Cross-disciplinary practice in engineering contexts – a developmental phenomenographical perspective

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Abstract: This paper presents an overview of results from a phenomenographic study that investigates critical differences and similarities in the ways people experience cross-disciplinary practice in engineering contexts. Study implications are discussed regarding developmental perspectives on cross-disciplinary ways of thinking, acting, and being.

Introduction

Many complex engineering problems facing society such as climate change, healthcare and international security require cross-disciplinary approaches that integrate diverse perspectives into a collective whole. Here, "cross-disciplinary" refers to practices associated with thinking and working across different perspectives such as multidisciplinary, interdisciplinary, and transdisciplinary. Reports on the future of engineering education stress preparing engineers to become "emerging professionals" who can deal with complexity, innovate, flexibly adapt to new situations, and bridge disciplinary boundaries to produce deeper insights (NAE, 2004). There has been substantial investment and interest in cross-disciplinary practice; however, the level of empirical attention is considerably less (Bromme, 2000). Studies focus on humanities and social sciences (e.g., Klein, 1996; Lattuca, 2001), although there are some studies on the physical and natural sciences (Galison, 1997; Nerssessian, 2006; Newstetter et al, 2004) and engineering design (Adams et al, 2009a).

While understanding how groups work together and create new knowledge is an important research focus, this study moves the lens from groups to individuals to make visible the development of cross-disciplinary practices. Phenomenographical methods were used to investigate critical similarities and differences in how individuals experience and comprehend cross-disciplinary practice in engineering contexts. Using experience as a lens for investigation acknowledges the relationship between experience and learning (Tuan, 2007, p. 16): "the modes through which a person knows and constructs a reality…and learn from what one has undergone." Phenomenography also provides unique understandings of practice that can readily contribute to course and program renewal and redevelopment (Daly et al, 2008). In this paper we present an overview of study results and discuss some implications for research and education.

Theoretical Frameworks

Three frameworks guided this study. The first framework involved a synthesis of cross-disciplinarity at the group level of analysis (Adams et al, 2009a) that revealed important variations regarding: problem orientation (from thematic oriented projects to systems oriented participatory projects), mode of knowledge production (from juxtaposition of perspectives to an overarching and transformative synthesis), outcome (from no change in knowledge to knowledge fusion through critical reflection), interaction structures (from collaborating as disciplinarians to transcending disciplines), discourse practices (from common interests to creation of new language and logic), and impacts on participants (from retaining a disciplinary identity to critical reflection on pluralistic identities). While the synthesis illustrates how multidisciplinarity, interdisciplinarity, and transdisciplinarity differ in significant ways, they all presuppose that cross-disciplinary practice is driven by problems beyond the confines of any single discipline and involves transgressing disciplines. Disciplinary practices are systems of inquiry characterized by theories and concepts, and modes of observation, interpretation, and arguing claims regarding truth and validity (Klein, 2004). Cross-disciplinary practice at the individual level is likely to involve confronting, recognizing, and respecting different epistemological views (Lattuca, 2001; Klein, 1996) in which deep learning interacts with identity development (Sfard & Prusak, 2005). This synthesis aided this study by (1) highlighting important variations in cross-disciplinary practice to guide participant recruitment, (2) revealing the need for empirical research at the individual, not group, level unit of analysis, (3) indicating theories of epistemological and identity development that may emerge from this study, and (4) characterizing cross-disciplinary practice as a situated practice.

The second framework is based on Dall'Alba's (2009) model of professional development. Dall'Alba and Sandberg (2006) describe understanding as embedded in dynamic, intersubjective practice – a notion that integrates thinking, acting, and being into an unfolding "professional-way-of-being" that makes visible the situated nature of professional development, variations in skill development, and characteristics of skillful performance. This connects to theories of situated learning, reflective practice, and communities of practice. For this model, skill progression represents how individuals might become increasingly adept at tasks that they routinely practice. Skillful performance (an embodied understanding of practice) represents a limited number of qualitatively different ways a practice is understood. Advancement along this dimension is marked by increasingly comprehensive ways of understanding – an "unfolding circularity" of ongoing inquiry to achieve more complex and comprehensive understandings of the central ideas of their practice. This framework aided this study by (1) identifying ways to characterize an embodied understanding of cross-disciplinary practice, (2) further locating this study in theories of situated cognition, and (3) informing the choice of phenomenography as a research framework.

