new standard from existing, shared understanding. Note that reasoning together cannot create shared understanding *ex nihilo*; much must already be shared.

This conception of 'reasoning together' emphasizes (1) team members must have shared resources for evaluating a claim and (2) the goal of reasoning depends on the local context of a targeted action. Participants in collaborative *research* are trying to take an action of assertion that leads to the subsequent action of shared *understanding*, whether understanding of truth, action, value, authentic expression, or discourse itself. This shared understanding, ideally, enables further coordinated actions beyond the research project, e.g., spending $12 million to upgrade causeways.

To clarify relationships among key concepts thus far: We reason to go from understanding less to understanding more by making inferences. We make inferences by evaluating whether some relatively well-established claims support other claims. Evaluating support involves applying standards for what counts as support, where applying such standards may first require creating or revising them. When reasoning as a team, all participants must agree with and understand those standards. Reasoning then results in warranted, assertible conclusions that enable a series of coordinated actions. Assertion itself is a kind of coordinated communicative action, but it typically

serves a more distal action. In a surgery team, that action is a successful surgery. In a research team, that action is shared understanding of a phenomenon. Eventually, shared understanding from research may influence actions beyond the research project, such as a more successful surgery. The top half of Figure 1 charts this definition of 'reasoning together.'

Collaborative, Interdisciplinary Reasoning Defined

From here, to define CIR we need only specify what it means to reason together in an interdisciplinary way. Given the prevalence and promise of interdisciplinary research described above, a relatively clear consensus has emerged about what it means to be "interdisciplinary." The authoritative definition from the National Academies in their 2005 report *Facilitating Interdisciplinary Research* is widely recognized: interdisciplinarity entails "integrat[ing] information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge" (National Research Council, 2005, p. 2). Combining this definition with the above definition of 'reasoning together' suggests the following definition of CIR:

> *Collaborative, interdisciplinary reasoning is the attempted integration of disciplinary contributions to co-apply, co-revise, or co-create intersubjective standards for what counts as good reasons and inferences in a local social exchange so that people can understand a mystery and then continue working together.*

Or, a shorter way to express the same concept:

> *CIR is the attempted integration of disciplinary contributions to exchange, evaluate, and assert claims that enable shared understanding and eventually action in a local context.*

The bottom half of Figure 2 shows how this definition of CIR specifies the more general definition of 'reasoning together.'

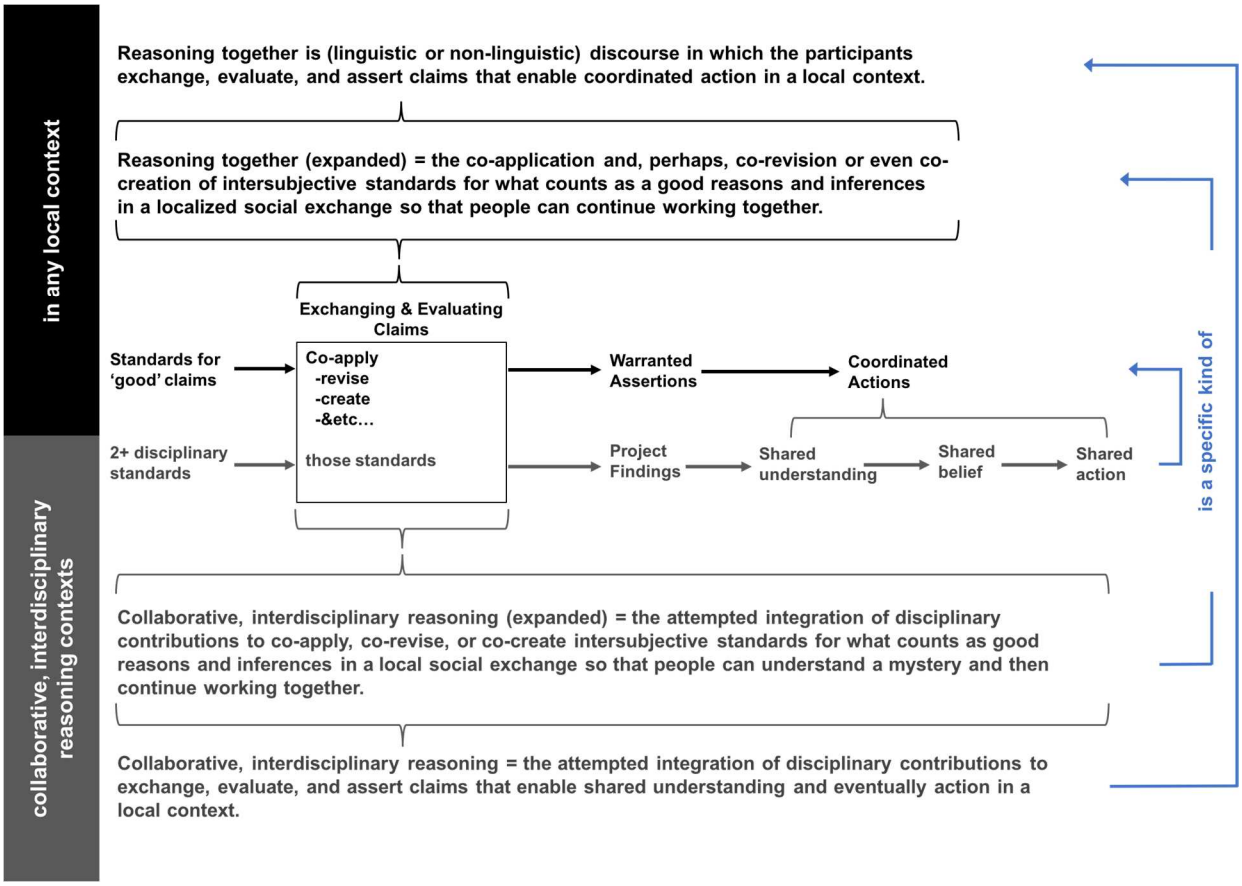

Figure 2: Reasoning together in any local context vs. collaborative, interdisciplinary contexts. The latter is a specific kind of the former; thus the bottom half of the figure mirrors the top half.

Standards for reasoning already exist in most disciplinary discourses, but they must often be revised or created in interdisciplinary discourses because all disciplinarians bring their own standards to the team (Cetina, 2009; Eigenbrode et al., 2007). Disciplinary standards may not only have different thresholds (e.g., $p < 0.1$ versus 0.05), they may also have different content and meanings altogether (e.g., "significant" = relevant, credible, actionable; versus $p < 0.05$). Co-revision consists in sorting out mismatched understandings of standards, while co-creation consists in establishing new standards. Some teams may be able to co-apply an intersubjective standard right away—perhaps having worked together before. Usually, however, teams will first need to co-revise or co-create such a standard through the process of explicative discourse.

As Habermas observed, a discourse that makes claims can be understood as an argument, where the more established claims are premises and the inferred claim is the conclusion. A

reasoning team is trying to craft a cogent argument all of its members endorse. The argument contains premises each interlocutor can evaluate for "allegations of support" of the conclusion (Wright, 1995, p. 570), and the conclusion captures the result of co-applying the standard to those premises. In some cases, the conclusion will itself be a standard to co-apply in another argument. In such cases, as an instance of explicative discourse, the argument is co-repairing or co-creating a shared standard for later reasoning. For example, the city council that approved the causeway renovation probably had an earlier meeting or series of meetings in which they decided that conclusions about climate change and what to do about it require certain kinds of evidence (e.g., regional climate models, climate risk assessment). Therefore, when they got this evidence, they were able to make an argument asserting climate change is real and causeway renovation is an appropriate next step. In an interdisciplinary group (perhaps the city council qualifies), the argument premises will often be crafted from various disciplinary contributions. The example in the next section illustrates how collaborative, interdisciplinary conversations can be understood as instances of CIR. It focuses specifically on explicative discourse—the co-creation of standards for group reasoning about another topic.

First, though, it is crucial to emphasize that interlocutors need not succeed in achieving intersubjectivity to engage in CIR. All three philosophers above emphasize, as Wright observes, "The practice of giving reasons is of value in our deliberations *when and because we are equipped* to evaluate the allegation of support [of a reason]" emphasis added (1995, p. 570). When we are not so equipped, reasons don't help much. In other words, it is quite possible to give reasons in a way that is *not* valuable and nevertheless be engaged in reasoning together. We often reason together quite poorly. Defining exactly what it means to reason together well or poorly in CIR remains a future project, but some warnings about the general process of reasoning together apply.

Wright and Campolo stress that we are equipped to evaluate allegations of support when the standards by which we evaluate them are (a) shared, (b) relevant, and (c) informed. If any one

of these three criteria are absent, then we ought not to reason together. Here's why. There are two options when participants realize they do not share enough foundational, relevant, informed commitments to make reliable inferences that solve the problem. One option is to stop reasoning and try another coordination approach, such as following orders. The other option is to continue reasoning, but this option is dangerous. To continue reasoning using claims they do not hold or understand, participants must create an appearance of informed consensus. This illusion can be constructed in at least two ways: either stronger participants force weaker participants to adopt their views and/or participants feign understanding. In the first case, great harm might be done through epistemic oppression *and* valuable understanding might be suppressed that could have helped solve the problem (Dotson, 2012; 2014). In the second case, which could also be a form of testimonial injustice (Dotson, 2011), it is unlikely the group will solve the problem and this could be harmful in itself. In addition, any success participants might have will be due to luck—good inferences will have nothing to do with it. This can also be harmful as it may reinforce bad reasoning habits.

Collaborators must therefore have quite a bit in common before reasoning together becomes possible or useful. While it is possible to have *an* explicative discourse, i.e., to reason together to co-create a shared standard for another discourse, it is not possible to have explicative discourses about explicative discourses *ad infinitum*. We must, eventually, agree on some standard for reasoning to get off the ground. These basic shared standards arise from our shared experiences; for instance, our experience as academics. As Campolo puts it,

> "Reasoning together in a fruitful way depends upon our existing shared practice, shared knowledge, and shared competence. Under the right conditions, reasoning together can restore that intersubjectivity. Under almost no circumstances can reasoning together create that intersubjectivity where it does not already exist" (2005, p. 45).

Thus, to judge whether a group is reasoning well or poorly, we must know the nature of their shared background. Therefore, the example below goes so far as to affirm reasoning did succeed to some extent, but a full evaluation is beyond the scope of this study.

Collaborative, Interdisciplinary Reasoning Exemplified

CIR can be found in many places. The appendix documents an excerpt from a transcript of a Toolbox workshop. Toolbox workshops host lightly facilitated, cross-disciplinary team discussions about project-related work. The facilitator rarely speaks, but the written instrument each participant completes provides some structure in the form of a menu of project-related assumptions participants can discuss at will. (For more information about the Toolbox Dialogue Initiative, formerly known as the "Toolbox Project", see O'Rourke and Crowley (2013)). The excerpt in the Appendix is a conversation thread about 40 speaking turns long, including minor interruptions and affirmations such as "Mmmhmm," and "Right" excluded from this analysis. In this thread, interlocutors discuss what counts as modeling in their interdisciplinary project. They evaluate and integrate each other's claims into a coherent argument supporting a conclusion about modeling that allows them to go on together. Of the twelve team members present, only three participate in this thread: a sociologist, a hydrologist, and an engineer. They integrate contributions from their three disciplines into five argument premises (P1-5) that together support a single conclusion about what counts as modeling in their project.

This section begins by overviewing the argument. Next, it describes the methods used in reconstructing the argument and then the reconstruction itself, i.e., how each premise is developed in the dialogue. Lastly, the section concludes by showing how this example of explicative discourse enables future coordinated action for the participants. This section is an example that other analysts can follow with interdisciplinary conversations wherever they occur.

Argument Overview

The numbers in parentheses below after a given premise refer to speaking turns that contribute to that premise. The first premise is mostly implicit in the dialogue, which is indicated by brackets. (Noteworthy: the sociologist does utter a few words gesturing in this direction). Similarly, the conclusion does not appear in any speaking turns because no one spoke the entire conclusion out loud; it also appears in brackets. However, implicit conclusions are not necessarily unreasonable or problematic. Explicit articulation is not logically required since the conclusion follows from the premises, which were already well-established, and it summarizes the general position that participants in the excerpt constructed.

P1. [The practices of the people here decide what modeling is in our project.] (64, 66)
P2. Everyone here uses statistics with empirical observations to build their models. (66, 68, 69, 79, 89, 91)
P3. Hydrologists and engineers use statistics to correlate inputs and outputs among processes they already know. (70, 75-79, 83, 85, 87)
P4. Sociologists use statistics to discover processes. (70, 77, 81, 85, 92, 94, 96, 98, 100)
P5. These two practices both use the input-process-output framework although their operationalizations of the framework differ. (72, 74, 88, 91, 103, 104)

C. [Therefore, modeling in our project involves using statistics with empirical observations to operationalize the input-process-output concept.]

With this conclusion, conversational participants are now on the same page about what modeling is in their project, enabling them to continue modeling together. Because their modeling practice was at stake, interrupted by misunderstanding, they co-revised their standard for what counts as a reasonable claim about modeling. Now, they could co-apply this standard to their shared modeling practices in future interdisciplinary dialogues—until another disruption requires them to co-revise. Their conclusion is an inference that allowed them to go from understanding less about modeling to understanding more. It is an assertion that enables future chains of coordinated action.

Argument Reconstruction Methods

Reconstructing arguments from ordinary language—especially un-rehearsed dialogues—is difficult and controversial. Pragma-dialectic argumentation scholars recognize the tension between

getting the reconstruction right while also assuming the speakers are making the strongest argument possible, consistent with their argumentative intentions (van Eemeren, Garssen, Krabbe, Henkemans, et al., 2014a). This assumption requires an analyst to fit the speakers' words into a cogent argument form—even if it is not the form in which the speaker presented claims. There is no easy to way to resolve the tension between accuracy and charity; indeed, we can think of argument reconstruction as more of an art than a science. Others may see a different argument in the excerpt than the one I present below.

However, any such disagreement merely illustrates the proposition that reasoning together is about exchanging and evaluating reasons for one's assertions. Specifically, some might give reasons to disagree with the reconstruction, underscoring that we rely upon reason-giving in research discourse and this difficult task requires balancing accurate and charitable interpretations of what others have said. Thus, the main purpose of this example is not to get the reconstruction "objectively right" (if there is such a thing). The purpose, rather, is to illustrate collaborative, interdisciplinary reasoning, whether through the example itself and/or how we talk about it.

In this reconstruction the following guiding principles apply.

1. The definition of CIR identifies four nodes or knots in the reasoning tapestry: discussants, disciplines, premises, and a conclusion that increases understanding and eventually leads to action.
2. Brief verbal affirmations such as "Mmmhmm," and "Right" are not contributions but rather indicate acceptance, and so they are excluded from the analysis.
3. The remaining, substantive speaking turns may contain more than one distinct idea.
4. Each distinct idea is coded as a separate "contribution."
5. The speaker's own disciplinary identity indicates which disciplinary perspective is driving the contribution, *unless* the speaker explicitly notes they are taking on the perspective of another discipline or disciplinarian.
6. These disciplinary contributions contribute to argument premises, and the premises a conclusion.
7. The premises and conclusion are assumed to be grammatically complete, contextually meaningful, and logically coherent (i.e., "well-formed") claims.

8. A well-formed claim may or may not be spoken aloud. In cases where it is not, the analyst supplies the missing pieces by surmising what the speakers intended to say or believe they did say. Listening to the audio recording can help in resolving ambiguity.

The full application of these principles to the excerpt is documented in the Appendix.

Argument Reconstruction

P1. [The practices of the people here decide what modeling is in our project.]

Understanding the origin of Premise 1 requires first looking at the dialogue's context. Participants requested a Toolbox workshop *because* they wanted to get on the same page about key concepts in their project. Thus, this excerpt about modeling takes place in a conversational context designed to help them increase mutual understanding, which includes mutual understanding about what modeling is in their project. The assumption behind the dialogue is that the people present have a significant role to play in determining how things are understood within their project. In fact, the sociologist implies as much when he opens the excerpted dialogue:

> Sociologist (64, 66): "Well one of the things I found working with many of the people in the room is a term I'm still trying to wrap my mind around, that I don't think we all use the same way is the word 'modeling'…We actually confronted this one when we tried to write our grant."

