INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'09
24 - 27 AUGUST 2009, STANFORD UNIVERSITY, STANFORD, CA, USA

CROSS-DISCIPLINARY PRACTICE IN ENGINEERING CONTEXTS

Robin S. Adams[1], Llewellyn Mann[2], Tiago Forin[1] and Shawn Jordan[1]
(1) Purdue University (2) Central Queensland University

ABSTRACT
This paper presents results from the first phase of 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 education and ways to enable cross-disciplinary practice and work environments.

Keywords: cross-disciplinary practice, phenomenography, transformative practice, epistemology

1 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 [1-3]. Reports emphasize how engineering design involves "wicked" problems, integrating technical and non-technical considerations, negotiating differences and territories of expertise [4-5], transformative processes [6-7], reasoning within and across domains [8], and managing trade-offs involving interdisciplinary criteria [9].
There has been substantial investment and national interest in cross-disciplinary practice [3, 10]; however, the level of empirical attention paid is considerably less than the level of endorsement [11]. While research focuses on humanities and social sciences [e.g., 12] there are some studies of cross-disciplinary research laboratories [e.g., 13-14] and engineering design [e.g., 15]. Advancing this scholarship is necessary to move beyond trait-based characterizations to cognitive-based characterizations that can guide education and practice. This study focuses on understanding critical differences and similarities in the ways people experience cross-disciplinary practice in engineering contexts [16-17]. Phenomenography offers unique and concrete understandings of practice that can readily inform program renewal [18]. In this paper we present the results from the first phase of this study and discuss implications for enabling cross-disciplinary practice and environments.

2 BACKGROUND
For this study, the term *cross-disciplinary* is used to characterize a collection of practices associated with thinking and working across disciplinary boundaries: multidisciplinary, interdisciplinary, and transdisciplinary [13, 19-21]. Where disciplinary practice is often signified as a deepening along a vertical axis, cross-disciplinary practice is often signified as a horizontal axis of breadth, comprehensiveness, and synthesis [19, pg. 212]. This is often represented as a "T", and those who work cross-disciplinarily are often referred to as "T people" or complex systems thinkers.
A literature review suggests important variations in cross-disciplinary practice related to: 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 real change in knowledge to knowledge fusion through critical reflection), interaction structures (from collaborating as disciplinarians to beyond disciplinary structures), discourse practices (from perceived common ground to creation of new language and logic), and impacts on participants (from retaining a disciplinary identity to critical reflection on

pluralistic identities) [see 15, 22]. Many of these variations represent philosophical claims and have not been substantiated by empirical research.

3 METHODS

This study investigates the critical differences and similarities in the ways people experience and comprehend cross-disciplinary practice in engineering contexts. Phenomenography is a qualitative mode of inquiry that offers a way of investigating different ways of experiencing and understanding aspects of practice [16-17, 23]. Phenomenographical methods parallel the idea of generating an inclusive and expansive design problem space by purposefully eliciting diverse perspectives. 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 is consistent with phenomenographic studies, which generally range between fifteen and twenty participants. Sample variations include: context of work (academia, private industry, and community service), years of cross-disciplinary experience, gender, nature of experience in terms of project scale, and epistemological distance.

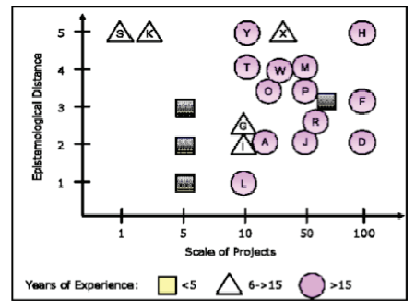

Figure 1. Sample distribution among key characteristics. Letters represent participant identifier code (e.g., G = Grace, I = Isabella)

Figure 1 shows key sample variations: years of experience, project scale, and epistemological difference. Epistemological difference is the extent to which an individual interacts with those with similar ways of knowing such as an engineer working other kinds of engineer or substantially different such as an engineer working with a social scientist. Data was collected using a semi-structured critical incident interview where participants were asked to recall a cross-disciplinary experience [see 24]. This was followed by probes for meaning such as asking participants to explain what they meant by "complexity" or details on the ways they worked through collaboration challenges. Interviews lasted 30 minutes and were audio recorded then transcribed. Analysis began with reading transcripts as a collection, and discussing what was significant within a whole transcript and in relation to other transcripts. Transcripts were sorted into piles of similarities (within a grouping) and differences (relationships across groupings). This was a rigorous 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.