Phenomenography is a qualitative method to investigate different ways of experiencing and understanding aspects of practice (Bowden & Green, 2005; Marton & Booth, 1997). It is used to reveal surface and deep approaches to learning and has been used to investigate the experience of learning, teaching, concepts such as programming and velocity, and more recently professional practice. In phenomenography the "phenomenon" is a person's experience in relation to an aspect of the world and the outcome of phenomenographic study is the researcher's interpretation of that phenomenon (Mann et al, 2007). It is an empirically derived method where a theory of variations is emerging as a way to explain the existence of categories and how they are related. In phenomenography, the goal is to identify categories of description comprising distinct groupings of qualitatively different ways of experiencing a phenomenon and internal relationships among groupings as increasingly complex ways of experiencing the phenomenon and a growing awareness and comprehension of practice (Bowden & Green, 2005). In this way phenomenography creates a link between experience and awareness where variations in experiences may reveal characteristics of an embodied understanding of practice.

Research Design

Twenty-two (22) engineers and non-engineers who work in engineering contexts were strategically recruited to maximize diversity and establish an inclusive "outcome space". This sample size and strategy is consistent with typical phenomenographic studies. Variations in the sample were identified through a literature review and include: context of work (academia, private industry, and community service), years of cross-disciplinary experience, gender, nature of experience in terms of project scale (i.e., size of teams) and complexity (i.e., number of disciplines involved), and epistemological distance (i.e., scale of disciplinary similarity or difference). Epistemological distance is the extent to which an individual interacts with those with similar ways of knowing such as an engineer working with other kinds of engineers or substantially different such as an engineer working with a social scientist or artist. Figure 1 shows key sample variations: years of experience, project scale, and epistemological distance.

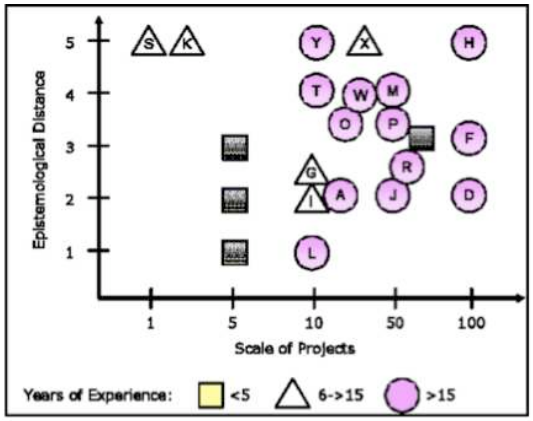

Figure 1. Sample distribution among key characteristics. Letters represent participant identifier code (e.g., G = Grace, I = Isabella)

Data was collected using a semi-structured interview protocol in which participants were asked to bring to mind concrete experiences of cross-disciplinary practice (see Mann et al, 2007). Follow up questions ask interviewees to elaborate on their experiences and what they mean by certain concepts. Probes may include information about the situation or characteristics of that situation that represent their ideas of cross-disciplinary practice. All probes were based upon what the participant expressed so far in the interview, and not formed through predetermined ideas and questions from the interviewer. Interviews lasted 30 minutes and were audio recorded then transcribed.