The sociologist references use of the term "modeling" in their proposal writing process, indicating that the following discussion is about use of the term in this project by people participating in the project. The others take up this conversation, below, implying they agree with this first premise.

What has happened is that the participants immediately applied a shared, unspoken standard about what is assertible by the sociologist. What is assertible seems to be whatever has been experienced by anyone in the group—individually or collectively. It is not clear how they came to share this assertibility standard. They may have affirmed the validity of each other's experiences in previous discussions, or they may simply share that assumption based on their shared lifeworld as academics, where (usually) one's expertise is not questioned by those from other disciplines. When applying this standard to his claim, the sociologist here is not speaking as a sociologist but

more generally as a member of the project. Indeed, Figure 3 shows P1 comes from no particular disciplinary perspective.

P2. Everyone here uses statistics with empirical observations to build their models.

Premise 2 takes quite a while to become a full thought in the dialogue. Not until speaking turn 89 do participants discover what exactly they all have in common when modeling. They spend much of the dialogue trying to find the commonality by showing how they use terms related to modeling, such as "calibration" and "significance." For example, the Sociologist explains that when he models,

> Sociologist (66): … we [Sociologists] go and do a fairly standardized set of mathematical type things that say, ok that is, that explains this much of what we were trying to explain, this well or with this much degree of confidence….
>
> Sociologist (68): [cont.] Um, but you're actually inferring sort of this significance of relationships and so.
>
> Hydrologist (69): [overlap] Well you just described what <u>we</u> do.

In this brief exchange, the hydrologist and sociologist agree that for them, significance means mathematically significant, a definition that likely refers to statistics given the use of the terms "degree of confidence" and "significant." The engineer never disagrees with this conclusion, suggesting that it also describes his practice. A longer exchange (75-89) centers on the term "calibration," but in fact the process of calibration is so technical they cannot fully compare the various meanings-in-practice during this brief dialogue. They are satisfied to know calibration eventually ends by determining the statistical significance of their empirical observations.

By comparing and contrasting related terms such as "calibration" and "significance," the interlocutors (the sociologist, hydrologist, and engineer) can triangulate on where the focus term, "modeling," fits in their respective meaning structures (Mohr, 1998). In locating the target term in relation to other terms, they can discern its core meaning: they examine which terms it is related to in the same way in the meaning structures of all participants. They decide that the core feature of modeling for them is use of statistics with empirical observations.

> Sociologist (66): "[The way] we model in the social sciences – some of us do – is basically an exercise of developing some theoretical models and testing them against the world and seeing how well that model fits."
>
> Hydrologist (89): "But what you described is what you do for a model anyway, you're approach to modeling? I'm just sitting here going, hmmm yep."

Again, we see the participants applying their shared standard for what is assertible, namely whatever has been experienced by the participants. When they apply this standard to the anecdotes given by the sociologist and hydrologist, they establish a new claim about the necessary role of statistics. Now that they know what they have in common, they must articulate their differences to develop an integrative definition of modeling. Figure 3 shows P2 is an interdisciplinary premise, established by sociology, hydrology, and a general perspective integrated into a coherent claim.

P3. Hydrologists and engineers use statistics to correlate inputs and outputs among processes they already know.

Premises 3 and 4 take even longer than Premise 2 to formulate. In fact, not until the engineer introduces the boundary crossing metaphor of a "box" do the sociologist and hydrologist/engineering camps articulate their practices in a shared language or terminology so they can compare them.

> Engineer (72): "I think one aspect of it is, there's like, think about it as a box. There's inputs, and there's outputs. One type of model is trying to correlate those and show how inputs match with the outputs just however mathematically or statistical description. The other type is processes."

Most modelers are aware of the box metaphor. It provides a common framework (the IPO framework) within which are different components—inputs, processes, and outputs—with different roles for different modelers. Still, interlocutors in this example struggle for a while to locate each other within this framework. Applying their "whatever we've experienced" standard is not as easy as it was in the first two premises. The difficulty seems to stem from the fact that, in contrast to their common use of statistics, they either don't use the IPO framework to understand their own modeling practices or, if they do, they use it differently from each other. Reconciling those different uses takes some conversational work.

Taking up the engineer's "box" proposal, the hydrologist leans into the IPO framework to describe her modeling practice in detail in speaking turns 75 and 77. She ends with a provocative summary, "We [hydrologists] have some fundamental processes we know occur." The sociologist immediately understands and critiques this sort of modeling, signaling that this approach is somehow essential to the differences between sociological and hydrological IPO modeling; premises 3 and 4 co-evolve. The engineer identified two ways to use the IPO framework: (1) correlating inputs and outputs, and (2) specifying the processes. Once it becomes clear the sociologist does the latter, it is simultaneously clear the hydrologist and engineer do the former. Hence the fullness of Premise 3 depends conversationally but not logically upon Premise 4. Figure 3 shows P3 is also an interdisciplinary premise, established by the same contributing perspectives as P2, but from different utterances. The figure also shows that P3 takes the most words and therefore the longest to establish; it proved to be the trickiest premise for everyone to understand. This makes sense since P3 initiated P4 yet also depends conversationally upon it.

P4. Sociologists use statistics to discover processes.

Because Premises 3 and 4 unfold simultaneously, it is worth requoting the hydrologist's summary from speaking turn 77 more completely:

> Hydrologist (77): "[You sociologists are] trying to – your conceptual knowledge is trying to get put together somehow. We [hydrologists] have some fundamental processes we know occur [in the world], so we have to figure out whether or not we're missing some [in this model]."

This comment distinguishing the two modeling practices makes more sense later in the dialogue, after discussing the particular practice of calibration:

> Sociologist (92): "We [sociologists] just don't start with any process relationships, those are all to be discovered."

That is, if hydrologists and engineers are correlating inputs and outputs because they already know (a potential list of) the processes involved, then what is different is that sociologists do not yet know their processes. One can see how this integrated understanding of modeling would serve

their project very well because the disciplinary practices complement each other. Figure 3 shows P4 is actually a disciplinary claim from sociology; the sociologist is, after all, speaking for himself. However, we know he is responding to hydrological and engineering perspectives, so again we see that P4 depends conversationally but not logically upon P3. P4 therefore takes almost as many words as P3 to establish. Applying the "whatever we've experienced" standard to this claim takes as much effort as that for the previous claim.

P5. These two practices both use the input-process-output framework although their operationalizations of the framework differ.

Finally, now that participants have identified their common use of empirical statistics and their different roles in the IPO framework, they need to show how the commonality and the difference are both part of the same practice, namely modeling. This is a bit of a conversational formality as they have been assuming all along that these are part of modeling. But they are not satisfied until they explicate exactly how those practices relate. Near the end, the hydrologist has an epiphany that brings it all together:

> Hydrologist (103): "Hey! So maybe it's just that we all come up with conceptual models similarly, but it's [the difference is] the actual implementation of it?"
>
> Sociologist (104): "Seems to be. It's yeah the practice of what we actually do when say we go out and model."

The epiphany rests on the realization that the IPO framework is a conceptual model shared by both camps; everyone is assuming there are inputs, processes, and outputs in their models. However, when it comes time to build a model—to operationalize it—participants make different assumptions about what inputs, processes, and outputs to include. This is another application of the "whatever we've experienced" standard. In their experience, hydrologists and engineers (in this dialogue) assume they know what processes could be involved, so what is to be discovered through the model is to what extent the inputs and outputs correlate based on which processes are actually involved and what values their parameters have. Sociologists, on the other hand, do not assume they know which processes could be involved; "those are all to be discovered." In this way, both

camps model using the IPO concept although they operationalize it in two different ways—but always with statistics! Figure 3 shows P5 is also integrative, established by the engineering and general perspectives present.

C. [Therefore, modeling in our project involves using statistics with empirical observations to operationalize the input-process-output concept.]

The argument's conclusion follows logically and immediately from its five premises; essentially, participants have already reached this conclusion after expositing premise 5. The conclusion is a generalization from two kinds of modeling to all modeling that occurs or will occur in the project. Specifically, this takes the form of an inductive argument, also known as an inductive generalization. Such an argument establishes that certain features shared by a sample of members of a set are likely shared by all members of that set. Just how likely this prospect is depends upon how representative the sample is of the set. In this case, our discussants believe they are remembering past instances of their modeling practices that accurately represent the types of modeling they will do in the future. This is what justifies their application of the "whatever we've experienced is assertible" standard. Time will tell how accurate this belief is, but for now they have good reasons to believe their memories accurately reflect the past and predict the future. Therefore, this inductive argument yields a plausible, cogently-inferred, interdisciplinary conclusion that allows them to move forward with modeling. Figure 2 shows that all five premises, and therefore the total volume of words spoken in the exchange, contribute to the conclusion. Because these premises were established by several disciplines, and because we know the premises and conclusion are cogent, Figure 3 shows us that interdisciplinary integration resulted in the conclusion discussed above.

This conclusion, of an explicative discourse, functions as a standard they can apply in future forms of discourse. It is a standard that was co-created from the application of another standard that was already shared. If participants did not already share that standard, they would not have

been able to have this conversation. In other words, instances of CIR depend upon shared, intersubjective standards that must pre-exist the focal question. Such pre-existing standards can be established through other rounds of CIR or shared lifeworld experiences that create shared assumptions.

Argument Visualization

Visual analysis complements argument reconstruction. Argument reconstruction highlights the logical structure and rhetorical presentation of the discourse. In doing so, it de-emphasizes the amount of conversation that occurs, the overall sources and locations of integration, and who plays particular roles across the entire argument. A parallel sets chart, on the other hand, emphasizes those very things (Figure 3). A parallel sets chart illustrates flows between sets, e.g., visualizing the flow of money through accounts or energy through trophic levels.[26]

In our case, we are tracking the reasoning process from individual participants to a shared conclusion. The "sets" are sources and sites of inference along the way, viz., (1) participants, (2) disciplines, (3) premises, and (4) argument conclusion. (Participants are separate from disciplines since participants can infer the perspective of several disciplines.) The "flow" is the reasons asserted, viz., words uttered. By tracking the words through the reasoning process, we can visualize sources and sites of integration and participant reasoning roles in the entire conversation at a glance. These quantitative insights complement the qualitative argument reconstruction, helping analysts and practitioners identify which disciplines tend to make certain kinds of contributions to the integrative work, and who tends to represent those disciplines in what ways.

While not the only way to visualize reasoning, this set-and-flow chart falls directly out of the definition of CIR given above. In that definition, CIR is the transformation of disciplinary

[26] For the basics of parallel sets charts, see https://datavizcatalogue.com/methods/parallel_sets.html. Sometimes these are also called Sankey diagrams, e.g., https://developers.google.com/chart/interactive/docs/gallery/sankey.

contributions into an interdisciplinary conclusion through the exchange of reasons. In this example, words flow from participants, pictured on the left side of the chart (Figure 3), through various disciplines and premises to the conclusion, on the right side. The word flows represent the exchange, evaluation, and assertion of claims between participant-disciplines (inputs), coherent premises (process), and a conclusion or warranted assertion (output), per the IPO model of integration (O'Rourke et al., 2016).

Note that the chart alone *does not* visualize integration or intersubjectivity; those must be assessed through the argument reconstruction. To wit, just because two disciplinary contributions are relevant to the same premise does *not necessarily* mean they are integrated beyond a mere, multidisciplinary 'stapling together.' We must examine the construction of the premise to assess its integration. Likewise, just because two people contribute to two disciplines which contribute to a single premise does *not necessarily* mean the people each understand that premise in the same way. We must carefully read the transcript. Integration and intersubjectivity are *qualities* of the exchange, not *quantities* that can be charted. We can only locate integration and intersubjectivity in the chart if we use our qualitative knowledge of what the chart represents.

While we cannot use the chart without the argument reconstruction, the argument reconstruction can stand alone as evidence of CIR. However, because it pictures the entire exchange at once, the chart does make some dynamics of CIR more visible than in the reconstruction alone.

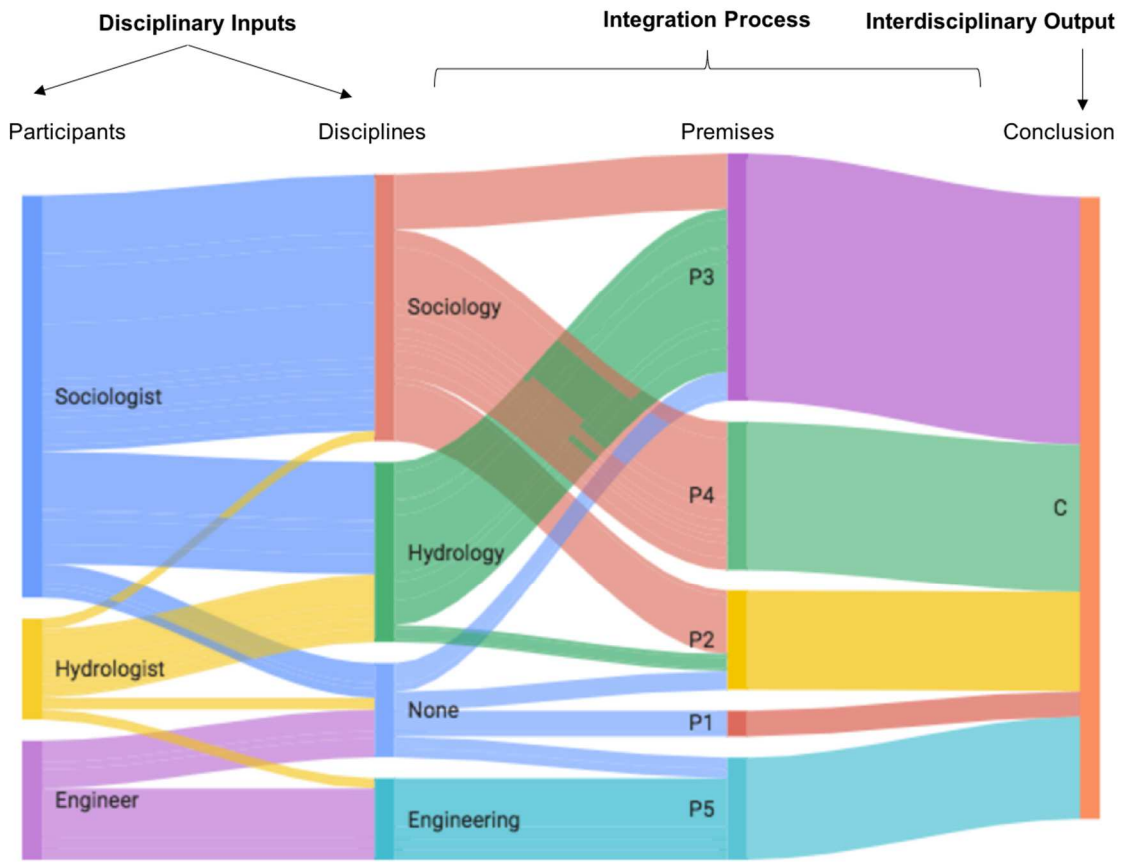

Figure 3: Flow of words (and therefore reasons) from speakers to disciplines, premises, and conclusion in the dialogue excerpt (26 speaking turns, 34 contributions, 1294 words). The width of the link represents the number of words. The full volume of words is represented from the first nodes and they flow through the other node sets. You can follow a word from its utterance on the very left to its contribution to the conclusion on the very right.

Figure 3 helps us identify disciplinary sources of integration and participant reasoning roles. We see the conversation takes 1294 words, which is not very many, so we must keep that in mind when interpreting the chart. The colors in Figure 3 identify the originating nodes; therefore each node has a unique color. (Remember that participants are distinct from disciplines, so the sociologist has a different color from sociology). This helps us track who or what is contributing to a given node. Through the chart we can quantify both the number of disciplines contributing to integration points and also the volume or amount of their contribution. This approach may help evaluate the breadth and/or depth of the interdisciplinarity, depending on how those constructs are measured (Kelly, 1996).