4 RESULTS

The goals of the analysis were to characterize (1) a landscape view of the different ways people experience cross-disciplinary practice, (2) critical variations within this landscape, and (3) relationships among these variations that reveal increasingly advanced ways of experiencing cross-disciplinary practice. The outcome is four hierarchically related categories of variation (Figure 2). The progression from Category 1 to Category 4 represents increasingly complex ways of experiencing cross-disciplinary practice and a growing awareness and comprehension of cross-disciplinary practice. In other words, the experiences of Category 4 encompass Categories 1 through 3 plus unique additions. The following sections describe each category through supporting evidence.

Figure 2. Relationship among categories of variation

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*. This involves (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 how people think and communicate. Experiences in this category focus on communication and collaboration – being aware of how to engage people with different training, ask questions and listen for understanding, find points of synergy, and take personal responsibility to be an effective collaborator. This suggests that interactions with people are a crucial resource in cross-disciplinary practice, whether they are on a team or representing a stakeholder. For Emily, this involved "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. From the engineering side what they are doing, and from the other side, what needs to be improved, what details need to be in there….It's kind of a question, try something, go back and talk to them about it, question process." [Emily]

Similarly, Grace notes "probably the biggest challenge is getting the two to communicate." She emphasized a need "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 puts this responsibility on herself by developing an awareness of "hey this person doesn't understand me, I need to make it more clear…seeing on people's faces that they weren't understanding me." She also expects this of her collaborators:

"Just say what capacitance means to a biologist is totally different than what it means to an electrical engineer. So say in a meeting where both groups were represented, the idea of capacitance came up and the electrical engineer just continues with what they were trying to say, and right away the two go along different paths because the electrical engineer knows what they are trying to say, but the biologist hears capacitance and thinks in a totally different direction. And without that engineer knowing that the two don't mesh, they just start separating right there. So it's up to both parties to make sure that they're talking about the same thing." [Grace]

For Isabella, the process involved "baby step(s)" where group members would "go away and work on a little bit of something and bring it back and ask 'how about this' and then we'd talk about it some more." She describes an intricate questioning-listening process of asking seemingly simple questions to elicit implicit knowledge and taking the risk of looking "ignorant" while maintaining a culture of respect within the group. The outcome is new knowledge about what is possible or impossible.

"So it became trying to maintain the respect for the other discipline but at the same time trying to communicate what you need or want was really tricky….Asked a lot of questions. Not be afraid to say, 'I don't know what that means, can you explain it' rather than you know acting like I already understood just to save face which I think a lot of people who are working on multi-disciplinary stuff do just because it's very intimidating to work with somebody that talks something you don't understand. So you have to be really ready to sort of play the ignorant person and have the other person explain it to you." [Isabella]

"…and we hit this impasse because I didn't know what was feasible in terms of their discipline and they didn't know what I wanted in terms of this web utility. And so just getting to the point, because I didn't want to suggest something that was going to be very difficult or impossible, but I didn't know about the constraints and they couldn't communicate them to me." [Isabella]

Emily notes that the importance of this iterative communication process is "to be sure that we're going the right way. So that you don't end up going too far down the wrong road." For her, "good feedback goes both ways" – where the engineers need to be "willing to ask the questions" and listen as well as "sharing what their idea might be." Her concern was that by not having everyone share what they know, expertise would be missing and the project might fail.

"But if they hadn't shared that with me, I never would have known. And I never could have pointed it out right off, and they would have started and done the whole project and that would have been a waste of time and money." [Emily]

All Category 1 experiences were directed towards a shared goal of producing a better outcome that leveraged a cross-disciplinary approach. For Emily a better outcome was defined in terms of meeting the client's needs; for Grace, creating new applications that extended current practice; and for Isabella, finding elegant solutions to problems that she couldn't have conceived of on her own.