Analysis began with reading and re-reading transcripts as a collection and identifying what was significant within a whole transcript and in relation to other transcripts. Transcripts were sorted into piles

of similarities and differences and assessed by identifying substantive excerpts from the transcripts that supported patterns in each pile. Over time the number and description of the different piles settled and became the categories of description. Subsequent passes through the data focused on articulating and substantiating the relationships among these categories, drawing from the data as well as theoretical frameworks. Relationships among categories were examined in terms of how categories related to a set of common ideas and to differences in breadth and depth of understanding. In this study, the relationship among categories mapped out increasingly more comprehensive understandings of cross-disciplinary practice. Overall, the analysis was a rigorously iterative process of being disciplined by the data, looking for empirical evidence of patterns, and seeking logical arguments in how patterns mapped to theoretical frameworks. In this way findings emerged through a co-evolutionary process of discovery of categories and construction of structural relationships between categories.

Results

Below we summarize key findings: the four categories of description that emerged, critical variations across categories, and relationships among categories that reveal increasingly advanced ways of experiencing and comprehending cross-disciplinary practice in engineering contexts. Progression from Category 1 to Category 4 represents increasingly complex ways of experiencing and understanding cross-disciplinary practice in engineering contexts. In this paper we provide illustrative examples of the categories of description and present new findings on the hierarchical relationships among categories. An in-depth analysis of the categories is provided elsewhere (Adams et al, 2009b).

Category 1: Working together – Emily, Grace, and Isabella

The experiences in Category 1 illustrate *cross-disciplinary practice as working together with people who have different training to effectively find a better solution*. The following excerpts highlight some of the key attributes of this category: (1) an iterative process of asking questions, challenging assumptions, and listening for understanding, (2) being comfortable with asking for information that might seem obvious, (3) knowing what you and others contribute, and (4) recognizing differences in what people know and how they communicate, (5) and the need to take personal responsibility to be an effective collaborator.

> "For me cross-disciplinary practice is probably working with someone of another discipline in a rather intricate way. In a way that's as brief as possible so that each party can continue their own work, but as thorough as possible when you get together so that you have very good information for each other…what needs to be improved, what details need to be in there." [Emily]
>
> "I mean it's very much learning how to talk to people that don't come from the same background that you do, academically. Being able to communicate what you want to do in a language that is accessible to an average level PhD scientist but not someone inside your own discipline necessarily….Just don't jump right in to the gritty details of it." [Isabella]
>
> "…probably the biggest challenge is getting the two to communicate…to listen and be very clear as to what you're trying to say and to make sure that the people listening to you are understanding that so, listening, asking questions to follow up is the biggest thing." [Grace]
>
> "I think it's vital. I think that's the only way to do it. If you don't have value for the other discipline, what are you even doing working with them? If you don't value what they are doing, you are not going to care how they do it, why they do it. You're not going to ask enough questions, and the questions are going to be important for the way you design what ever you're designing." [Emily]
>
> "Give people more respect as far as what they can contribute….I found that there were lots of good ideas that came from the engineers when they spoke up and there were lots of really important things that the nursing staff could contribute that I didn't think they could. Engineering people look at nursing people and think they're smart but in a whole different way that's not really that smart. They don't think of it as being difficult knowledge because it's all really, it seems like common knowledge like take chicken soup for a cold or something….really have their own special way of knowledge and I've come to appreciate that a lot." [Emily]

Category 2: Intentional learning – Uri, Olivia, Pablo, Brianna, Ryan, Nadia

Where the experiences in Category 1 focus on the dynamics between people, the experiences that represent Category 2 focus on individuals' intentional learning. For Category 2, *cross-disciplinary practice is intentional learning so that everyone gains (me, my team, and my stakeholders)*. The following excerpts highlight some attributes of this category: (1) creating opportunities to learn new perspectives or ways of knowing, (2) purposefully educating each other to collectively enable a systems perspective, (3) learning

through experience and failure, (4) learning *how* to negotiate meanings across perspectives and formulate or investigate problems through multiple lenses, and (5) a passion and appreciate for continual learning.