Figure 3 also showcases clues about conversational roles other studies have shown are important for interdisciplinary communication: dominators (Bondy, 2010; M. S. Reed, 2008), boundary crossers (Klein, 2014a, pp. 17-18), and integration specialists (Bammer, 2013). Figure 2 shows the sociologist speaks most; he may be a controller in this exchange. The reconstruction can help us interpret the nature of his control. Figure 3 also shows the hydrologist is the most flexible thinker as she contributes to all perspectives in the exchange; she acts as the boundary crosser with interactional expertise (Collins & Evans, 2002). The engineer may be the integration specialist as nearly one-third of his words fall into a general perspective that applies to all parts of the argument, except P3. Indeed, most of the engineer's words contribute to P5, which is the final premise needed to tie all the others together in a coherent, cogent conclusion. Thus, we see Figure 3 not only identifies sources and sites of integration, it also aids the quick, visual identification of key conversational roles that can spark further analysis or team interventions. Together, the parallel sets chart and argument reconstruction provide a quantitative and qualitative understanding of the nature of interdisciplinary integration in this discourse. The new definition of CIR proposed above makes these analyses possible.

From Disruption to Conclusion to Action

The above dialogue excerpt is an example of what Habermas calls "explicative discourse," which is discourse about the standards for discourse, as noted above. Habermas explains,

> "*Explicative discourse* is a form of argumentation in which the comprehensibility, well-formedness, or rule-correctness of symbolic expressions is no longer naively supposed or contested but is thematized as a controversial claim." (emphasis original, Habermas, 1985, p. 23)

"Thematized" means abstracted from specifics into a principle that can be interrogated. In this case, specific instances of purportedly "well-formed" definitions of modeling are abstracted into a general definition of modeling for their project. Another way of describing this form of discourse is a shift to a 'meta-level'—from the current topic to *how we ought to talk about the topic*. The team is not trying to model right now; they are talking about *how* to model within their project.

This shift to explicative discourse is triggered because they keep using the term in different ways, disrupting their shared understanding of modeling in their project. The sociologist opens this discussion by noticing this disruption and bringing it to the group, shifting discourse from a naïve supposition to a controversial claim. As a result, they want to know what counts as a good reason to trust each other's modeling approaches. Explicative discourse, like any other discourse, becomes interdisciplinary when these standards for 'good reasons' are created or revised through the integration of disciplinary contributions. As the example illustrates, choosing a team modeling approach is a common example of interdisciplinary explicative discourse, and therefore is also an instance of CIR.

Now that they have an intersubjective standard for what counts as modeling, they can go on with modeling; their practice will require co-applying this standard in other kinds of discourse. For example, they might try to get at the truth of something, and therefore apply this standard of modeling in a future theoretical discourse. They might ask, "What could be the impact of residential water use on this aquifer?" Collaborative consideration of this question will be another instance of CIR, but it is also the action-outcome of the first instance. Their first instance of CIR established what modeling is. This step will enable them to take the action of modeling the aquifer, which will be the second instance of CIR. In short, since actions count as non-linguistic expressions, the outcome of one discourse is another discourse, and so on. Humans are in ongoing conversation with each other, and interdisciplinary research is no exception.

Collaborative, Interdisciplinary Reasoning Qualified

Of course, to introduce the concept of CIR I chose an example that successfully reached an integrated, logical conclusion (in only 6 minutes of conversation!). Its brevity might lead one to believe CIR is easy. It is not. Toolbox transcripts also contain muddled, confused arguments that never resolve. Dialogical impasses can be caused by many factors, including: the illusion of agreement; the illusion of disagreement; fuzzy concepts; information overload; implicit (or explicit)

bias; competing values; moral dilemmas; incommensurable epistemologies and ontologies; and, almost inevitably, the jerk in the room. Freeing these impasses requires first diagnosing which factor—among others—is the root cause. Thinking in terms of CIR can help with this diagnosis. By tracking which disciplinary standards are being integrated into an argument and how, a theorist or practitioner will find the point of impasse. Several tracking questions aid this process: Does everyone agree on the type of discourse we're having right now (e.g., explicative, practical)? If so, which reasons nevertheless fell flat? Who disagreed or got confused? Gently digging into the sticking point like a surgeon examining a wound will reveal the root causes. At bottom may be a difference in meanings, values, goals, or personalities that can be resolved. One must continue querying reasons for the impasse and considering answers from many perspectives. The solution to problems with CIR is often more CIR, increasingly targeted where there is lack of intersubjectivity.

However, sometimes more reasoning isn't the solution. For instance, it is not clear that reasoning alone would be enough to involve the other nine participants in the exchange analyzed above. Perhaps some did not speak due to testimonial smothering of themselves or quieting by more powerful members (Dotson, 2011). If so, more CIR would simply perpetuate this harm, making things worse. Perhaps some did not agree with the assumed standard of assertibility ("whatever we've experienced is assertible.") This may be a deep disagreement that is incommensurable; no matter what is said the disagreement would remain and participation would be divided. Although it was successful, the excerpt above is not perfectly ideal; intersubjectivity only extended to one-fourth of the group.

While a lot of CIR isn't as quickly resolved as the example I analyzed above, unresolved attempts at CIR are not complete failures. In the process of genuinely engaging one another's disciplinary standards, we learn a lot that will help us down the road—so long as we keep an open mind. We learn intellectual humility, charity, and patience (Ferkany & Whyte, 2011). We learn new vocabulary words (Jeffrey 2003). We learn who is motivated by what (Boix Mansilla, Lamont, &

Sato, 2015). We learn how to midwife half-formed ideas (Burnyeat 1977; Plato 1997, 148e-151d). By building these and other capacities (Salazar, Lant, Fiore, & Salas, 2012), we may eventually be able to integrate our reasons into a shared assertion. But perhaps, more importantly, we become better people along the way.

Conclusion

This article has argued that CIR entails integration of disciplinary contributions to co-apply, co-repair, or co-create intersubjective standards for what counts as 'good' reasons and inferences in a team research project. The extended example illustrates this definition. Disciplinary integration is the intended consequence of people from different disciplines trying to reason together. As Habermas, Wright, and Campolo conceive of it, reasoning together requires intersubjective standards for evaluating claims. These intersubjective standards constitute standards for reasonableness in the dialogue, whether talking about reasonable standards of modeling, evidence, methodological adequacy, advocacy, or figure design—to name a few areas of possible conflict in research teams. Achieving such intersubjectivity requires teammates to integrate their respective standards for epistemic (e.g., truth, justification) and non-epistemic success (e.g., justice, feasibility) as well as the meaning of shared concepts, because these standards and meanings often vary in different disciplines. That is, CIR is sensitive not only to the purpose of the dialogue but also to the epistemic cultures of the interlocutors. Engineers, for example, employ different standards of reasonableness and meaning than sociologists.

To conclude, CIR is a unique instance of reasoning together that has heretofore been under-theorized by both argumentation theorists and scholars of interdisciplinarity. While all instances of reasoning together depend upon intersubjectivity, as shown above CIR co-applies, co-repairs, or co-creates that intersubjectivity *by integrating disciplinary contributions*. Identifying the reasoning moves within communicative actions facilitates intersubjectivity, enabling both theorists and practitioners to more effectively diagnose dialogical impasses and analyze the structure of

interdisciplinary inferences. CIR is an engine of knowledge integration in interdisciplinary teams, but it doesn't always work well. Nonetheless, if we can better understand the mechanism, we can better understand and improve the transformation of disciplinary contributions into interdisciplinary insights.

Furthermore, understanding CIR could also foster better understanding of *trans*disciplinary reasoning. Widely regarded as a transformative form of interdisciplinarity (Klein 2014), transdisciplinarity is compatible with the definition of CIR above, leading to an expanded definition of C*T*R integration in which disciplinary contributions result in a new paradigm—a novel *kind* of standard for exchanging and evaluating reasons. Given this novelty, we can perhaps view CTR as creative while CIR as *re*-creative. Both types of collaborative reasoning rely upon the ability of participants to assess the cogency of claims being made in dialogue and to assert a conclusion with one voice.

At the same time, if transdisciplinarity is understood as collaboration between academics and non-academics (Klein, 2014b), speaking in unison and in academic discourse is not necessary. Shared standards of reasoning then include different professional and cultural forms of knowledge. Inputs to Figure 1 for this form of CTR will differ from those in transformative CTR or in CIR. The process may also differ if integrated, univocal conclusions are not the goal. If multivocality is an important end (Suthers, Lund, Rosé, Teplovs, & Law, 2013), the only standard of reasoning everyone must adopt may be "Each to their own." This sort of reasoning together may be sufficient for some kinds of coordinated action, such as university and private entities sharing space in the same building.

More work remains to thicken the construct of CIR by relating it to other "cognitive" or "learning" type constructs in interdisciplinarity literature (Boix Mansilla, 2010; Boix Mansilla et al., 2015; Derry et al., 2013; Nikitina, 2005), as well as more specific types of argumentation from the argumentation and reasoning literatures (Juthe, 2015; van Eemeren, Garssen, Krabbe, Snoeck

Henkemans, et al., 2014b; Walton, Reed, & Macagno, 2008). Future research should then articulate what it means to do CIR well or poorly. Recent work on the role of values in setting scientific standards will be helpful here (e.g., Douglas, 2009; Elliott, 2017; Winsberg, Huebner, & Kukla, 2014), along with work on epistemic harm (e.g., Dotson, 2012; Fricker, 2007) and ignorance (e.g., Ortega, 2006; Piso et al., 2016; Tuana, 2006). From here, we will be able to evaluate instances of CIR and identify areas for improvement. These areas for improvement can then be matched to new or existing team science tools. From the other direction, we can understand why certain tools are or are not effective by examining how they enable or inhibit good CIR. All of these research efforts will benefit from the sort of close conversation analysis of real team discourses exemplified in this paper (Choi & Richards, 2017). In summary, developing the theory and analysis of collaborative, interdisciplinary reasoning is a necessary step in realizing the promise of interdisciplinary research.

APPENDIX

APPENDIX

Table 2: Analytic transcript of a Toolbox workshop showing the full utterance of each speaking turn, each separate contribution from the full utterance, the speaker, which disciplinary perspective they used in their contribution, the word count of the contribution, and to which premise of the overall argument the contribution contributed.

Full Speaking Turn	**Contribution**	**Speaker**	**Disciplinary Perspective Used**	**Word Count**	**Premise Contributed To**
10:56 64 SOCIOLOGIST: Well one of the things I found working with many of the people in the room is a term I'm still trying to wrap my mind around, that I don't think we all use the same way is the word modeling.	Well one of the things I found working with many of the people in the room is a term I'm still trying to wrap my mind around that I don't think we all use the same way is the word modeling.	Sociologist	Sociology	41	P1
65 P?: Yeah, that's one that..				0	
66 SOCIOLOGIST: [cont'] We actually confronted this one when we tried to write our grant, we came to a heavy place that allowed us to write the grant. [laughter] And it was actually trying to engage the fact that modeling can mean such different things to different fields. And in engineering particularly I've come to appreciate as a view... And until I got going on our little bear project five years ago, to me modeling – we model in the social sciences – some of us do --is basically an exercise of developing some theoretical models and testing them against the world and seeing how well that model fits. And so we specify the model that fits, as certain relationships among things we can measure, and then we go and do a fairly standardized set of mathematical type things that say, ok that is, that explains this much of what we were trying to explain, this well or with this much degree of confidence. And then you might go back to the drawing board and re-specify and tweak and try to figure out how to make your model fit those data better.	We actually confronted this one when we tried to write our grant	Sociologist	Sociology	12	P1

Table 2 (cont'd)

Full Speaking Turn	Contribution	Speaker	Disciplinary Perspective Used	Word Count	Premise Contributed To
	to me modeling – we model in the social sciences – some of us do --is basically an exercise of developing some theoretical models and testing them against the world and seeing how well that model fits. And so we specify the model that fits, as certain relationships among things we can measure, and then we go and do a fairly standardized set of mathematical type things that say, ok that is, that explains this much of what we were trying to explain, this well or with this much degree of confidence. And then you might go back to the drawing board and re-specify and tweak and try to figure out how to make your model fit those data better.	Sociologist	Sociology	120	P2
67 P?: [overlap] mm hmm				0	
68 SOCIOLOGIST: [cont'] Um, but you're actually inferring sort of this significance of relationships and so.	but you're actually inferring sort of this significance of relationships and so.	Sociologist	Sociology	12	P2
69 HYDROLOGIST: [overlap] Well you just described what we do.	Well you just described what we do.	Hydrologist	Hydrology	7	P2
70 SOCIOLOGIST: [cont'] So I thought it would be part of our project to explain, you know variability in water quality, that we would get all this raw data in water quality variability and we would try to explain it using behavioral variability and so forth at these various scales. And what I found was we weren't actually doing that. What we were doing was we were simulating rigid models and calibrating to measured outcomes and there was, it kind of works or it doesn't	So I thought it would be part of our project to explain, you know variability in water quality, that we would get all this raw data in water quality variability and we would try to explain it using behavioral variability and so forth at these various scales. And what I found was we weren't actually	Sociologist	Sociology	120	P4

Table 2 (cont'd)

Full Speaking Turn	Contribution	Speaker	Disciplinary Perspective Used	Word Count	Premise Contributed To
work. There wasn't the same kind of process as I was, it's different in some fundamental way. I'm still trying to understand what that difference is because I feel like we're going to have to figure this out.	doing that. What we were doing was we were simulating rigid models and calibrating to measured outcomes and there was, it kind of works or it doesn't work. There wasn't the same kind of process as I was, it's different in some fundamental way. I'm still trying to understand what that difference is because I feel like we're going to have to figure this out.				
	So I thought it would be part of our project to explain, you know variability in water quality, that we would get all this raw data in water quality variability and we would try to explain it using behavioral variability and so forth at these various scales. And what I found was we weren't actually doing that. What we were doing was we were simulating rigid models and calibrating to measured outcomes and there was, it kind of works or it doesn't work. There wasn't the same kind of process as I was, it's different in some fundamental way. I'm still trying to understand what that difference is because I feel like we're going to have to figure this out.	Sociologist	Hydrology	120	P3
71 P?: yeah				0	

Table 2 (cont'd)

Full Speaking Turn	Contribution	Speaker	Disciplinary Perspective Used	Word Count	Premise Contributed To
72 ENGINEER: [overlap] We were talking about this is morning, [name], and I think one aspect of it is, there's like, think about it as a box. There's inputs, and there's outputs. One type of model is trying to correlate those and show how inputs match with the outputs just however mathematically or statistical description. Then other type is processes. Trying to explain how you start here and where you go next, and where you go next, and where you go next, and where you go next, and where you go next. And then ultimately what comes out that you can measure or see.	We were talking about this this morning, [name], and I think one aspect of it is, there's like, think about it as a box. There's inputs, and there's outputs. One type of model is trying to correlate those and show how inputs match with the outputs just however mathematically or statistical description. Then other type is processes. Trying to explain how you start here and where you go next, and where you go next, and where you go next, and where you go next. And then ultimately what comes out that you can measure or see.	Engineer	Engineering	100	P5
73 P?: [overlap] mm hmm				0	
74 ENGINEER: [cont'] And there's I think probably other aspects of the problem that do that too, but that seemed to, that resonates, that definitely resonates with me.	And there's I think probably other aspects of the problem that do that too, but that seemed to, that resonates, that definitely resonates with me.	Engineer	Engineering	25	P5
75 HYDROLOGIST: [overlap] So I think maybe one of the key differences of that whole, you know you get all these data and then you calibrate you know the model to match what happens with the data or what you see and it seems like you're kind of like you're just tuning things to just to make it all work.	So I think maybe one of the key differences of that whole, you know you get all these data and then you calibrate you know the model to match what happens with the data or what you see and it feels like you're kind of like you're just tuning things to just to make it all work.	Hydrologist	Hydrology	57	P3
76 SOCIOLOGIST: [overlap] Just like turning knobs.	Just like turning knobs.	Sociologist	Hydrology	4	P3
77 HYDROLOGIST: Yeah, but in reality there's very fundamental concepts or processes that are	Yeah, but in reality there's very fundamental concepts or	Hydrologist	Hydrology	30	P3