"If you get something that truly fits the client, you have just a stellar, stellar thing for them and especially in the case of something where it's to suit a particular need, like this ventilator box, this could be used by multiple people that are of this same clientele group." [Emily]

"If we can now take that information or that knowledge and apply it to medical and biological applications, we can extend our medical facilities, our medical practices so much more. I think that's the great potential there." [Grace]

"It would have been a lot less elegant if I wasn't working with them because I, because they have ways of dealing with problems that I couldn't conceive of. And I knew that going in and that's what I wanted from them." [Isabella]

Recognizing differences in disciplinary training (goals, methods, language and communication styles, etc.) and appreciating those who can move beyond disciplinary mindsets facilitated a link between an iterative communication approach and a goal of creating a better outcome.

"everybody's got a different twinge in their discipline. But let's just use engineering and biologists. They're brought up in two different ways. When you look at say the biology curriculum from my stand point, it's a lot of memorization, a lot of here's the facts, this is how you use them. For engineering it's more like here's a problem, here's how you figure it out. And so you're kind of brought up or taught or trained in different ways. And so we really get into being the biologist, your mindset is in that way as opposed to an engineer who might look at something and say, well, I can kind of figure this out, I'll figure out how to make it better. So they both have their pluses and minuses, but I just think they're trained in different ways and they get into those mindsets too much….That has a huge impact as far as you know, number one how they communicate but how they approach the problem or the challenge I should say. How each individual will approach a challenge makes the impact as to how it will get done and if it can get done." [Grace]

"the very first thing you really need to do when you're talking to someone who is in another discipline is understand what makes their perspective of their discipline unique and like what are the boundaries of their discipline and how does it interact with other parts of their discipline…because when I started working with ecologists, I thought of them as all being the same, but then I realized that there are people who study organisms, there's like organismal ecology, there's population ecology, there's community ecology, there's ecosystem science. Like those are really distinct sub-disciplines and they think differently and they have different skill sets and it's the same way with engineering." [Isabella]

Underlying this understanding was a belief that everyone has something to contribute or as Emily notes that everyone is "smart but in a whole different way" – to respect that everyone has "their own special way of knowledge and I've come to appreciate that a lot." Emily notes that when you encounter others what they know may look like "common knowledge like take chicken soup for a cold or something" but it's much more "intricate". Leveraging these different perspectives to address truly complex problems was the main driver for spending considerable time learning how to work together.

"I think it's vital…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]

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).* Intentional learning involves (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, and (4) learning *how* to negotiate meanings across perspectives and formulate or investigate problems through multiple lenses. A common feature of the experiences in this category is an overwhelming passion and appreciation for learning:

"I love it. I'd rather do that than anything else….I mean there's just so much to learn out there and so many cool things, so many talented people at a place like UNIVERSITY..." [Pablo]

"I guess I'm pretty comfortable with knowing that I don't know everything and having areas of expertise….So I think it's just a willingness and an openness to just not know everything and being willing to learn about some of the other things." [Brianna]

"it's part of the me that I like learning about what you do and if there's some kind of synergy" [Olivia]

Intentionality also plays out in being proactive in creating opportunities to learn. For Ryan, being "naturally open" and having a "curious mind" is an important personal motivator. Nadia did her own needs-assessment on her university experience and realized that she wasn't "getting enough science and math", that she wasn't "getting a comprehensive view on what's going on", and decided to explore different kinds of courses that were not required for her degree. Similarly, Olivia started with reading a sophomore level textbook to train herself in a new discipline and in the process develop a respect for a new way of thinking. Understanding how complex problems require not just new knowledge but also new approaches to learning triggers intentional learning. Pablo, a self-professed learner, notes "societal problems that need – you can't solve them in a single discipline anymore. I mean you could make incremental steps and that then can come in and help some area, but these problems are way too complicated…and I think the most successful people in the future at universities are going to be those that really aspire, want to, and work really hard at being interdisciplinary." Olivia uses metaphors of the "tail wagging the dog", "immunizations", and "injections" to explain why she continually expands her skill set.