> "…and every time I work with one of these people you have to understand something about what they do and you always, when you first start and everybody I've ever talked to seems to have this same perspective; you underestimate how hard the other person's field is. You've spent all this time and effort developing your capability; and oh, by the way you'll pick that up too and you learn pretty quickly if/that if you're not just going to do this superficially; that you know they've traveled their long road too. And so you have to meet as equals but you have to, and respect each other, but you have to learn about they're problem if you're really going to be successful in at least some amount and commit to that. But that's fun so…" [Olivia]

> "…a you help me/I help you kind of thing but and I would come back and I would never know enough so you'd have to read more and the best way of doing it was in an immersion kind of mode..." [Olivia]

> "I think I've become more convinced that the people need, it's like you go along in you need your immunizations, you need to have these points in life of injection of something and I think that it's important to plant those seeds along the way and I haven't really thought about that…" [Olivia]

> "I want to say I just became more open minded towards other disciplines. I used to think, we're engineering, it's much more difficult than everything else and although we can't communicate as well as the business people, but we're more technical, but when you start working with them, everyone sort of has their own set of abilities and weaknesses that they have to work together. I think by working cross-disciplinary, it sort of strengthens everybody." [Uri]

Category 3: Strategic leadership – Jacob, Michael, Fergus, Tyler, Daniel, Yvonne

Where the experiences of Category 2 focus on learning, the experiences that represent Category 3 focus on applying learning to actively enable cross-disciplinary work and outcomes. In other words, *cross-disciplinary practice is strategic leadership to enable cross-disciplinary work and synergy for the best outcome*. Leadership is central in that it involves being the "interface", "connector", or "communication specialist" to enable innovation or proactively transform a negative working environment into a positive one. The following excerpts highlight some attributes of this category: (1) make or enable conceptual connections, (2) build allegiances and trust, and (3) facilitate systems-oriented strategies or frameworks that leverage diverse perspectives. Some strategies involve actively transforming a negative working environment into a positive one.

> "…cross-disciplinary engineering is creating or innovating across multiple disciplines, so that's just saying it differently. But the strongest thing that does come for me is across markets or educational pillars. The other one which doesn't fit real nicely, but these days a lot of people do, is across different cultures." [Daniel]

> "I've got components, now I've got to think about, based on this organization, who are the right people that I need to speak with and get on a team so that we can ensure that we drive this thing forward." [Fergus]

> "I'm a communications specialist…I get a sense for people so I also get a sense of what they mean when they're telling me something. And so I would use that capability to get minds met. I would use a lot of other techniques, but I was a bridge." [Jacob]

> "…I believe, because there is a possibility that people who come in late don't get the same deal, don't get treated the same way. You've missed a lot of the discussions, you don't understand. In addition, if you're really adding a valuable team member, the discussions probably weren't as productive and fruitful as they could have been without his missing voice. So if you believe in a balanced approach to the problem-solving which I happen to believe, statistically you're more likely to have a better solution if you have more voices that are reasonable and respected sitting in the room….So balance, to me, says that you, you and I and three or four other people, whatever the size of the team is, are sitting around and we respect each other, ok, and we're willing to listen to each other and consider that these things, these issues that are raised or solutions that are raised are real and should be considered. That's what I mean by balanced problem solving….So everybody's in on the ground floor. It's important because you get a better solution in my opinion. You also have owners of the solution." [Jacob]

> "We're so busy trying to be sure that we're understood by others, that we don't seek to understand….So that is absolutely critical in order to be trusted, to trust people, you have to be trustworthy yourself. So it really starts with you and then you model behavior you want. It's also important in this team. And then probably the one that (captures) it best is believing in the value of synergy." [Jacob]

Category 4: Challenging and transforming practice to integrate systems – Anthony, Xavier, Hannah, Logan, Samantha, Wendy, Kelvin

Where the experiences of Category 3 focus on enabling cross-disciplinary work, the experiences of Category 4 represent transformative reflective practice that challenges prior training and ways of thinking.

For this category, *cross-disciplinary practice is challenging and transforming practice to integrate systems and produce an outcome greater than the sum of its parts*. The following excerpts highlight some attributes of this category: (1) critically challenging disciplinary practice and the ways conflict can be transformative, (2) integrating stakeholders as collaborators, (3) attuning to the human aspect of complex systems, (4) advocating perspectives by taking into account the broader context, and (5) embracing cross-disciplinarity as everyday practice.