Table 2 (cont'd)

Full Speaking Turn	Contribution	Speaker	Disciplinary Perspective Used	Word Count	Premise Contributed To
represented through physics, whatever, that we have representations in there and then those parameters are the question marks.[BL1] So you guys maybe are more empirically based and you're trying to, your conceptual knowledge is trying to get put together somehow. We have some fundamental processes we know occur, so we have to figure out whether or not we're missing some.	processes that are represented through physics, whatever, that we have representations in there and then those parameters are the question marks				
	So you guys maybe are more empirically based and you're trying to, you conceptual knowledge is trying to get put together somehow.	Hydrologist	Sociology	22	P4
	We have some fundamental processes we know occur, so we have to figure out whether or not we're missing some.	Hydrologist	Hydrology	20	P3
14:23 78 SOCIOLOGIST [interrupting]: this becomes a really big issue in building human dimensions in, because we're not usually able -- and we're always asked, I was asked just today -- to serve up a sort of direct process relationship. So "if you do this, this is what happens," or "this is how people will behave," because it's like we need to know that to be able to use this in this framework. We understand sort of how water moves in the soil in this really complicated way with all these equations, and now we need to understand if the humans are going to be a part of that process model, how do we write the code to represent [cut off by laughter]	this becomes a really big issue in building human dimensions in, because we're not usually able -- and we're always asked, I was asked just today -- to serve up a sort of direct process relationship. So "if you do this, this is what happens," or "this is how people will behave," because it's like we need to know that to be able to use this in this framework. We understand sort of how water moves in the soil in this really complicated way with all these equations, and now we need to understand if the humans are going to be a part of that process	Sociologist	Sociology	115	P3

Table 2 (cont'd)

Full Speaking Turn	Contribution	Speaker	Disciplinary Perspective Used	Word Count	Premise Contributed To
	model, how do we write the code to represent				
15:00 79 ENGINEER: [overlap] Well you can do it two ways though right? Because you could just, say the hydro-economic stuff that I presented last time was just embedding that, that economic understanding, the empirics of that into that process without really understanding in detail what's driving that behavior, or you can try and, you can try and go with that some more too. [long pause] It seems like though, that as I'm thinking about it, and I'm curious to hear what everyone else's thoughts are on this, is that if you have an empirically based model, that's a method of calibration in a sense.	Well you can do it two ways though right? Because you could just, say the hydro-economic stuff that I presented last time was just embedding that, that economic understanding, the empirics of that into that process without really understanding in detail what's driving that behavior	Engineer	Engineering	45	P3
	or you can try and, you can try and go with that some more too.	Engineer	Engineering	15	P3
	It seems like though, that as I'm thinking about it, and I'm curious to hear what everyone else's thoughts are on this, is that if you have an empirically based model, that's a method of calibration in a sense.	Engineer	Engineering	39	P2
80 HYDROLOGIST: Right.				0	
81 SOCIOLOGIST: I actually calibrated a model just the other day so I could tell you if that's true or not.	I actually calibrated a model just the other day so I could tell you if that's true or not.	Sociologist	Sociology	19	P4
82 HYDROLOGIST: Right.		Hydrologist		0	
[laughter]				0	
83 SOCIOLOGIST: I'd like to sit down when you're calibrating some models, or I'd be willing to take name's class	I'd like to sit down when you're calibrating some models, or I'd be willing to take name's class	Sociologist	Hydrology	18	P3
84 P?: [overlap] mm hmm				0	

Table 2 (cont'd)

Full Speaking Turn	Contribution	Speaker	Disciplinary Perspective Used	Word Count	Premise Contributed To
16:00 85 SOCIOLOGIST: [cont'] so I can tweak some knobs and find out, ok, "now I actually understand what you mean when you say that," um and whether it's really the same or different from what I'm used to doing, training my students to do. When I do just my sociology it's over here, and that's what I do. And when I work on these teams I've not always been able to bring that into the conversation, especially in modeling part.	so I can tweak some knobs and find out, ok, "now I actually understand what you mean when you say that," um and whether it's really the same or different from what I'm used to doing, training my students to do.	Sociologist	Hydrology	41	P3
	When I do just my sociology it's over here, and that's what I do. And when I work on these teams I've not always been able to bring that into the conversation, especially in modeling part.	Sociologist	Sociology	36	P4
86 P?: [overlap] mm hmm				0	
87 SOCIOLOGIST: [cont'] The modeling part is always sort of what you guys are used to doing and I'm trying to figure out, how to insert important things that I understand into that, but it doesn't strike me as the same exercise. Or maybe it's more so the same and I don't understand.	The modeling part is always sort of what you guys are used to doing and I'm trying to figure out, how to insert important things that I understand into that, but it doesn't strike me as the same exercise. Or maybe it's more so the same and I don't understand.	Sociologist	Hydrology	50	P3
88 ENGINEER: I think it could be both. Meaning there's similarities, and there's obviously different contexts, [unclear] so there's the opportunity for difference as well.	I think it could be both. Meaning there's similarities, and there's obviously different contexts, [unclear] so there's the opportunity for difference as well.	Engineer	Engineering	23	P5
89 HYDROLOGIST: But what you described is what you do for a model, you're approach to modeling? I'm just sitting here going, hmmm yep.	But what you described is what you do for a model anyway, you're approach to modeling? I'm just sitting here going, hmmm yep.	Hydrologist	Hydrology	23	P2
90 P?: [overlap] mm hmm				0	

Table 2 (cont'd)

Full Speaking Turn	Contribution	Speaker	Disciplinary Perspective Used	Word Count	Premise Contributed To
91 HYDROLOGIST: [overlap] cont Sounds like what we do. So it's kind of interesting that we can do this and sometimes diverge at the end, at least in terms of understanding each other.	Sounds like what we do.	Hydrologist	Hydrology	5	P2
	So it's kind of interesting that we can do this and sometimes diverge at the end, at least in terms of understanding each other.	Hydrologist	Engineering	24	P5
92 SOCIOLOGIST: We just don't start with any process relationships, those are all to be discovered.	We just don't start with any process relationships, those are all to be discovered.	Sociologist	Sociology	14	P4
93 HYDROLOGIST: [overlap] Right.				0	
94 SOCIOLOGIST: [cont'] And tested, so we don't understand anything at the outset that we can put into that model that says this will always do that or these will be the fixed relationships.	And tested, so we don't understand anything at the outset that we can put into that model that says this will always do that or these will be the fixed relationships.	Sociologist	Sociology	31	P4
95 ENGINEER: [overlap] mm hm.				0	
HYDROLOGIST: Right				0	
96 SOCIOLOGIST: [cont'] We do in fact do that in the sense that we specify a model with a certain structure and it defines how it could work,	We do in fact do that in the sense that we specify a model with a certain structure and it defines how it could work,	Sociologist	Sociology	25	P4
97 P?: [overlap] Right.				0	
98 SOCIOLOGIST: [cont'] but people – some people like me -- obsess about getting specification right,	but people – some people like me -- obsess about getting specification right,	Sociologist	Sociology	13	P4
99 P?: [overlap] Right.				0	
100 SOCIOLOGIST: [cont'] and others don't worry about it – throw a model out there. Move on to the next paper. You know. Who cares if your operationalization was stupid.	and others don't worry about it – throw a model out there. Move on to the next paper. You know. Who cares if you're not operationalization was stupid.	Sociologist	Sociology	28	P4

Table 2 (cont'd)

Full Speaking Turn	Contribution	Speaker	Disciplinary Perspective Used	Word Count	Premise Contributed To
101 P?: [overlap] yeah				0	
17:43 102 SOCIOLOGIST: [cont'] you know whatever, but [unclear]				0	
103 HYDROLOGIST: Hey! So maybe it's just that we all come up with conceptual models similarly, but it's the actual implementation of it?	Hey! So maybe it's just that we all come up with conceptual models similarly, but it's the actual implementation of it?	Hydrologist	Engineering	21	P5
104 SOCIOLOGIST: Seems to be. It's yeah the practice of what we actually do when say we go out and model.	Seems to be. It's yeah the practice of what we actually do when say we go out and model.	Sociologist	Sociology	19	P5

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CHAPTER 4: THINKING WITH KLEIN ABOUT INTEGRATION

co-authored with Michael O'Rourke

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Abstract

Integration is crucial to interdisciplinary and transdisciplinary work and it therefore deserves perennial attention by scholars and practitioners of such work. Few have thought so carefully, deeply, and tenaciously about integration as Julie Thompson Klein. In this article, we recount the development of Klein's thinking on integration, from her early stepwise model in 1990 to her current socio-linguistic model. After summarizing Klein's views, we compare the socio-linguistic model to a more recent view of integration known as the IPO (input-process-output) model. We show how these two models of integration relate to one another, and then we demonstrate their complementarity using an example of integrative argumentation from a Toolbox workshop. We conclude that we can understand instances of cross-disciplinary integration better with both models than with only one or the other. This theoretical stereoscope opens new avenues of research about the types of integrative relations collaborators use, what is involved in social/rhetorical integration, and the extent to which it is feasible to specify all of the parameters in an instance of integration.

Keywords: argumentation, integration theory, interdisciplinarity, Julie Thompson Klein, reasoning

Introduction

All interdisciplinary work will be improved by more self-conscious focus on the process of integration.

(Klein, 2001, p. 54)

There are few topics more near and dear to Julie Thompson Klein and to us than integration. The topic is both a personal and professional preoccupation, shared, we know, by nearly all readers of this journal. Many of us have been thinking with Klein about integration for decades. In this article, we provide a scenic overview of our journey, looking intently at where Klein has been and where we might go henceforth together. We begin by reviewing two models of integration that can be recovered from Klein's work – a stepwise model from Klein (in 1990) and what we call the "socio-linguistic model" from her later work. After presenting a model that we favor, the IPO or input-process-output model, we compare it with Klein's socio-linguistic model. We conclude by discussing an example of integrative argumentation from a Toolbox workshop that demonstrates we can understand instances of cross-disciplinary integration better with both models than with only one or the other.

The Development of Klein's Thinking about Cross-Disciplinary Integration

We begin with two snapshots of Klein's thinking about the concept of *integration*. The first is an early account of integration developed in Klein's 1990 book, *Interdisciplinarity: History, Theory, and Practice.* This early work conducts a wide-ranging survey of the literature then extant on interdisciplinarity. The stepwise model presented in this book represents integration as a roughly linear, algorithmic process, a way of thinking about integration that has had a significant influence on other theorists interested in interdisciplinary process (e.g., Newell, 2001; Repko, 2008). We then describe her more recent view, the "socio-linguistic model," which emerged in subsequent work (e.g., Klein, 2001, 2004a, Klein, 2004b; Bruun, Hukkinen, Huutoniemi, & Klein, 2005) and is most clearly and forcefully articulated in her chapter "Research Integration: A Comparative Knowledge Base" in *Case Studies in Interdisciplinary Research* (Klein, 2012).

The Stepwise Model

We begin our discussion of Klein's view on integration with its early development in *Interdisciplinarity: History, Theory, and Practice* (Klein, 1990). In this seminal book, she provides one of the first systematic accounts of integration in interdisciplinary contexts and the first comprehensive examination of interdisciplinarity and its literature up to that time. Her synoptic take on interdisciplinarity addresses a number of themes that were taken up by others in later work, for example, fragmentation (cf. Bammer, 2013), metaphor (cf. Boix Mansilla, 2010), communication (cf. Thompson, 2009), collaboration (cf. Stokols, Hall, Taylor, & Moser, 2008), and complexity (cf. Newell, 2001; Repko, 2008), to name just a few. Her mastery of the literature and attention to detail support a robust exposition of interdisciplinarity that is historically grounded and international in scope. As she traces themes through the literature, her own view of interdisciplinarity emerges as a function of what she foregrounds and what she backgrounds. Integration figures centrally in her discussions of interdisciplinary activity, and in this section of our article, we reconstruct an account of her thinking in 1990 that will serve as a baseline for understanding her more recent reflections on the topic.

In addition to the fact that the verb "to integrate" and its cognates are used frequently in the book, the preeminence of the noun *integration* in Klein (1990) is underscored by her indication early on that "in general practice" she uses the adjectives "interdisciplinary" and "integrative" "interchangeably" (p. 15). There are moments where she distinguishes the two terms, for example, when allowing that "integration" can be used more broadly to describe features of *multidisciplinary* work, but most of what she writes in the book reflects her views on *interdisciplinary* integration. This emphasis on interdisciplinary integration is reflected in her summary of the book's central argument: "Interdisciplinarity is a means of solving problems and answering questions that cannot be satisfactorily addressed using single methods or approaches" (Klein 1990, p. 196). Whether focused on teaching, research, or practice, interdisciplinary activity is integrative activity, that is,

activity that combines methods and approaches in pursuit of a complex understanding that does justice to the complexity of the phenomena under study.

In the book, when Klein asks "What may be said about a concept that is so vast, so complex, and so various?" (Klein 1990, p. 182), she is speaking of *interdisciplinarity*, but given her "general practice," we believe that her question works equally well for *integration*. The complexity of interdisciplinary integration prompts her to examine it from a variety of different perspectives, for example, historic, conceptual, theoretical, contextual, and practical. In the process, she discusses interdisciplinarians' *ways of speaking* about integration, *ways of thinking* about it, and *ways of acting* in light of it.

Ways of speaking about integration and interdisciplinarity are an important point of emphasis in Klein (1990), and the book includes one chapter on the interdisciplinary lexicon and another on the rhetoric of interdisciplinarity. Her interest in how we speak about these topics is also reflected in numerous other parts of the book, such as discussions of Burke's (1966, pp. 45-46, 49) description of technical vocabulary as a "terministic screen" and dialogue as an integrating mechanism. Klein's consideration of the subject opens with a historical account of the "evolution" of interdisciplinarity (p. 19) as a look back on what people said about integration in the past. The "area" approach to interdisciplinarity that emerged in American universities in the late 1930s, exemplified by women's studies and American studies, supported a conception of *integration* as *unification* that belonged to a "higher and more powerful category than 'interdisciplinarity'" (p. 26). Similarly, earlier theoretical work in education associated *interdisciplinarity* with "linking existing disciplinary categories" and *integration* with the "transmutation" or "unification" of those categories (p. 27). These early distinctions gave way to the conceptual synthesis that supported the "interchangeable" use of these terms.

A second way of speaking about integration that receives attention in Klein (1990) involves the importance of metaphor to our understanding of the concept. "Bridge-building" and

"restructuring" (pp. 27-28) join "fusion" (p. 43), "transmutation" (p. 79), "symbiosis" (p. 80), "borrowing" (p. 85), and many other terms invoking images of different ways things can be brought together. Metaphor is a useful mechanism for making connections across disparate domains; as Lakoff and Johnson (1980) put it, "The essence of metaphor is understanding and experiencing one kind of thing in terms of another" (p. 5). Metaphors are thus "evocative approximations of interdisciplinary cognition" (Boix Mansilla, 2010, p. 289), calling our attention to features of integration that should figure in a more abstract analysis of the concept.

The different *ways of thinking* about integration Klein found in the literature she reviewed for the book help us get beneath the surface of semantics, exposing the structures that justify the similarities expressed by the metaphors. For example, Klein (1990) emphasizes the conceptual connection between *integration* and *differentiation* – to integrate *A* and *B* presupposes that *A* and *B* are differentiated (p. 43), and conversely, "[e]very differentiation postulates the existence of integrated elements" (p. 53). This reinforces the idea that integration involves *putting things together*, which of course entails a starting point where the things in question are not joined or combined. She also recognizes integration as a core process within interdisciplinary activity, calling interdisciplinarity "a process for achieving an integrative synthesis…that usually begins with a problem, question, topic, or issue" (p. 188).