"You know, here comes the tail wagging the dog because now you've got this problem that is now kind of motivating your research but for which you develop this skill-set. And this really was where I would say there was this major broadening of my career because I had the tools for doing the analysis and I developed tools for doing analysis but I had this major interest in terms of really understanding an application as well…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 before. I still think and I'm pretty convinced and I don't know if this has changed or not I don't think maybe is hadn't; but you need to have this disciplinary strength; but I would say that definitely I've gotten more respect for you know how difficult it is and how much effort it is to learn the other person's field or something about it." [Olivia]

Intentional learning involves educating others to co-develop a cross-disciplinary awareness and skill set. Ryan describes this process as learning "enough of someone else's job" to know how two jobs can "mesh". Similarly, Pablo notes that cross-disciplinary practice involves educating others about what you do, how you think, and broadening points of view in order to imagine new possibilities. Olivia purposely puts her students into situations where they must learn how to work cross-disciplinarily in order to be successful. She places students with different disciplinary perspectives in a project team:

"The first difficult problem for the class project was, "well what problem do we do?" "I'm not telling you what problem, you go out and find a problem of interest and it can't be either one of your dissertations and you know…there's got to be something from both of you. And so then they have to propose that, so that was a major issue. Just what could they do to communicate and then of course you always have a strong student dominating weak students in sense of telling them "okay, we're going to do this and you go do that", but you know its all part of the learning experience too for them to be able to work with people who are different and ask the right questions." [Olivia]

The experiences in this category emphasize learning through immersion or "on the job", from reflecting on failures, or confronting a challenging cross-disciplinary situation. Ryan describes a situation in which the company he worked for got sued, which triggered a need for him to learn about patents: "If that other company hadn't sued us, then I wouldn't know what I know. I wouldn't be doing patents for this group." Nadia talked about the importance of "hands-on learning by mistake" in developing an understanding of critical cross-disciplinary issues. Similarly, Brianna observed that her students had difficulty "understanding outside their discipline" which reflected a "reluctance of students to want to venture out of their comfort zone." For Olivia, learning was an immersion process that involved iterative cycles of monitoring the knowledge needed to fully collaborate:

"those experiences involved field work; significant field work which I didn't as an engineer have any experience in so I had to learn about that. In Australia, I worked with a collaborator actually. I had collaborators at New South Wales and we went out to sites and I learned to do vegetation surveys and I learned what they were doing…so we had kind of 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 I think…" [Olivia]

Outcomes span learning how to communicate and interact, seek connections among what may seem at first glance very different viewpoints, improve the conditions needed to work in cross-disciplinary situations, and improve an understanding of the problem (particularly its social and environmental context). As Ryan notes "I inherently know things that I wouldn't know otherwise." For Uri, learning

how to communicate and interact with people who have different backgrounds opened up an appreciation for other ways of thinking:

"mostly I've learnt how to communicate with other people which is, and I've learned it because you have to do so much of it and I think that's important because you need to be able to communicate with people out in the world, especially people that don't know exactly what you do. People that are in different fields have different backgrounds and I've really had to pick that up and how to communicate and talk to these people without their ideas getting completely messed up coming to me or mine vice versa….you'll learn that here's the experiences that they've had up to that point, and here's the experience I've had up to that point, and you'll realize that it was very difficult and you learn how specific people deal with their situations..." [Uri]

Overall, the full benefit of intentional learning is that everyone gains: the individuals, the team, and stakeholders. As Brianna notes, "I think it's essential. It allows to get the benefit, if we're working in parallel and not learning from each other, the product is not going to be better if we do that. It's essentially to really capture those different ideas." Olivia notes that even society gains – by "build(ing) capability, capacity building in a way with bright people very fast that didn't have the same background." This capacity building includes a new appreciation for different points of view, a respect for how "hard the other person's field is", and a new open-mindedness towards other disciplines that "strengthens everybody".

"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]

"…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…" [Olivia]

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 (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.

All of the experiences in this category involve a common approach or identity – being an interface, an enabler, and working towards a "worthwhile goal" – all which may or may not be associated with a formalized leadership position. For Jacob, his experiences involved being the communication specialist, someone who helps "people understand each other" and has 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." Fergus' experience involved interfacing with lawyers and marketing people to "translate their needs to a technical engineering perspective." Similarly, Daniel described one of his first experiences as a developmental "guinea pig experiment" where the company he worked at "took an existing organization, they took one level, pushed it apart and stuck me in between layer A and layer B". An aspect of being the "interface" is the capability to lead and do what was necessary to get the job done well. For Michael this involved being the person "willing to step forward and, to a certain extent, take the risk" and "orchestrating the answers". Daniel notes that sometimes being a leader is letting "up on ego and individual things like that". Fergus describes leadership as a broad thinking approach where "at the end of the day, if all else fails you have those leadership capabilities, communications skills, where you can ask the right questions, kind of like you're doing right now, to come up with the answers. That's really the key and for me I think that's really what cross-disciplinarity is."