> "Perspective really comes from the experiences that one has had and not one person has had the same experiences....that gives me a different perspective because I've seen different things, I've been exposed to different things. Maybe I've traveled all over the world, or no, I've only lived in Indianapolis all my life. You know those kinds of things; it gives you, that brings perspective…" [Hannah].
>
> "For better or worse I am who I am and some people appreciate that….I don't do anything different here than I do at home as I'm looking through something. So this is not my 'day' personality." [Logan]
>
> "I've always thought that it's always a good interaction from the standpoint of a multi-disciplinary scientist, that when you go in you work with the stakeholders you're at, you're on equal ground, you're on equal footing. There is an exchange of information. They're kind of framing the problem in a much different way than what you see it. You tend to be more isolated as a scientist, as someone who is at a university. They're dealing with this on a day-to-day basis, they have the muddy-boots kind of experiences. So the way in which they articulate the problem, they way in which they see it, the way in which they, the constraints that they have, is very, very valuable to listen to that….So, working with stakeholders is not just, you know, something we take lightly. It's actually part of the science. It's incorporated into the whole methodology." [Xavier]
>
> "…there are a whole bunch of metaphors, like the idea of poaching or borrowing or, I can't think of any more now, ok there really are a whole bunch of metaphors, that I don't see as transformative enough. That's great; you went out and borrowed an idea from somewhere else, and you're like so how can I use that tool in my stuff? But does that transform your stuff? Does that transform your discipline? I don't think so." [Samantha]
>
> "Well, you know, we did it collaborating with social scientists, right, in some respects. I mean, I've invested a tremendous amount of my own time trying to learn what these methods are. You know, I'm reading, you know, qualitative methods. I've got the books around here too that my colleagues read and so I'm making the personal investment to sit down and learn what I can about their practice of science and how it integrates with my traditional practice of science. How do you structure mine and how do you structure theirs to come and do, you know, make the interface work." [Xavier]
>
> "…if either of the two disciplinary scientists aren't willing to give up some turf, it's never going to happen, you know, it's never going to happen productively." [Xavier]
>
> "does the home need to have institutionalization or institutional markers or some kind of outward existence or can it be a group of people who identify in certain ways are, that don't find their cognitive home somewhere else? I don't know. But it's a more dynamic place. It is a more revolutionary place." [Samantha]

Relationship Among Categories

The categories of description that emerged from the analysis are *distinct* – each captures a qualitatively different facet of cross-disciplinary practice in engineering contexts. These map to the framework for an embodied understanding of professional practice in terms of thinking (awareness of "difference", situation complexity, and goal direction), acting (engaging with "difference" and situation complexity), and being (self-perceived role or identity). Relationships among these categories are also *hierarchical* (see Figure 2). While attributes of each higher category encompass attributes of prior categories, critical variations of the more comprehensive categories are not evident in less comprehensive categories (see Table 1). This hierarchical progression is both data-driven (emerged from the analysis) and logical (attributes of higher categories move from surface to deep and narrow to broad comprehensions).

Figure 2. Relationship among categories of variation

Category 1 (Working Together) is distinct because of a focus on the experience of collaborating and communicating with people who have different perspectives, language, interaction styles, and ways of thinking. This appears to be a foundational category since the other categories build off of these ideas in increasingly complex ways. As shown in Table 1, critical attributes of Category 1 involve an awareness of differences in disciplinary training and how these differences complicate the process of working together towards an effective outcome. This awareness often triggers an iterative communication process of asking