By 1990, analysis of interdisciplinary integration had yielded a variety of distinctions among kinds of integration, and Klein canvasses many of those in the book. For instance, she lists a variety of integrative modalities under four fundamental kinds of interdisciplinary interaction: "(1) borrowing, (2) solving problems, (3) increased consistency of subjects or methods, and (4) the emergence of an interdiscipline" (Klein, 1990, p. 64). These modalities include *concept interdisciplinarity*, under (1), which involves use of a concept from one discipline to supplement a concept in another (p. 64); *border interdisciplinarity*, under (3), which signifies the creation of an intersection between two closely related disciplines (p. 65); and *structural interdisciplinarity*, under

(4), which refers to the formation of the "basic structure" of a new discipline (p. 65). Each of these modalities corresponds to a way of inducing dependencies among different disciplinary inputs to support thinking of them together as one.

A full account of interdisciplinary integration must address how one enacts interdisciplinarity in the world. That is, it must account for the interdisciplinary ways in which educators, researchers, and practitioners operate when pursuing integrative objectives. In discussing integrative techniques, strategies, and frameworks, Klein (1990) provides a rich and nuanced accounting of the practical and conceptual technology that had by then been developed to facilitate integrative activity. Late in the book, she lists 25 integrative techniques for achieving integration, focusing on *iteration* and *role clarification* as two "especially useful" techniques for integrating across disciplines (pp. 189-190). Iteration supports reflective engagement with an ongoing project, where collaborators have the opportunity to take turns being teachers and students, performers and critics. Given such turn-taking, role clarification is crucial as a way of assessing what the collaborators need and expect from one another.

Klein also discusses a number of integrative strategies, which are broader plans of action that constrain decision making about specific steps. These include "devising a set of abstract hypotheses" that can support integration by serving as shared objects of evaluation from different disciplinary points of view (p. 117; cf. the Toolbox approach in O'Rourke & Crowley, 2013), constructing a project "metalanguage" that can be used to coordinate different disciplinary contributions (p. 117), and building a team that includes "system generalists and disciplinary specialists" to iteratively appraise and interpret project data (pp. 190-191).

Another key feature of Klein (1990) is its detailed consideration of several integrative frameworks that provide conceptual structure for thinking and talking about integration, as well as practicing it in particular instances. Some of these are informal (e.g., Sjölander's 1985, 10 developmental stages of an interdisciplinary project, pp. 71-73), others are idealized (e.g.,

deWachter's 1982 model based on the "temporary suspension of all known methods," pp. 192-195), and still others are limited in scope (e.g., the models of integrative organization and communication from Rossini and colleagues, pp. 129-130; the "four major models of integrative education in the health sciences," p. 151).

The more formal, concrete, and generally applicable models of integrative process that Klein discusses include one from Hursh, Hass, and Moore (1983) and one of her own design. Her process specification for integration includes these 12 steps:

> 1a. defining the problem (question, topic, issue);
>
> b. determining all knowledge needs, including appropriate disciplinary representatives and consultants, as well as relevant models, traditions, and literatures;
>
> c. developing an integrative framework and appropriate questions to be investigated;
>
> 2a. specifying particular studies to be undertaken;
>
> b. engaging in "role negotiation" (in teamwork);
>
> c. gathering all current knowledge and searching for new information;
>
> d. resolving disciplinary conflicts by working toward a common vocabulary (and focusing on reciprocal learning in teamwork);
>
> e. building and maintaining communication through integrative techniques;
>
> 3a. collating all contributions and evaluating their adequacy, relevancy, and adaptability;
>
> b. integrating the individual pieces to determine a pattern of mutual relatedness and relevancy;
>
> c. confirming or disconfirming the proposed solution [to the problem defined at the start]; and
>
> d. deciding about future management or disposition of the task/project/patient/curriculum. (Klein, 1990, pp. 188-189)

This is a stepwise framework for pursuing integrative responses to problems or questions that require them, where integration is understood primarily as a process. As such, the framework outlines a progression from the earliest stages in which the problem or question is defined to the late stages in which the response is confirmed or disconfirmed. In introducing this framework, Klein (1990) acknowledges that there is "no absolute linear progression" to integration (p. 188),

which is consistent with her contention that iteration is an important integrative technique. Nevertheless, she defends a model of integration as a process that can be pursued in an algorithmic and orderly fashion.

It is worth lingering for a moment over these steps. Klein organizes them in an order that breaks down into three stages: an *orientation* stage that focuses on understanding the problem or question, a *preliminary* stage that involves preparing both knowledge and social resources for the business of integration, and an *execution* stage during which the integration itself is effected. Not all of the steps are obviously integrative. Some are – 1c, 2b, 2d, 2e, and of course 3b – but the rest focus on meeting the material or structural preconditions that must be in place before integration can be pursued.

Of the integrative steps, the first four (i.e., 1c, 2b, 2d, and 2e) focus on creating the epistemic, social, and communicative infrastructure conducive to integrative success. Step 3b is really where the action is – that is where the integrative response is generated. Although the specification of 3b largely presents integration as a black box, it does give us an important clue about one condition necessary for the success of integration, namely, that there is "mutual relatedness and relevancy" among the inputs to the integrative process. That is, the process of integration makes process inputs depend on one another, with the integrated result being an assembly of mutually related and mutually relevant parts.

The Socio-Linguistic Model

As Klein developed her views, she recognized that her original attempt to describe integration in 1990 was too linear to model the cases of integration she had observed in the earlier history of interdisciplinary work and was observing in her own day. Her 1996 book, *Crossing Boundaries: Knowledge, Disciplinarities, and Interdisciplinarities*, blended her previous, stepwise model of integration with an iterative, dialogic understanding of integration (p. 223). By 2001,

when Newell used her 1990 model as one starting point in his own theorizing (Newell 2001), Klein (2001) responded thus:

> Some time ago, I moved beyond this [1990] description….*The new model is a socio-linguistic conceptualization of managing complex problems*….The earlier descriptive steps reappear, but they are extended and recontextualized in an iterative model of communicative action in the dynamics of data, information, knowledge, intuition and insight, judgment, retrospection, and decision making. In a subsequent proposal for a generic model of integrative process, I retained the fundamental dialogical coexistence of differentiation and unity (Klein, 1996, pp. 222-224; 1990-1991). (p.53, emphasis added)

Klein has continued developing this socio-linguistic model ever since, working to place interdisciplinary integration in its contexts. Together, her writings reveal a coherent view of integration as involving instances of socio-linguistic practice subject only to guiding principles, never mechanistic rules. Figure 4 illustrates how this view hangs together as successively more specific (narrower) theories, and the next sections of this article describe the relationships between the levels.

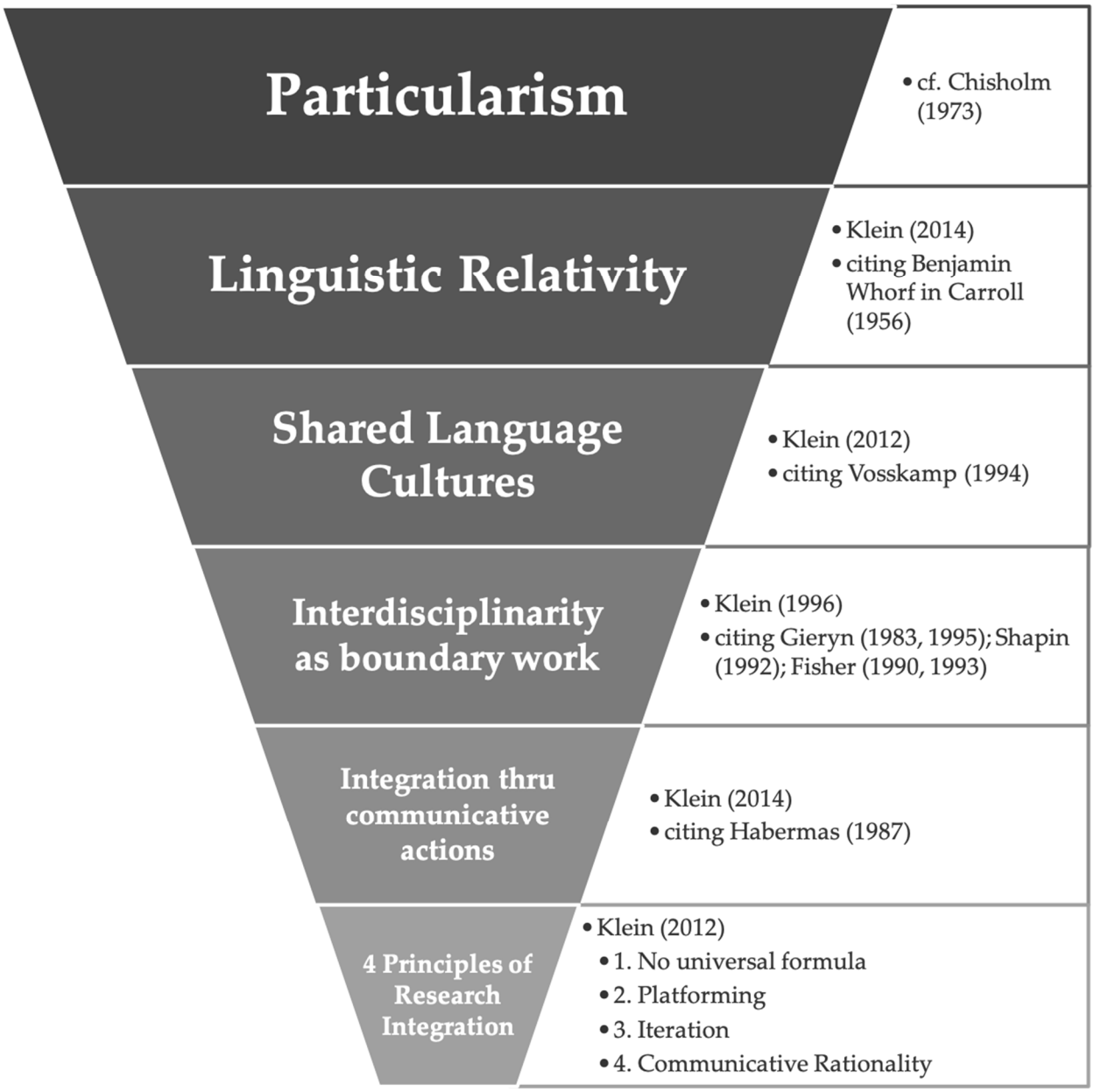

Figure 4: Klein's layered approach to understanding cross-disciplinary integration as a socio-linguistic phenomenon. Her approach proceeds from a more encompassing epistemology of particularism to a narrower theory of research integration. The citations for each level document the provenance of Klein's ideas as she cited them.

Particularism

Although she does not explicitly say so, Klein's fundamental approach to understanding integration is to study particular instances of it and then infer general principles from them. This bottom-up approach to defining a phenomenon, known as *particularism* (Chisholm, 1973), places more confidence in one's ability to recognize integration when one sees it than in defining it

without exemplars. This approach is why much of Klein's work involves intellectual history rather than, say, set theory. These recountings are not merely interesting; they are, in fact, the source of her insights.

Linguistic Relativity

From her observations, Klein – as a trained rhetorician and literature scholar – notices the importance of language in interdisciplinary practice. She finds this observation summarized profoundly in the concept of linguistic relativity. In Klein (2014), she explains,

> The concept of linguistic relativity is central to understanding interdisciplinary communication…. The core premise is that language shapes the ways speakers conceptualize their worldviews, including the ways they think (cognition) and act (behavior). (p.15)

Linguistic relativity is an organizing concept that allows Klein to understand disciplines further as shared language cultures, not just worldviews or communities of practice.

Shared Language Cultures

If language shapes worldviews, and if worldviews go on to influence thoughts and actions, and if thoughts and actions are central parts of culture, then language is a key driver of a group's culture. It is, in addition, a key constituent of culture in its own right. In the language-as-culture view, disciplines are shared language cultures insofar as members understand each other through language. In fact, Klein (2012) claims, "The quality of [interdisciplinary] outcomes…cannot be separated from development and richness of a shared language culture" (p. 295). When people share a language culture, they can coordinate their insights and actions. This coordination enforces borders around the group that make interdisciplinary integration a matter of crossing the boundaries of disciplinary language cultures.

Interdisciplinarity as Boundary Work

Klein dedicated her entire 1996 book, *Crossing Boundaries: Knowledge, Disciplinarities, and Interdisciplinarities,* to explaining interdisciplinarity as boundary work. This article is too short to

recount, indeed, even outline, all the insights the book contains, but we can summarize an important lesson thus: Just as there are many ways to interact across ethnic cultures, there are many ways to interact across disciplinary cultures, and all of these require language in some way. Direct communication typically requires language, and so does coordinated action, such as deciding whom to ask for permission to use a lab's data by understanding what those researchers mean by terms like "principle investigator" and "data manager."

Integration through Communicative Actions

Because interdisciplinary work is intercultural language work, interdisciplinarity is a form of communicative action. In developing this thought, Klein draws on the work of Jürgen Habermas, who emphasizes that communication is neither rational nor productive when people do not share a language culture (Habermas, 1985, pp. 9-17, 86, 94-101). Habermas asserts that rational, productive communication must be "transsubjective" (Habermas, 1985, p. 9) or, alternatively, "intersubjective." Simply put, for integration to occur, people need to understand each other. Integration, in this view, consists of the many "trades" or communicative transactions in the trading zones (Galison, 1997) between disciplines. Because each disciplinary culture and each meeting of these cultures is different, the socio-linguistic model of integration, influenced by Klein's reading of Habermas, remains a high-level heuristic of interdisciplinary integration, and it emphasizes the actions of knowers rather than the products of knowledge they create. This cultural view of integration depends so much upon situation-specific interactions that it thwarts attempts to align it with Klein's 1990 stepwise model – even though that model was meant to be iterative and situation-specific. Instead of inviting a stepwise summary, Klein's more recent socio-linguistic model is best summarized as involving principles that act "more like guidelines than actual rules."[27]

[27] To echo Blackbeard the Pirate, another famous thinker who operated at cultural boundaries (Bruckheimer & Verbinski, 2003).

The Four Principles of Research Integration

Klein (2012) summarizes the general characteristics of her socio-linguistic view of integration with the help of the following four principles:

1. "The Principle of Variance: No Universal Formula for Integration." (p. 293)
2. "The Principle of Platforming: Interaction Structure, Integration Potential, Fundament." (p. 294)
3. "The Principle of Iteration: Moving Back and Forth, Bootstrapping, Triangulation, Reflective Balance, and Weaving." (pp. 294-295)
4. "The Principle of Communicative Rationality: Shared Language Culture, Social Learning, Translation-Negotiation-Mediation, Intersubjectivity." (p. 295)

Each principle derives from Klein's approach to interdisciplinary integration as illustrated in Figure 1 – from her particularism (Principle 1: Variance), to her view of integration as language cultures meeting in trading zones (Principle 2: Platforming), to her recognition of the messiness of intercultural boundary work (Principle 3: Iteration), to her commitment to intersubjectivity (Principle 4: Communicative Rationality). In what remains of this section of our article, we consider each of these principles in turn.

The Principle of Variance. Klein develops the Principle of Variance by observing that cross-disciplinary research projects vary along many dimensions, including context, focus, goals, participants, and scope. This variance implies that no universal formula of integration can account for all of the variables that figure into interdisciplinary and transdisciplinary research, and since such an accounting would be required of such a formula, no universal formula for integration can exist. We wonder, however, what she means when she denies the existence of a universal formula: Does she mean to deny possibility or just feasibility? The stronger version of the Principle of Variance would hold there is no *possible* universal formula for cross-disciplinary integration. A weaker version of this principle might be that there is no one *workable* or *tractable* formula, that is, no single formula that we could realistically and practically use to guide deliberation and action across the full range of interdisciplinary and transdisciplinary research projects. As we argue

below, whether or not you agree with this principle may depend on the level at which you are conceiving of integration. We will argue below that there is a universal formula if you are conceiving of it at a very high, abstract level, but that this is not the case if you are conceiving of it at a lower, more concrete level.