Building and enabling system connections was a crucial aspect of Category 3 experiences, and much of this emphasized problem formulation activities. When discussing why he brought on certain people for a specific project, Fergus describes, "So very early on I realized, man we have to have all of those individual pieces connected if we're going to be successful with getting something to launch." Similarly, Tyler notes that one of his strategies involves knowing the "set of skills and maybe even opinions that you think need to be brought to bear to resolve a problem efficiently and effectively." Yvonne best exemplifies this idea of building systems-oriented networks of people as she describes her process for knowing what kinds of people need to be brought into a project. For her, the reward is "turning your lens in a way you couldn't have."

"a broader view of what it would take to design a game and how one might use it. It was clear that it is an area of study that has no disciplinary ownership. It is an area of study that has no historical disciplinary home….all of these academic disciplines are approaching this area of study, you want to get as many of those people involved in the work that you can. I wanted to know more. I wanted to know the technical side; I wanted to know the social science aspect of it. We have a humanist who's involved who's looking at the story, you know, the narrative structure, looking at issues of race and gender…so why do you bring people from different backgrounds together? Because the complexity of the area of study demands it." [Yvonne]

"I built a network of people, constructed a network of people who are interested in serious games…from computer graphics, from electrical and computer engineering, from engineering education, from communications studies, from computer science…from visual and performing arts, people from, who are interested in nano-technology, people from the veterinary school….you can't do interdisciplinary research if you can't see those intersections; if you can't see relevance of one domain of knowledge to another. There are not connections everywhere, but I think you have to be able to know if there is." [Yvonne]

Yvonne notes that while she may see the connections that drive her to bring a particular expert into a project, not everyone has this capability. As she notes "extremely bright people sometimes cannot see intersections".

"…building a network of people that you think have a background that would bring something to the group, I've had these one-on-one conversations and I'll tell them what I'm interested in…I'd ask them about their work, they'd tell me about their work and then they'd say, I don't think I have anything to contribute. And I would say, how? But look, you do this and we're looking at this and so what you're doing can be applied to this. Some people can't do that…you can see it almost right away….He just kind of sat there and didn't know. I said well I would love it, would you come and join us. Anyway, he said, I don't really think my work has anything to do with what you're talking about. I said have you ever done any applied work? And he said, yes, he had worked for a helicopter design firm in designing displays for helicopter dashboards. And I said 'and you don't see that relevant?'." [Yvonne]

Another key strategy is proactively building allegiance and trust, a strategy that comes from learning where and how projects fail. Fergus notes that the biggest issue was people issues not technical issues – getting "the right people involved in the decision-making at the appropriate time" and "project management skills, driving things forward and managing risk, communicating risk." Others also targeted a goal of enabling communication and collaboration, whether it involved disciplinary training, organizational functions, or global cultures. Jacob's strategy is to "seek first to understand, then be understood." He also works to persuade people to learn from each other by expanding "their minds to understand that there were things outside of their discipline that they needed to understand" and changing "their parameters of how they approached the problem." The goal of this process was to "find common ground to build before they actually met in person, because there were some very confrontational meetings." Daniel's strategy to "get a bunch of people to play together well" and "have fun doing it" involves creating a trust-based system:

"I get a set of people excited and positive about what the job is. So I'm not a detail person actually. I'm bad at that. But I'm a good judge of other people. My management style is a trust-based system. I mean if I have someone working for me, I have a high trust level. Basically I just convey the big picture and stay out of their way, if they have a problem they come and ask me but I'm really not involved very much. It scares a lot; I mean I've had bosses that think this is going to be a train wreck….For most people, they enjoy working in an environment where they have a trust level but it also means you have to earn and hold that trust. You can't break it." [Daniel]

Jacob also believes that establishing trust is crucial: "you have to be trustworthy yourself. So it really starts with you and then you model the behavior you want." Another challenge was combating a "human tendency to blame the new thing when everything else worked right before we changed to put the new thing in." To deal with this, Jacob worked with individuals to develop "the value of synergy" and appreciate "treading in a new space." This involved developing shared ownership so that "everybody's in on the ground floor" and everybody feels "like a father to what they're doing and then of course they own it." Fergus learned through experience the value of "involving people, partnering with people, getting alignment around, having people feel like they're a part of it, it's theirs."