TABLE 1. CRITICAL VARIATIONS IN CROSS-DISCIPLINARY PRACTICE

	Category 1: Working together	Category 2: Intentional learning	Category 3: Strategic leadership	Category 4: Challenge & transform practice
AWARENESS OF COLLABORATION DIFFERENCES	• Difference = disciplinary training • "Difference" makes collaboration complicated • Everyone "smart" in own way • Respect as "value-added"	• Difference = disciplinary perspective • "Difference" as opportunity • Respect for difficulty of disciplinary training	• Difference = disciplinary, organizational, cultural • "Differences" clash; need strategies and new paradigms to enable collaboration and innovation • Aware of need for common ground, trust, shared ownership • Respect for the interfaces	• Difference = lived experiences; transcends disciplinary boundaries • "Differences" enable transformation • Honor other ways of knowing; no way is better than another
AWARENESS OF SITUATION COMPLEXITY	• Complexity as function of client and technological needs • Aware of limits regarding technological feasibility • Problems as client-driven, theme-driven	• Complexity as function of societal and global dimensions • Aware of limits of own knowledge • Problems as emergent	• Complexity drives need new paradigm of societal, global, economic views • Aware of limits of disciplinary approaches and frameworks • Problems require organizational thinking	• Complexity requires attuning to human context • Aware of stakeholder risks and consequences • Aware of system boundaries (disciplinary, organizational, cultural) • Problems require integrated technological – social – human systems thinking
AWARENESS OF GOAL	• Meet needs, expand application, identify what is feasible from another disciplinary perspective	• Learning as its own goal – self, team, stakeholders • Interaction yields new insights • New partnerships	• Worthwhile outcome for all • Successful launch • Common ground as an outcome	• System level and participatory outcome greater than sum of parts • Shape decisions • Give up disciplinary turf • Integrative synthesis that transcends disciplines • Transform views on good practice, good science
ENGAGEMENT WITH SITUATION	• Iterative communication process	• Self-directed intentional learning process • Create opportunities to learn - immersion and failure • Build partnerships	• Change the parameters to discovery and cross-disciplinary paradigms • Focus on problem formulation through multiple perspectives (not "jump too quick to implementation") • Create collaboration networks	• Work at the interface; work at mile high system view • Complex systems thinking • Bring all aspects of lived experiences together • Passion to improve system performance
ENGAGEMENT WITH DIFFERENCES	• Client / partner as information source • Take responsibility for being effective communicator	• Meet as learners, educators • Learn how to think between disciplines, synthesize • Learn how to collaborate	• Proactively manage and leverage differences • Orchestrate discovery and innovation • Bring people together around shared goal; build expert network • Build trust, shared ownership, allegiance, common ground	• Engage stakeholders as partners • Advocate different perspectives; be altruistic • Diversity and conflict as transformative
IDENTITY	• Responsible for contributing training as disciplinary team member • Team member	• Passion for learning, dealing with complexity • Learner and educator	• "Let up on the ego" – enable team • Take the risk and lead • Facilitate synergy at interface, synergy angels • Interface, bridge, translator, etc.	• Live at interface as transformational learning site • Revolutionary new "home"; perceived loss of disciplinary home • Cross-disciplinarity as everyday practice – integrates work and life
	From Category 2 to 1: Improving the conditions needed to work together with people with different training to address complex problems of social and global significance	From Category 3 to 2: Applying prior learning on the challenges and affordances of cross-disciplinary practice to proactively enable successful cross-disciplinary discovery and innovation	From Category 4 to 3: Critical reflective practice to enable transformative learning and outcomes (for self, teams, stakeholders, and disciplinary practices)	

questions and listening for understanding with those who are perceived as a relevant for determining what is desired or feasible within a bounded application space such as meeting a specific client's needs. This also often involves taking individual responsibility for being an effective communicator and collaborator. Different perspectives are seen as a "value-added" but not understood in a deep way.