The Principle of Platforming. This principle highlights the importance of "a set of actions aimed at building a foundation for integration"; for collaborative projects, this means "putting into place the antecedent conditions and contextual factors" required for epistemic and social integration (Klein, 2012, p. 294). Klein develops this principle by highlighting the structure of a project, both in terms of its timeline and its parts, including subprojects. This structure supports interaction among the parts of a project, including the people involved, as well.

This principle focuses on *project structure*, which we can take to be a systematic set of relationships among project elements. Within an interdisciplinary or transdisciplinary project, each element should be understood partly in terms of its "integration potential" (Klein, 2012, p. 294), that is, its ability to contribute to the integration required for project success. Klein distinguishes those elements that are essentially integrative, for example, *bridge concepts* and *common foci*, from other elements (e.g., research questions, methods, disciplines represented) that may have more or less integrative potential, depending on the specific project context. Further, she introduces the notion of *interaction structure* to highlight that part of project structure that frames the contact among the different elements and creates the possibility of integration.

One important message entailed by this principle is that social and epistemic integration can happen at any time and any place in a project. That is, almost any location in a complex, cross-disciplinary project can be a site for integration. This widespread potential should not be surprising in light of the Principle of Variance. After all, if integration is sensitive to the great variability of interdisciplinary and transdisciplinary projects, this variability should include the various times and places integration might occur in a project.

The Principle of Iteration. The third principle emphasizes that the process of integration is not an uninterrupted, linear progression from unintegrated to integrated; rather, it can unfold in complex ways from more integrated to less integrated and back, or from interdisciplinary whole to disciplinary part and back. As Klein (2012) puts it, "These movements emphasize the importance of patterning and testing throughout the research process" (p. 295). Such "patterning" and "testing" are iterative reconsiderations that should track changes in understanding, objectives, and circumstances. This principle highlights the dynamic complexity of integration when it is a process platformed by certain elements in the project structure that vary along many dimensions. Following her own earlier work and that of Boix Mansilla (2010), Klein emphasizes *balance* in connection with this principle. That is, iteration keeps the many elements of the project in productive and not destructive tension.

The Principle of Communicative Rationality. The fourth principle articulates the importance of communication to integrative outcomes, especially when those are pursued by groups of collaborators. Klein (2012) illuminates how epistemic and social integration interact as collaborators communicate in moving toward intersubjectivity or "making sense together" (p. 295). Integrative communication requires "mediation" among different perspectives (p. 296). Mediating communication supports both reflexivity and perspective taking, creating the capacity for collaborators to achieve mutual understanding. Such communication encourages the progressive sharing of "meanings, diagnoses, and objectives" (p. 296), and this progressive sharing is what creates intersubjectivity. Misunderstanding is always a risk in interdisciplinary contexts, but this can be mitigated by the creation and maintenance of a shared language culture that makes interdisciplinary dialogue possible. Although this principle acknowledges the roles of both epistemic and social elements in interdisciplinary integration, it foregrounds the social elements and reminds us how central communication is to integration.

In summary, the four principles bring out various aspects of integration as a process, highlighting among other things inputs (e.g., mediating communication) and outputs (e.g., mutual understanding) of the process. "The process," Klein (2012) tells us, "is not algorithmic. It is heuristic and constructivist at heart" (p. 296). The principles are also interrelated. For example, one might take the Principle of Variance to highlight the elements that figure into a specification of the process, the Principles of Platforming and Iteration the structural and functional aspects of the process, and the Principle of Communicative Rationality the role that people play in generating integrative outcomes.

The IPO Model of Cross-Disciplinary Integration

If we as authors are to think with Klein about integration, it will help to be clear about our own way of thinking, which is the view of interdisciplinary integration developed in O'Rourke, Crowley, and Gonnerman (2016). This is an input-process-output (IPO) model that highlights the importance of integration as a *process* while still making room for understanding it as a *product* (i.e., as the *output* of the integrative process). In this section of our article we articulate this view, a view that has been influenced by Klein's work, especially Klein (1990) and Klein (2012). We describe the view in some detail here for purposes of comparing it with Klein's views, drawing out ways in which her ideas align with the IPO model and also ways in which the IPO model contrasts with her ideas.

O'Rourke et al. (2016) provide a theoretical account of what the authors call "cross-disciplinary integration," which is integration as it appears in the full range of complex activities that involve combination of disciplinary elements, e.g., multidisciplinarity, interdisciplinarity, and transdisciplinarity. To account for cross-disciplinary integration, they develop a model of integration in general. As they understand it, *integration* is a process that produces outputs that are typically different from and fewer in number than the inputs, where this reduction is a result of the process. This reduction is of course to be expected given that they take integration to be the

combination of elements into a whole (p. 67). Further, the processing involved typically puts the input elements into mutual dependence (cf. Andersen & Wagenknecht, 2013), where the contribution of a particular input to the output will depend in some (potentially complex) way upon its relationship with other inputs. (This typical impact of the process on the inputs rules out, by the way, the possibility of deleting one of the inputs as a means to integration.)

Three considerations serve as the basis for this account of integration. The first is the observation that people speak of "integration" in many different contexts even beyond cross-disciplinarity, such as art, politics, psychology, biology, and philosophy. Although in many of these contexts the term has a technical gloss, there is a core meaning that is part of common parlance. One aim of the IPO account of integration in O'Rourke et al. (2016) is to provide a *general* model of these different occurrences of the term and its cognates, subsuming them all under an abstract characterization of the concept. According to this approach, interdisciplinary integration is an instance, itself general, of a more general and widely-found process, where the specific properties of this instance are tied to the social and epistemic attributes of interdisciplinary activity. One important virtue of the general theoretical approach is that it supports the systematic transfer of insights about integration from one integrative context to another.

A conceptual model of the sort presented by O'Rourke and his colleagues (2016) could function simply to characterize logical connections at a general level, but the IPO model of integration is also intended to be specifiable so that it represents concrete integrative processes in specific contexts. As such, the IPO model is *schematic*, with abstract elements that are to be specified concretely when the model is applied in particular situations. These include the categories of *inputs*, *integrative relations,* and *outputs,* and parameters such as *commensurability, scale,* and *comprehensiveness*. In any particular instance, such as in a case of interdisciplinary integration, these categories and parameters will be specified in a way that renders the model more concrete.

This rendering will involve quantitative aspects (e.g., the *number* of inputs) and qualitative aspects (e.g., the *types* of inputs).

The third consideration underlying the thinking of O'Rourke et al. (2016) concerns the role played by *integrative relations* in the model. Consistent with the idea that integration involves *combining* inputs into outputs, the IPO model of integration gives privilege of place to what it calls "integrative relations." So conceived, this can be understood as a *relational* model of integration, where the work of explaining integration involves identifying the characteristic features of integrative relations. Thus, the relational model aims to work out the details of step 3b in the Klein (1990) model, shining light on the contents of the previously mentioned black box.

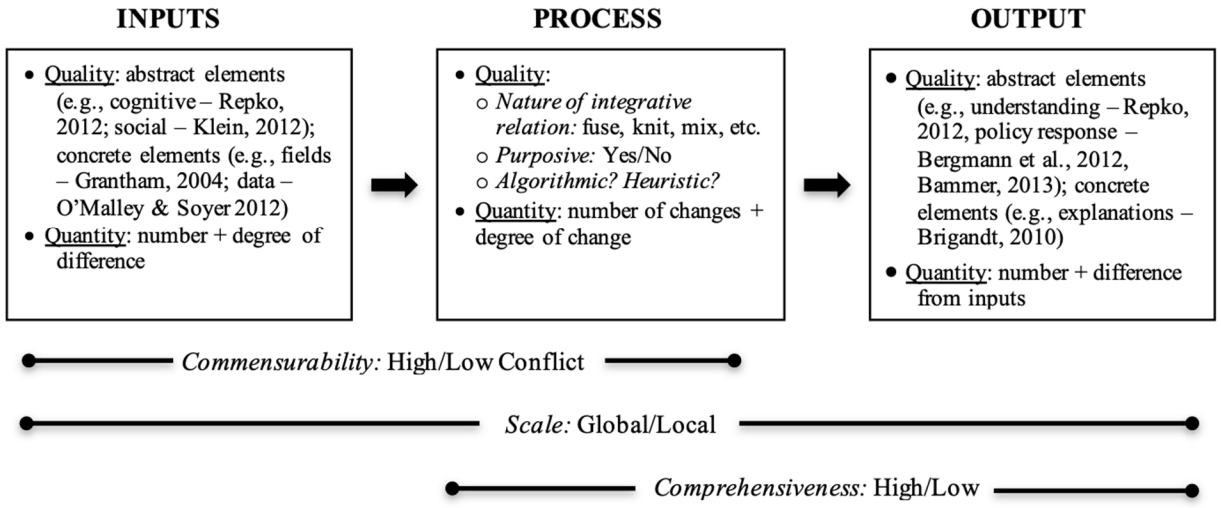

Figure 5: The specifiable but universal input-process-output (IPO) model of integration developed in O'Rourke et al. (2016) and pictured there on p. 69. The quality/quantity distinction classifies salient characteristics of inputs, processes, and outputs involved in episodes of integration. Reprinted from Studies in the History and Philosophy of Science Part C: Biological and Biomedical Sciences*, 56, Michael O'Rourke, Stephen Crowley, & Chad Gonnerman, On the nature of cross-disciplinary integration: A philosophical framework, Page 69, Copyright (2016), with permission from Elsevier.*

The IPO model of integration is summarized in Figure 5, reprinted from O'Rourke et al. (2016). As noted above, it is an abstract, schematic model of integration that is intended to be rendered concrete through the specification of the variables that are built into the model. Using an IPO schema to model interdisciplinary integration requires identifying the inputs (e.g., a complex research question referencing multiple disciplines, researchers representing different disciplines if

the project is collaborative), processes (e.g., collaboration, modeling), and outputs (e.g., published article with multiple authors, policy advice) that are relevant to the instance of integration under consideration.

The model is intended to represent integrative processes at different scales, and so in the interdisciplinary case it could represent integration that takes place over the lifecycle of a project as well as integration that takes place in a brief episode in which collaborators from different disciplines find a way to relate their alternative perspectives on a specific problem. The same model can be made to work at such different levels by specification of the values of the *scale* parameter – are we interested in integration at the more global, project-level scale or the more local, sense-making scale? The other parameters mentioned in Figure 2 also influence the nature of the integrative process: The *commensurability* parameter is set by the degree of difference that obtains between inputs (e.g., low conflict between biochemistry and microbiology, high conflict between civil engineering and theater art), while the *comprehensibility* parameter corresponds to the extent to which the inputs are recoverable from the output (e.g., high comprehensiveness if input identity is lost in the integrative process, and low if input identity is retained).

The real action in this model takes place in the process box and involves the *integrative relations*. The integrating process puts inputs into these relations, thereby integrating them in generating the output. Not all relations are integrative. We can distinguish *integrative* relations from those that actively differentiate inputs—call these *disintegrative* relations—and those that leave inputs alone—call these *preservative* relations. Integrative relations change inputs by inducing dependencies among them, producing outputs that will typically (but not always) be fewer in number than the inputs. Disintegrative relations relate two things in a way that undermines existing dependencies, generating outputs that will typically be greater in number than the inputs. Preservative relations relate two things without changing them or inducing any dependencies that can reduce their number under the aspect of the output. Examples of integrative relations include

blending (Nissani, 1995), extension (Newell, 2006), collaboration (Plutynski, 2013), and coupling (MacLeod & Nagatsu, 2016).

The IPO model of integration resembles other models that are available in the literature, for example, the idealized model of interdisciplinarity presented by deWachter (1982) and discussed in Klein (1990), and the model that is central to information integration theory, presented in detail in Anderson (1981).[28] Our interest in this article, though, is with the relationships between this model and Klein's views. While we will devote the next section to considering the relationship between the IPO model and the view developed in Klein (2012), we will close this section by considering its relationship with Klein (1990).

The stepwise model in Klein (1990) focuses on how one might engage in integrative activity from the initial phases to the final phase, providing people with guidance as they engage in interdisciplinary integration. In that sense, it is a *normative* model – it supplies a standard set of steps that, if executed, should result in integrative success. The IPO model, though, is descriptive, and is less focused on the full arc of an integrative activity than it is on the integrative episodes within that activity. Recall that the stepwise model in Klein (1990) includes a number of steps meant to ensure the preconditions for integration and the infrastructure necessary for integrative activity. The IPO model, by contrast, focuses on the moment when the inputs are brought together into integrated combination – the *process* box is the key location of this model. It seeks to show schematically (and, when specified, concretely and in detail) what must take place for integrative combination to occur.

[28] DeWachter's (1982) model sets up interdisciplinarity as an IPO, with the process of integration black-boxed in the fifth stage, where in response to a global, interdisciplinary question, one "integrates all particular answers available" (p. 280). Anderson's (1981) account is more formal, detailed, and general. Information integration theory concerns how people combine information in making judgments, and Anderson's model of this type of integration is also an IPO model, with an emphasis on functional integration. Information integration theory depends on algebraic models, including "additive, averaging, and subtractive models" (Anderson, 1970, p. 156). In emphasizing relations, the IPO model in O'Rourke et al. (2016) is quite similar to Anderson's, but it is not limited to algebraic integration functions. This is not the place to develop a robust comparison of these two views, however.

Comparing the IPO and Socio-Linguistic Models

In this section, we compare the IPO model of integration developed in O'Rourke et al. (2016) and the socio-linguistic model of Klein, represented in summary by the four principles that conclude Klein (2012), discussed above. The IPO model is similar in a number of ways to the view that emerges from Klein (2012), in that both emphasize integration as a process that varies according to inputs, process characteristics, and outputs. In fact, Klein's socio-linguistic model served as an important influence on O'Rourke et al. (2016), as is explicitly acknowledged therein. Here we dive deeper into the similarities and differences among the two models so we can then show how they complement each other. (See Table 3 at the end of this section for a summary.)

In considering similarities and differences, we take Klein's four principles to be our guides. We begin with the Principle of Variance. One of the main motivations behind the IPO model in O'Rourke et al. (2016) is the variability of integrative processes, which range across a wide variety of phenomena and not just interdisciplinary or transdisciplinary activity. O'Rourke and his colleagues emphasize integration as a means to accommodate the manifold variability that Klein notes under this principle. The IPO model is intended to be universal in the sense that it applies across all contexts where one might find integration, although it is schematic and must be loaded contextually to model any specific instance. So, in a sense, O'Rourke and his colleagues both disagree and agree with Klein – there is a level of abstraction at which one can find a formula that subsumes all instances of integration, but also there is no maximally specific formula that applies to all particular instances of integration.

Klein's Principle of Platforming emphasizes the importance of thinking about integration at all points in an interdisciplinary or transdisciplinary project. The IPO model can represent integrative processes at various levels and temporal locations in interdisciplinary research. As those pursuing a project adjust the inputs involved, the various integrative relations that are a central part of the integrative process, and the scale parameter, which can be set globally or more

locally, contextually loaded instances of the model can represent high-level integration (e.g., integration that results in the production of a new field, cf. Bechtel, 1993) or lower-level integration (e.g., at the level of data, cf. Leonelli, 2013).

The contextual flexibility of the IPO model also enables it to do justice to Klein's Principle of Iteration. There is nothing that keeps the IPO model from being instantiated in specific contexts that are brief and local, and there is no reason why it cannot be used in sequence to model a series of integrative episodes. Again, adjustments of variables and parameters make it possible to capture the iterative nature of project integration designed to strike a balance among different project elements.