Finding connections, building allegiance and trust, and valuing cross-disciplinary approaches all support a systems-oriented cross-disciplinary methodological framework. Yvonne notes that is necessary given the complexity of the problem: it's "complex when domain specificity can't answer all the questions for you. It's complex when even knowing who the community is, is not clear. When you have more questions than answers, it's complex." For Tyler, an "interdisciplinary framework" is the "only appropriate way of dealing with" the significant problems facing society. Fergus described one experience where he was in his "own little shell" designing a product where he didn't talk to others who represented the client's needs. He explained, "the product manager wasn't overly thrilled because it didn't really meet their need so there were a lot of things that were sort of missing. So that was probably the biggest wake up moment for me from a standpoint that you just can't assume that what you're putting together is going to meet everyone's needs." He learned that "you've got to ask questions, you've got to engage folks, you've gotta really start developing some systems engineering type skills and understand requirements, before you just jump and put a solution together." He described this as a systems level communication failure where the leader had "pushed too far into implementation phase" before investigating the problem formulation aspects of the process.

Similarly, Jacob notes how an "integrative motif, procedure, process, culture" enables the best outcome by facilitating a balanced approach to problem solving in which all voices are heard and respected, and all share ownership in a process of cooperative discovery:

> *"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."* [Jacob]

Category 4: Challenging and transforming practice to span 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*. This involves (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 (4) embracing cross-disciplinarity as everyday practice.

Category 4 experiences are often triggered by an awareness of human-sociological-technological interactions within cross-disciplinary problems and discontinuities in training that enable transformative critical reflection. For Wendy, "the great societal problems that we do…all take interdisciplinary approaches." In developing a cancer prevention expertise network she prioritized "collaborating with the department of English so in that; but still that can be a scientific approach in the sense that many physicians will tell you and I think many social scientists as well, and there's some evidence for that how you react emotionally to cancer may have a baring on how well you do." For Hannah, cross-disciplinary problems involve not "just technical things but attorneys, financial people, controllers, all of that" because it brings "so many different facets together." Xavier notes that when you "insert human behavior in the whole thing" you mix "quantitative and qualitative approaches (which) is sometimes straightforward but often times very difficult."

Discontinuities in training span questions about the practice of science, effective engineering practices, support for cross-disciplinary work within organizations, and the relationship between engineering

education and social justice. Logan notes discontinuities enable transformative thinking: "If everyone thinks like I do then the world is not going to be too good in the sense that you need some diversity, you want someone with other backgrounds to bring to the party. You need some conflict or some diversity….If we all think the same way, you're going to miss a lot…Now would things run a little smoother? Maybe because everyone is agreeing, but that's not a good thing either." Diversity creates conflict, involves taking risks, and challenging boundaries in order to open up new ways of thinking: "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…we need everyone together as a team. No one thing is better than the other."

Xavier challenges claims about cross-disciplinary collaboration and the practice of science. He reflects, "I see a lot of people claiming to be doing, what they would say, multidisciplinary or disciplinary science…I kind of look at it and say, well, not really." For Xavier, cross-disciplinary practice is not "taking stuff from me and stuff from someone else, and putting them together" but rather something that challenges your way of thinking. A sign of a substantive cross-disciplinary collaboration is "when you sit down across the table from someone else and you listen to the way in which they do their science and you become very suspicious at first." "(Y)ou recognize you don't "share common ideas, share common language", that the "gap between those are huge, they're, I mean, to the point where 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." Rather, Xavier notes that cross-disciplinary practice involves "looking at the science between the disciplines" because disciplines differ regarding the practice of science: "Practice of science is – what is good science? How do you actually collect information? How do you test your ideas? Where do your ideas come from? How are they developed? What is the nature of theories?" Reflection around these questions transforms a reductionist view of the "practice of science" to a more inclusive and pluralistic view.