Category 2 (Intentional Learning) distinctly focuses on the process and outcomes of collaborative and situational learning. This category builds off of Category 1 (Working Together) because it represents a process of *improving the conditions needed to work together with people with different training to address complex problems of social and global significance*. As shown in Table 1, a focus on cooperation and collaboration expands to include social learning, a focus on complex problems expands to include social and global elements, and a role evolves from being a collaborator to being a self-directed learner. Awareness of differences changes from recognizing disciplinary differences to respecting the difficulty of disciplinary training and learning at the intersection of differences. Creating opportunities to address complex challenges emerge from intentional learning experiences that involve seeing failure through an opportunistic mindset and having a passion for self-directed learning. Here, personal learning occurs in parallel with efforts to be an educator so that collaborators can co-create a shared understanding.

Category 3 (Strategic Leadership) distinctly focuses on proactively enabling successful cross-disciplinary discovery and innovation through managing and leveraging differences. "Orchestrating" is emphasized explicitly through a self-identified role of being a facilitator at the cross-disciplinary interface and taking the risk of leading projects towards successful outcomes. As shown in Table 1, this is a leadership role that is about enabling the team rather than promoting individual egos. Like Category 1 (Working Together) elements of collaboration and successful outcomes are evident in Category 3; however, an awareness and understanding of what enables success expands to include issues of trust, respect, shared ownership, and inclusivity such that disciplinary, organizational, and cultural perspectives can be synergistic and open up new ways of thinking. Category 3 builds off of Category 2 (Working Together) by *applying prior learning on the challenges and affordances of cross-disciplinary practice to proactively enable successful cross-disciplinary discovery and innovation*. As shown in Table 1, prior experiences have established an awareness of how cross-disciplinary work can break down: differences in perspectives across disciplinary, organizational, and cultural perspectives; poor problem formulation that leads to ineffective and inappropriate solutions; an inability of disciplinary paradigms to meet the needs of complex situations that involve economic and political dimensions; a need to engage a social network of expertise; and the importance of building allegiance, a common vision, and collaborative decision making.

Category 4 (Challenge and Transform Practice) distinctly focuses on questioning practices and boundaries. Where Category 3 (Strategic Leadership) involves leading teams in creating common ground and new ways of thinking, a leadership role for Category 4 expands to include *being a transformative agent as well as being transformed*; where Category 3 focuses on enabling cross-disciplinary discovery and innovation, Category 4 is about *critical reflective practice to enable transformative learning and outcomes (for individuals, teams, stakeholders, and disciplinary practices)*. As shown in Table 1, Category 4 involves expanding the idea of "difference" to include lived experiences and recognizing how boundaries between differences are socially constructed. This awareness facilitates critical analysis of the idea of "difference" and a critical exploration into similarities across different perspectives, which leads to new inclusive practices, theories, and identities. The essence of Category 4 is challenging epistemic frames comprised of skills, knowledge, values, identity, and theories of knowledge, as well as honoring differences and how diversity enables transformative thinking and transcending boundaries. Part of this is attuning to the human and contextual aspects of complex problems. This focus on human issues is evident in participatory strategies that engage diverse stakeholders as partners, not just information resources. When human and contextual factors are integrated into the system, the limits of prior views of "good practice" or "good science" are revealed and enable new ways of thinking about system performance. For Category 4 there is a unique and explicit identity of "being cross-disciplinary". This new identity may involve disrespect within and exclusion from prior disciplinary communities as well as seeking out new revolutionary "homes".

Implications and Future Work

While there are a number of theoretical implications of this study, a central contribution is a developmental framework of cross-disciplinary thinking, acting, and being at the individual level. Overall, the analysis revealed four hierarchically related categories of variation that emphasize (1) the ways "difference", complexity, and goal motivations are experienced and (2) how these experience shape actions and self-

perceived identities. Across these variations are themes of epistemological development, respect for "difference", social networking and participatory acts to create common ground, and identity development (for self and in relation to others). F or example, an expanding awareness of "difference" is associated with epistemological reflection and an evolving respect for different perspectives. This is evident in the ways "difference" is described (from disciplines to organizational structures to cultures to lived experiences), the actions associated with an awareness of difference (as something to be overcome, explored, leveraged and managed, and critically reflected upon and transformative), and how it is characterized in reference to other perspectives (as a relevant "value-added", as respected as difficult, as respected in decision making, and as honored as a way of knowing). In this way, studies of cross-disciplinary practice may help understand how disciplinary and cross-disciplinary learning interact.