Finally, the IPO model can be used to represent the processes of making sense together and building intersubjectivity and mutual understanding through both instrumental and relational communication (Hall & O'Rourke, 2014). These are social processes that involve epistemic elements in a central role, but the IPO model is designed to accommodate both epistemic and social integration, among other forms. Klein's development of the Principle of Communicative Rationality highlights the importance of a "shared language culture" to the mediation of information and relationships required to achieve integrative objectives in interdisciplinary and transdisciplinary projects. As introduced in O'Rourke et al. (2016), the IPO model would have difficulty representing this; however, there was no suggestion that the three parameters introduced in 2016 are the only relevant parameters. For instance, in accordance with Klein's argument concerning shared language cultures, the IPO model could include something like a *medium* parameter that concerns the medium in which communication takes place during collaborative instances of the use of the IPO model.

In sum, Klein's four principles either articulate aspects of integration that are important to the IPO model in O'Rourke et al. (2016) or phenomena that are critical to its implementation in a particular project. In our view, the IPO model and the socio-linguistic model are interrelated: On the

one hand, something like the IPO model is presupposed by Klein's principles; on the other, Klein's principles and the socio-linguistic model they articulate are crucial to specifying the IPO model when it is used to describe cross-disciplinary integration. We exemplify this interdependence in the next section of this article by using both models to analyze a key form of cross-disciplinary integration – collaborative, interdisciplinary reasoning (Laursen, 2018a).

Table 3: A summary of the relationships between Klein (2012)'s four principles of integration and the input-process-output (IPO) model of O'Rourke et al. (2016).

Principle	**Socio-Linguistic Model**	**IPO Model**
1. Variance	Particularism shows every trading zone between language cultures requires different boundary work.	There is a universal IPO formula at a high level of abstraction, but no universal formula at the level of particular instances of integration.
2. Platforming	We need to be prepared to create these trading zones at any stage or level of an interdisciplinary project.	The IPO model can apply to integration at any stage or level in an interdisciplinary project.
3. Iteration	The boundary work required for interdisciplinary balance is not typically one-and-done, but is rather iterative and complex.	The IPO model can represent iterations and the complex ways in which integration manifests in interdisciplinary projects.
4. Communicative Rationality	Shared understanding through language is necessary.	Communicative integration can be represented by the IPO model, although it may need a new parameter to reflect shared language culture.

Integrating the Models of Integration: A Worked Example

The IPO model aims to characterize integration in general, while Klein's socio-linguistic model describes cross-disciplinary integration. As described above, Klein's model presupposes something like the IPO model, and the two models are therefore compatible. In this section, we argue by example that the models are more than compatible – they are complementary. As such, they are more useful together than apart in describing instances of cross-disciplinary integration.

Our example is a thread of collaborative, interdisciplinary reasoning excerpted from a Toolbox workshop transcript (cf. O'Rourke & Crowley, 2013). The Toolbox Dialogue Initiative hosts dialogue-based workshops for cross-disciplinary and cross-functional teams.[29] These dialogues are semi-structured by prompts that articulate assumptions that researchers and professionals usually leave implicit in their work but that would likely derail their team if left implicit because not everyone on the team holds those assumptions. The prompts invite each participant to respond on a Likert scale of "Strongly Disagree" to "Strongly Agree"; "Neither agree nor disagree," "I don't know," and "N/A" are also options. However, the prompts are worded with vague and sometimes extreme language that requires participants to define their terms or express qualifications in order to respond. These definitions and qualifications reveal hidden assumptions, making them available for discussion. Participants respond to all of the prompts first in writing on their own. Then, participants discuss their responses, and usually participants are invited to re-take the instrument to see if their views have changed.

We draw on Laursen (2018a) to show how instances of collaborative, interdisciplinary reasoning such as the Toolbox workshop below can be characterized as argumentation. This example will show that argumentation is one of the socio-linguistic routes to cross-disciplinary integration, and that it and similar routes stand to benefit from a dual application of the IPO and socio-linguistic models. This example also shows how the fields of argumentation and interdisciplinarity enlighten each other, as proposed in Laursen (2018b), published in this journal last year.

Example

In this example, a cross-disciplinary research group is mid-way through their 90-minute dialogue session. They've discussed several prompts already. Now they are discussing two prompts

[29] http://tdi.msu.edu

about reductionism vs. emergentism. First, they discuss Prompt 30: "The world under investigation is fully explicable as the assembly of its constituent parts." Participants 1 and 3 (P1 and P3) disagree with this statement, but P2 doesn't know because they can see it both ways:

Speaking Turn	**Utterance**
203	P2: I didn't know. I think when you talk about an assembly of things, yes they are constituent parts but they're assembled and so they're still connected. Sometimes you have to reduce it into smaller systems so you can comprehend and make quantitative answers and then you're always looking at, well I guess I never see it as one of these systems is totally independent from all of its connected parts. So this huge system and everything that we're looking at can always be taken into more systems or more parts and is always connected to other things.

The group then turns to the next prompt, Prompt 31, which reads, "The world under investigation must be explained in terms of the emergent properties arising from the interactions of its individual components." After reporting their agree/disagree scores to each other, Participants 1 and 2 (P1 and P2) discover they both agree.

Speaking Turn	**Utterance**
210	P1/P3: Woah! [laughter]
211	P1: We haven't agreed this whole time! I strongly agreed with that statement and I think it's my training and my background honestly that encourage me to say that because for example I remember from my introductory ecology class I took in college, the first day it was like the quote up on the PowerPoint slide was "the sum is more than all the parts" or whatever that statement is that says that essentially.
212	P2: I see how this is supposed to be kind of a converse of the previous statement but I interpreted it somewhat the same in terms of if you can't always understand the individual components it's kind of hard to explain the interactions as well but yeah I probably went a little farther than I would on [my own] on that one. I was thinking "fully" explained I guess, but that word wasn't in this one.
213	P3: Yeah I think to look at anything you have to simplify it somehow in your head so that you can understand it and then from the simplifications you then bring them back together.

Speaking Turn	Utterance
214	P1: And things arise that you probably wouldn't have seen just by looking at the individual components. And that's how I interpret emergent properties anyways.

In some respects, Prompts 30 and 31 are opposite and one would expect a participant who agrees with one to disagree with the other. However, P2 doesn't; while they are uncertain about reductionism they agree with emergentism. If we just looked at the scores, we might think P2 isn't reading the prompts carefully or lacks introspection skills. But the transcript tells a different story, showing that P2 holds a nuanced view that integrates aspects of both reductionism and emergentism, and this was hard to represent through responses to the prompts as written.

In the discussion, P2 explains how emergent explanations depend on identifying the parts in order to track the interactions between those parts. P2 indicates that they interpret Prompts 30 and 31 as "somewhat the same," which signals emphasis on the role played in both by the need to "understand the individual components" and on the fact that both prompts require the individual components to be related to one another – *assembled* in Prompt 30 and *interacting* in Prompt 31. Another way to look at this, articulated in ST 203 and reflected in ST 212, is that when it comes to complex systems, one needs to be willing to look at smaller and smaller parts in order to understand the whole, where this involves individual components at bottom. The difference in P2's reaction – scoring a "Don't know" to 30 and a "Strongly Agree" to 31 – is explained by the appearance of the word "fully" in 30 but not in 31. Collaborative reasoning with P2 moves P1 and P3 to acknowledge that it *is* important to pay attention to the parts of the world under investigation, including the individual components, even if one is a staunch emergentist.

It is clear this discussion thread contains some argumentation because claims and reasons are being exchanged, evaluated, and modified. In fact, the participants are eventually willing to entertain the nuanced position – championed by P2 – that reductionism and emergentism are not

so obviously contradictory. The claimed similarity between the views is even clearer if we schematize the argument that emerges from P2's comments in standard form.

> *Premise 1.* According to reductionism, if one doesn't understand the parts of complex systems (e.g., subsystems, individual components), then one cannot explain assemblies of those parts. (ST 203)
>
> *Premise 2.* According to emergentism, if one doesn't understand the parts of complex systems, one cannot explain interactions of those parts. (ST 212)
>
> *Premise 3.* According to reductionism, if one explains the parts of a complex system in relation to one another, then one explains assemblies of parts. (Implicit)
>
> *Premise 4.* According to emergentism, if one explains the parts of a complex system in relation to one another, then one explains interactions of parts. (Implicit)
>
> *5.* According to both reductionism and emergentism, if one explains the parts of complex systems in relation to one another, then one must understand the parts. (From P1, P2, P3, P4)
>
> *Premise 6.* If one fully explains a complex system, then one explains the parts of the complex system in relation to one another. (Implicit)
>
> ---
>
> *Conclusion*. Reductionism and emergentism both require an understanding of the parts to explain a complex system. (5, P6)

Thus, P2 has integrated reductionism and emergentism by asserting that they share a commitment to understanding the parts of complex systems. Now we will show that if we analyze this integration episode with both Klein's socio-linguistic model and the IPO model, we can more fully explain the integration happening here than if we rely solely upon one model or the other.

Analysis of the Example with Both Models

With regard to Klein's model, the following things are important to note here. First, this is not the only way to synthesize reductionism and emergentism. According to Principle 1: Variance, we ought not to expect this team to synthesize other inputs in this way in other episodes. In fact, this same team might synthesize the same theories in a different way later in their project or even in this workshop itself. In addition, we should not expect other teams to synthesize these two explanatory theories in just this way either. Second, this synthesis relies upon a foundation laid by

the structure of the Toolbox prompts themselves, which have asked participants to discuss their views on reductionism and emergentism. According to Principle 2: Platforming, "common foci" such as these prompts are a "fundament" or "interaction structure" for integration, enabling collaborators to focus on the same[30] research object to begin integrating their insights about it. Third, this conversation highlights the "patterning and testing" that are crucial to Principle 3: Iteration. In this part of the dialogue, P2 stands out as someone with a different opinion, testing alternative ways of thinking about Prompts 30 and 31. By ST 214, the initial disagreement and difference among the collaborators give way to a kind of balance (cf. Boix Mansilla, 2010). Fourth, integration requires a language culture that is shared to some extent, and integration, in turn, enhances this shared language culture. In this case, the prompts have provided shared language, and the collaborators work through the episode to coordinate their understanding of these prompts and come around to a shared way of thinking about them. According to Principle 4: Communicative Rationality, integration both requires and builds a shared language culture because this is what enables collaborators to understand, evaluate, and respond to each others' proposals.

If we are to use the IPO model to explain the integration here, we must identify the inputs and outputs of this integrative episode, as well as the integrative relation(s) used to transform the inputs into the outputs. If we focus on the content of the dialogue, that is, the *argument*, as opposed to the arguers, then the standard form helps us locate inputs and outputs; specifically, the inputs consist of the premises and the integrated outputs are the conclusions (i.e., intermediate step 5 and final Conclusion). The argument establishes that reductionism and emergentism share an interest in the same thing: the parts of a complex system. In effect, then, the integration here is subsumption of two ostensibly inconsistent theoretical views under a single category (viz., theories interested in

[30] Here, "same" does not mean everyone must understand the research object the same way. In fact, if they did, this would be the opposite of a platform for integration as there would be nothing to integrate – only sameness. Rather, "same" means "shared" as with a boundary object or bridging concept (Klein, 2012).

parts of complex systems). This subsumption under a common category explains why P2 believes that Prompt 30 and Prompt 31 are "somewhat the same" (ST 212).

From a rhetorical view, looking now at the *arguers*, we can take the inputs to be the social elements that are introduced into this exchange, such as the collaborators themselves, and take the outputs to include acknowledgement on the part of P1 and P3 that there is something to P2's complex view. The processes that transform these rhetorical inputs to outputs include social processes (e.g., trust-building through mutual enjoyment and use of the first-person pronoun, empathizing, acknowledgment) and cognitive processes (e.g., perspective-taking, explanation, illustration, collaborative reasoning). The integrative relations key to these processes from a social perspective could include recognition, greater trust, and enhanced team cohesion. In both the argument case and the arguer case, the IPO model also asks us to be explicit about the commensurability of the inputs (high), scale of the integration (local), and comprehensiveness of the entire episode (low, in the sense that we can recover the inputs in both cases).

It is clear, then, that the socio-linguistic and IPO models of integration give different but compatible views of the same episode. But they are not merely compatible – they are complementary. Klein's socio-linguistic model identifies what types of inputs, processes, and outputs are possible by articulating what led up to and is likely to follow from the integrative episode, while the IPO model structures and parameterizes these components. In instances of collaborative, interdisciplinary reasoning such as our example above, Klein's socio-linguistic model tells us to look for shared standards of reasoning and both logical/epistemic and social/rhetorical argumentation moves. The IPO model asks us to get specific about which elements, standards, and moves are being used as the integrative inputs, processes, and outputs (not necessarily respectively). Perhaps most importantly, the IPO model spotlights the integrative relation(s) deployed in the argumentation.

Conclusion

In conclusion, the IPO model is a general framework for integration intended to capture integration in any context, whereas Klein's socio-linguistic model is really focused on cross-disciplinary integration; as such, the latter could be used to help guide instantiation of the IPO model in particular cross-disciplinary cases. With such a stereoscopic view of collaborative, interdisciplinary reasoning, new explanations of integration become possible. For example, we can use argumentative examples like the Toolbox excerpt above to identify a range (and perhaps a typology or taxonomy) of integrative relations used by collaborators when speaking with one another or collectively to the outside world. We can also investigate the inputs, processes, and outputs that collaborators are using to integrate socially, such as using language to build team cohesion. Lastly, we can explore the feasibility of specifying the parameters in the universal IPO model into workable, situation-specific "formulas."

But, we hasten to conclude that in many respects, the foundation of an idea is more important than its future prospects since there can be no advancement without a beginning. Julie Thompson Klein's work on integration has been foundational for us. As we have shown, the IPO model, integrative relations, and integration through argumentation are all rooted in Klein's work on interdisciplinary integration, and we expect many other contributors to the literature on integration will find her work to be fertile soil for their own, as well.

Addendum to this Article for the Dissertation

This article presents CIR as an example of both the IPO model and Klein's socio-linguistic principles of cross-disciplinary integration (CDI), but it is more than an example—it is a theory in its own right. It is a theory in the same way the IPO model and socio-linguistic principles are theories: they all explain how CDI works. Their explanations are both constitutive and causal. Constitutively, each theory identifies the entities (e.g., people, processes, concepts) involved in CDI. The IPO model names inputs, processes, outputs, and parameters of each as the constituent components of CDI. Klein's socio-linguistic principles call out variance, interaction platforms, iteration, and communicative rationality as key phenomena, defining each in terms of people and their communication practices. CIR posits interdisciplinarians, claims, reasons, standards, and a local purpose as the important parts.

Causally, each theory also identifies how these definitional components interact to produce integrative results. The IPO model black boxes[31] these as CDI "processes" that vary according to a number of considerations, including the nature of the inputs, the type of outputs, and the parameters. Klein appeals to socio-linguistic encounters and lists examples such as creating pidgin or creole languages and using boundary objects. CIR specifies the process of reasoning together in neo-Pragmatist terms that emphasize mutual understanding and the ability to "go on" together. By clarifying what and who is involved in CDI and how these entities together cause integration, they each provide a theory that explains CDI.

The theories differ, however, in their levels of abstraction. From most to least abstract, the IPO model, Klein's socio-linguistic approach, and CIR propose increasingly concrete concepts and processes (Fig. 6). The IPO model generally calls for inputs, processes, and outputs of integration. The socio-linguistic model asserts that those components will be social and linguistic when the

[31] The IPO model provides some specificity in that integrative relations play a key role in the integrative process.

integration occurs in cross-disciplinary settings. CIR then specifies that these social and linguistic components will have argumentative functions such as claims, reasons, and evaluations of these. In other words, collaborative, interdisciplinary reasoning (CIR) instantiates both the socio-linguistic and IPO models of integration by specifying the inputs, processes, and outputs when integration is achieved through the socio-linguistic process of reasoning together. Together, these models function as a spotlight into the black box of cross-disciplinary integration, with the light getting progressively brighter as the models narrow in specificity. Ultimately, the three theories together hold instances of CDI in clear enough focus that we can observe, analyze, and evaluate even the intermediate steps to the final outcome—together, they describe micro-integrations (O'Rourke, Crowley, Gonnerman, & Robinson, 2018) and how they aggregate (Laursen & O'Rourke, 2019).

The three theories operate at different levels of abstraction and are thus suited for different kinds of projects. However, they are not only nested by their levels of abstraction; they are also nested by their logical dependence. That is, the socio-linguistic model assumes the IPO model and CIR assumes both the socio-linguistic and IPO models. At the apex of this chain of abstraction and logic, only the IPO model can be used without implying the others. Thus, as the least abstract and furthest down the chain of implications, CIR is not only consistent with the two existing theories of CDI, it logically depends upon them. CIR states that integrative reasoning is a common process for accomplishing CDI. As chapter 3 defined:

> *Collaborative, interdisciplinary reasoning is the attempted integration of disciplinary contributions to co-apply, co-revise, or co-create intersubjective standards for what counts as good reasons and inferences in a local social exchange so that people can understand a mystery and then continue working together.*

Reasoning, as CIR defines it in the neo-Pragmatist tradition, is a socio-linguistic practice. CIR thus presupposes the socio-linguistic approach to CDI reviewed in chapter 1. Chapter 4 went on to show that Klein's four principles of research integration epitomize the socio-linguistic approach. Although chapter 3 did not mention Klein's principles, CIR does manifest them. First, because CIR occurs in a local setting, every context and goal of CIR will be slightly different, causing the

reasoning to unfold in many different ways, e.g., types of argumentation (Principle 1: Variance). Second, CIR requires pre-existing common ground and an interaction space (Principle 2: Platforming). Third, CIR notes that multiple kinds and rounds of reasoning are possible by acknowledging co-applying, -creating, or -revising as legitimate reasoning actions: co-revision succeeds co-application which succeeds co-creation of standards, and co-revision can revisit standards at any level of the reasoning chain as implications are realized and assumptions are tested (Principle 3: Iteration). Fourth, using intersubjective standards of reasoning is what enables shared understanding through communication (Principle 4: Communicative Rationality).

In turn, as the above chapter states, "something like the IPO model is presupposed by Klein's principles" (p. 137). Klein assumes certain conditions are already present before integration begins such as a specific team and project; integration is not creation *ex nihilo*. These pre-existing conditions create the context marked by the IPO model as cross-cutting parameters. The context shapes the communicative contributions that constitute the inputs to integration so labeled by the IPO model. Like the IPO model, Klein is trying to explain integration because it is the outcome or output of a mysterious process. Her principles aim to summarize that process in much more specific terms than given by the IPO model. In short, Klein's view presupposes an unintegrated set of inputs, an integrated set of outputs, and an integrative process that connects the two. At the highest level of abstraction, the IPO model can stand on its own.

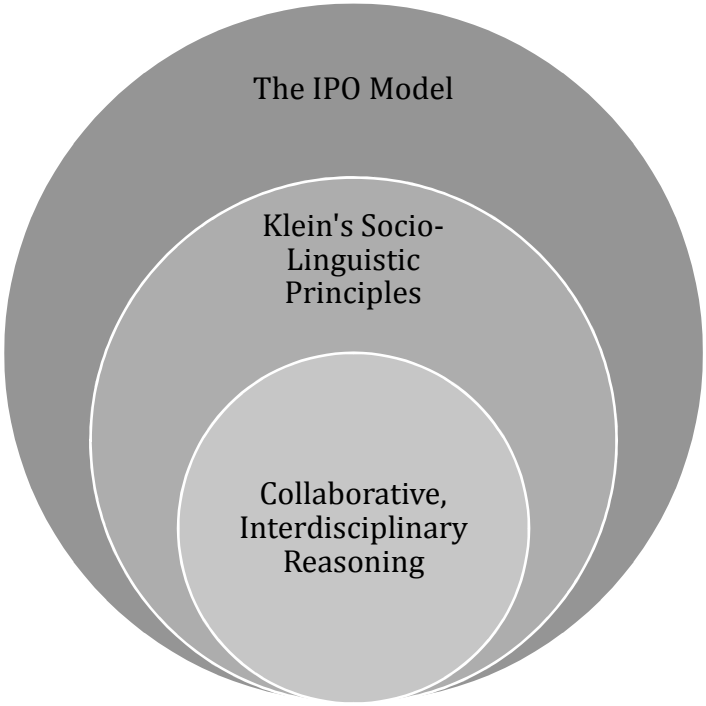

Figure 6: The IPO model, Klein's socio-linguistic principles, and CIR nest as successively concrete theories of CDI.

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CHAPTER 5: CONCLUSION

Summary & Contributions

Together, the four preceding chapters have claimed that cross-disciplinary reasoning (CDR) (epitomized by collaborative, interdisciplinary reasoning, CIR) is a main process by which investigators integrate diverse disciplinary knowledges. The argument unfolded in four parts. Chapter 1 established that cross-disciplinary integration (CDI) is crucial for solving wicked problems like sustainability yet it is also difficult and, to date, underspecified. This leaves funders, administrators, and researchers wondering how to nurture CDI, perhaps wasting millions of dollars and uncountable hours on CDI programs. Chapter 2 then showed that argumentation studies can shed valuable light on our ignorance by revealing how interdisciplinary integration results from making inferences using diverse disciplinary contributions. Chapter 3 specified a main process for making such inferences: collaborative, interdisciplinary reasoning (CIR). Chapter 4 argued that CIR allows remarkably clear understanding of CDI by showing how it specifies two existing theories of CDI: (1) the IPO model, and (2) Klein's socio-linguistic principles. Like the arguments the dissertation analyzes, the dissertation itself forms an argument with the four preceding chapters providing the premises for this final conclusion: cross-disciplinary reasoning provides substantial clarity into the processes we call "knowledge integration."

This conclusion and its supporting premises contribute to several research literatures. First, CDR exponentiates the explanatory power now available to cross-disciplinary theorists. CDR not only specifies a fine-grained causal process, it also opens a bridge to more explanatory resources available from argumentation studies. For example, we can now use existing work on argumentation schemes to categorize types of integrative work, e.g., inferences to the best explanation, arguments from authority. Better theory, in turn, contributes to better empirical work found in the literatures on cross-disciplinary collaboration and assessment. CDR defines the phenomenon of CDI more clearly, inviting more accurate measures and methods to be developed.

Cross-disciplinary reasoning also speaks to related literatures on the integration of new knowledge with old (learning), argumentation in other types of inquiry, team dynamics, and the ethical inclusion of stakeholders in wicked problems.

Practical Implications

These research contributions have direct and indirect practical implications for how we address sustainability problems. First, it focuses our investigative efforts upon the reasoning we use. Direct attention to reasoning may change how project meetings, empirical work, and writing proceed. Investigators may speak in terms of "claims" and "reasons," and they may draft standard form arguments to clarify their writing. They may map the flow of ideas from disciplines to conclusions to identify points of integration. And they and their facilitators may use such reasoning tools to intervene when integration is going astray during the project.

Second, cross-disciplinary reasoning calls for cross-disciplinary instructors to teach their learners (from undergraduates to veteran researchers) how to use these reasoning tools and skills before they leave the classroom. Investigating wicked problems requires advanced reasoning expertise to navigate ill-structured knowledge domains. Wicked problems are ill-structured knowledge domains because each case is uniquely complex; simple templates retrieved from memory will not suffice (Spiro, Feltovich, Jacobson, & Coulson, 1992). To accelerate the advanced reasoning required, educators must quickly teach students cognitive flexibility (Spiro et al., 2019). That is, they must teach students how to identify the multiple knowledge schemas involved in each wicked problem, deconstruct them, and reassemble them into an integrated "schema of the moment" that provides novel, useful insights (Spiro, 2015). CDR provides a mechanism to do exactly that. Reasoning together requires identifying the claims asserted and the reasons used to support those claims, which reveals the knowledge schemas being proposed. By identifying the reasons, the participants can more easily deconstruct these schemas by accepting or modifying some reasons and not others. Then, participants can construct new schemas suited for a new

problem by constructing new logical relationships between reasons that are left in play, eventually creating a new argument that integrates these reasons into a new, coherent claim. Knowing this, instructors of cross-disciplinarity—including those who lead convergence research trainings—can turn to the literatures on cognitive flexibility, reasoning, and accelerated expertise for principles and activities that accelerate this kind of learning (Spiro, Collins, Thota, & Feltovich, 2003).

Third, focusing on cross-disciplinary reasoning as a main process for integration makes it possible to evaluate if cross-disciplinary projects are succeeding at their integration task and to compare the relative success of various teams and programs against their peers. Many methods already exist for reconstructing arguments from written, oral, and visual communications (e.g., the Toulmin method (Toulmin, 2003); argumentation schemes (Walton, Reed, & Macagno, 2008); pragma-dialectics (van Eemeren et al., 2014); rhetorical analysis (Alcolea-Banegas, 2009); see also reconstruction tools (Kirschner, Buckingham Shum, & Carr, 2012)). With CDR as a framework, these existing argumentation methods now become available and applicable to CDI efforts that involve argumentation, which is many of them. In turn, these methods could enhance the evaluation of CDI by providing systematic resources that improve its accuracy and reliability. I am currently undertaking such an evaluation with the National Socio-Environmental Synthesis Center (SESYNC), which needs to determine if and how well the articles their teams produce integrate social and environmental knowledges. Developing the methodology and making it accessible to those without argumentation expertise is difficult—but at least now we recognize it as a way forward.

Future Research

Limitations of this Work

While CDR is a powerful insight for large swaths of cross-disciplinary activity, it does not comprehend the complexity of CDI. As mentioned in Chapter 1, CDR as I have described it has at least three limitations: (1) it only applies to investigations conducted—at least in part—by academically trained professionals, (2) it favors and risks reifying propositional knowledge, and (3)

it does not explain integration that occurs without reasoning. These limitations arise from my personal and conceptual starting points.

Personally, I am a child of the Western intellectual tradition as handed down through my upbringing and eventually crystallized in a "Great Books" curriculum conducted in the Socratic method of the dialectic. This program practiced and rewarded the assertion, evaluation, and exchange of reasons as a means of understanding en route to truth. I loved this approach because it gave me multiple insights every day into the enduring questions of humanity. These insights were unavailable from my own perspective; rather, they came from considering what truth could be found in every perspective I encountered in our curriculum. Thus, I personally found and continue to find reasoning through argumentation immensely valuable as a means for gaining insight and wisdom from multiple points of view. My personal experience is largely responsible for my recognition of reasoning as an important inquiry process.

Yet, despite my affinity for argumentation, I did not realize how it applied to formal sustainability inquiries until I encountered the literature on research integration. This literature prepared the conceptual ground that eventually bore the fruit harvested in this dissertation. The research integration literature frames the sustainability knowledge integration problem as a challenge arising from disciplinarity (Fazey et al., 2013; Pennington, 2015; Roche & Rickard, 2017; G. Tress, Tress, & Fry, 2007). Thus, by starting with the research integration literature, I took disciplines as fundamental when thinking about the various knowledges that should be involved in a sustainability study. Disciplines are treated in this literature as epistemic communities that primarily exist to produce knowledge through publications (Nučič, 2012; Palmer et al., 2016; Roche & Rickard, 2017; but see Murphy, 2011). This definition of a discipline leads to two limitations. First, it restricts sustainability inquiries to those involving academic disciplines, but we know such inquiries also occur beyond the academy (e.g., neighborhood association strategic plans, cultural resistance movements, forced migration responses, farm labor contracts). Second, reducing

knowledge to publications implies that disciplinary knowledge—at least, the disciplinary knowledge that is ultimately valuable for inquiry—must be able to be written down; it must be propositional. The need for knowledge integration then became, for this dissertation, the need for *cross-disciplinarity* as expressed primarily—although not necessarily—through the integration of propositional knowledge. Combining the research integration literature with my affinity for reasoning through argumentation, it is perhaps no wonder that I arrived at cross-disciplinary reasoning in my first attempt to explain knowledge integration for sustainability.

Future Research: Non-disciplinary & Non-propositional Knowledges

My personal and conceptual starting points remind us there are other possible starting points with their own implications; there is much territory to cover beyond the lamp I am using now. To explore this territory, sustainability studies must first acknowledge the crucial necessity of integrating non-disciplinary and non-propositional knowledges into its investigations. This will require releasing our grip on publications as the most valuable form of knowledge while increasing our desire for other forms of knowledge. Such a change in values requires sustainability investigators and theorists first to recognize that knowledge *exists* outside of publications. For this, we can turn to literatures from the critical traditions, such as decolonial and feminist studies, as well as literatures and experiences from cultures that prize symbolic and experiential understanding over propositional knowledge (e.g., Eastern philosophies, Christian mysticism). Then, from recognizing to integrating these diverse ways of knowing will require new theories and practices that go beyond reasoning or expand reasoning beyond its propositional traditions. Existing work on combining Indigenous and scientific knowledges, transformative learning, sensemaking, and the development of embodied expertise may provide starting points here. While I believe CDR as defined in this dissertation allows room for non-propositional reasoning, work remains to explain how such reasoning proceeds.

Realizing that non-propositional knowledge exists, is valuable, and can be integrated with propositional knowledge can help sustainability practitioners and theorists also learn to recognize, value, and integrate *non-disciplinary* knowledges because many of these are non-propositional. This is where my theory of CDR falls short of explaining all of the knowledge integration that needs to occur to pursue sustainability with as much wisdom and justice as possible. Non-disciplinary knowledge recognizes that non-academic communities of practice are also knowledgeable. Examples of these communities—all relevant to the pursuit of sustainability—include specific groups of children, families, ethnic cultures, religions, activists and unions, the skilled trades, people living with disabilities, politicians, LGBTQIA communities, and many others.

There are many entry points to learning about non-disciplinary knowledges. Researchers most comfortable retaining disciplinarity as a frame for their knowledge work can learn from participatory research traditions that have specialized for decades in how academic and non-academic communities can respectfully partner in research (e.g., Reason & Bradbury, 2008). More recent work on transdisciplinarity as cross-sectoral work retains a focus on research while eschewing disciplinarity to focus on knowledge co-production (e.g., Fam, Neuhauser, & Gibbs, 2018). But for those willing to pursue knowledge itself, beyond its use in investigations, there are many more ways to learn about non-disciplinary knowledges. The most powerful (and fun) way may be to join or sojourn with a non-disciplinary community to experience their knowledge from within. In this way, we are more likely to learn non-disciplinary knowledges on their own terms and less likely to translate the knowledge into disciplinary propositions in order to recognize it as knowledge. We are also more likely, as Chris Campolo is quoted below, to build intersubjectivity with other ways of knowing through such immersion than through reasoning alone.

Future Research: Other Kinds of Integration & Reasoning Prerequisites

Taking non-propositional and non-disciplinary knowledges seriously will also aid needed research on how CDR interfaces with other types of integration such as social integration. Different

ways of knowing are bound up with different ways of being together. For example, previous work has shown coordinating communication influences team cohesion (e.g., Troth, Jordan, & Lawrence, 2012), so we should ask, among other questions, "How do communication and cohesion relate when the communication is CDR?" Studying different ways of being and reasoning together will also highlight which conditions are prerequisites for CDR. For, as Chris Campolo (2005) reminds us,

> Reasoning together in a fruitful way depends upon our existing shared practice, shared knowledge, and shared competence. … But the path to expertise, competence, and intersubjectivity is paved with training, practice, study, apprenticeship, immersion in a tradition or way of doing something. Reasoning together, on its own, cannot bring about any of this-it first gets its foothold once all of this is already in place. (p.45)

In other words, when investigators work with dramatically different ways of knowing—such as disciplinary vs. non-disciplinary or propositional vs. non-propositional—the prerequisite intersubjectivity for CDR that Campolo describes is more likely to be thin or lacking altogether. Such situations provide excellent opportunities to theorize and reflect upon what common ground disparate communities must have before CDR becomes valuable in our cooperative quests for sustainability.

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