This study also suggests practical implications. In phenomenography, the link between practice and preparation for practice is that the way learners experience a phenomenon *in the past* will form *how they act in the future*. Some of the themes in the results have direct implications for structuring and sequencing learning opportunities. For example, a theme of learning to collaborate as well as learning through collaboration suggests the potential impact of engaging learners early and often in cross-disciplinary collaborations – regardless of their level of disciplinary grounding. Similarly, a theme of intentional learning suggests the potential for connecting self-directed and self-regulated learning strategies or mindsets to a broader agenda of cross-disciplinary learning. At a minimum, the role of variation in developing an awareness of cross-disciplinary practice suggests a critical need to provide learners with diverse experiences to enable an embodied understanding of practice.

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References

Adams, R.S., Mann, L., Jordan, S., and Daly, S. (2009a). "Exploring the boundaries: language, roles, and structures in cross-disciplinary design teams." In J. McDonnell and P. Lloyd (eds), *About Designing: Analysing Design Meetings*, 2009, Chapter 16. London: Taylor and Francis Group.

Adams, R.S., Forin, T., Mann, L. and Daly, S (2009b). "Cross-disciplinary practice in engineering contexts." Proceedings of the *International Conference on Engineering Design* (ICED), Palo Alto, August.

Bowden, J.A. & Green, P. (2005). *Doing Developmental Phenomenography*. Melbourne: RMIT University Press.

Bromme, R. (2000). "Beyond One's Own Perspective: The Psychology of Cognitive Interdisciplinarity." In P. Weingart & N. Stehr (Eds), *Practising Interdisciplinary*, pp. 115-133. Toronto: University of Toronto Press.

Daly, S., Mann, L., and Adams, R. (2008). "A new direction for engineering education research: Unique phenomenographic results that impact big picture understandings." In *Proceedings of the 2008 AaaE Conference*, Yeppoon, Australia.

Dall'Alba, G. (2009). *Learning to be Professionals. Innovation and Change in Professional Development, Volume 4*. Springer Science+Business Media B.V.

Dall'Alba, G. and J. Sandberg (2006). "Unveiling Professional Development: A Critical Review of Stage Models." *Review of Educational Research,* 76(3): 383 - 412.

Galison, P. (1997). *Image and Logic*, 1997. Chicago: The University of Chicago Press.

Klein, J. T. (1996). *Crossing boundaries: Knowledge, disciplinarities, and interdisciplinarities*. Charlottesville, VA: University Press of Virginia.

Klein, J. T. (2004). "Prospects for transdisciplinarity". *Futures*, 36: 515-526.

Lattuca, L. (2001). *Creating interdisciplinarity: Interdisciplinary research and teaching among college and university faculty*. Nashville: Vanderbilt University Press.

Mann, L. M. W., D. Radcliffe, and Dall'Alba, G. (2007). "Using Phenomenography to Investigate Different Ways of Experiencing Sustainable Design." In *Proceedings of the ASEE Annual Conference & Exposition*, Hawaii.

Marton, F. and Booth, S. (1997). *Learning and Awareness*. New Jersey: Lawrence Erlbaum Associates.

National Academy of Engineering (NAE) (2004). *Engineering of 2020: Visions of Engineering in the New Century*. Washington DC: National Academy of Engineering, National Academy Press.

Nersessian, N. J. (2006). "The Cognitive-Cultural Systems of the Research Laboratory." *Organizational Studies*, 27(1): 125-145.

Newstetter, W., E. Kurz-Milcke, et al. (2004). "Agentive Learning in Engineering Research Labs." Proceedings of the annual Frontiers in Education Conference.

Sfard, A. and A. Prusak (2005). "Telling identities: In search of an analytic tool for investigating learning as a culturally shaped activity." *Educational Researcher,* 34(4): 14-22.