> *"And when I began to do more reflection I thought that, okay, why is that we had these problems? You know, and that's where I started thinking more about what I called practice of science. What they valued most – well it's the reality vs. what a model can do. So what they value is good science, I value it much differently. My terms are very different, sometimes extremely technical. I can't be using those to communicate what it is I want to do." [Xavier]*
>
> *"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."* [Xavier]

For Hannah, integrating diverse stakeholder perspectives is crucial for addressing complex cross-disciplinary problems "because one solution may disadvantage another part of the project." She challenges a narrow view and argues for understanding "what some of the gaps were from the very high level perspective, so initially you were working at, what in industry they call the 50,000 ft. level." This high level view involves "working with a national government" and attuning to social and political issues. To ensure stakeholders are present in decision-making Hannah acts "as an advocate for the other company" because "at some point you have to be able to bring everything together, so you have to be able to come from those different perspectives." Hannah emphasizes a participatory relationship with key stakeholders because they "ultimately own the result of the problem", have "to pay to solve the problem", and "need to decide" if the results are "worth doing…is it a risk that they, as stakeholders, can accept." Similarly, Xavier notes, "working with stakeholders is not just, you know, something we take lightly. It's actually part of the science."

> *"these are the folks that have helped to identify the needs and identify the ways in which the solutions need to be delivered back, in many cases it's the general public, it is decision makers, it's industry, it's not-for-profit government organizations, government organizations, it's kind of a mix of a lot of different people that really do depend upon your work..."* [Xavier]
>
> *"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 …the constraints that they have, is very, very valuable to listen to that."* [Xavier]

Anthony challenged an engineering work practice of build-test-fail to develop a "new model for work…what I would call analysis-led design or analysis-led discovery." This new practice begins

with getting the "business questions clear." He notes, "nine times out of ten, when we get involved in the wrong modeling work, it's because we're not modeling the right thing." The second step involves translating the business question into an "abstract science question." Next, the "hardcore modeling begins" but the last step is to "simply and clearly, shape decisions", "changing the outcomes in innovation and at the end of the day, making money by delighting consumers and getting it in the market faster."

Kelvin experienced a critical transformation that began with a life-changing course on the nature of science that changed his "perception of what I thought science was, how I thought science moved" and he "realized that this was something I needed to deal with." He became curious about "why African American students were so unable to be successful in…learning science…liking science and eventually getting into professions with a scientific base." He "took a step back and said, well, all of the research that's gone into the nature of science that's produced this body of knowledge" is "only based on one group of individuals" and that this has "hurt people of color." Motivated by "the depths of inequity that children of color, particularly African Americans, have always had in the US education system", Xavier explored how a more inclusive picture of the nature of science may transform the experiences of African Americans in education systems.

"One of the things we don't teach is that, first of all, the scientific method is not the only way to do science, but one way. We don't teach about the cultural embeddedness of science. We do teach that science is strictly without value, human value. We teach that it's objective and that it's pure and what I know from my own research is that the same perspective has been used to hurt people of color because if the science says it, it's objective, I didn't have anything to do with it….science was developed by you, so you had a lot to do with it. It had your personal biases..." [Kelvin]

"...how you can start introducing these kids and saying yea, you are valued, you are part of it. Science is a human endeavor, it's a human construct, it comes from you. Whatever stories and whatever you may believe, you are science, you produce science, you do science." [Kelvin]

"...once I know the nature of science view, then that should have some affect on how we would structure pedagogy to take that into account. So ultimately it comes back to classroom and hopefully if the classroom changes, the interest in science changes and then the vocation of sciences is more I guess within the reach of those students, or within their interests." [Kelvin]

Like Kelvin, Samantha explored a nagging question about why engineering faculty "are never taught how to teach." An undergraduate feminist theory course challenged her views on the nature of engineering and had her mind "totally blown open" with "new insights" because people "talked about things I had never considered about the framework of what science was" and how that extended into engineering. Rather than turn away as if this new insight had "nothing to say to me" she went "whole hog" into exploring "other traditions or other areas or other methodologies that may not be represented or may not flow from peoples' experiences, but which have something to say." Her journey to integrate engineering and social justice involved using tools "from all kinds of stuff" which on their own couldn't provide an inclusive view "without the help of other disciplines."

Common across Category 4 experiences is a sense of significant personal investment – of time, hard work, sacrifice, putting the greater good first, and a life long endeavor.

"if people like me don't make this investment, then we're basically screwed." [Xavier]

"Hard work and sacrifices….You know, hard work in terms of investment of time. Investment of energy, sitting down and trying to train yourself." [Xavier]

"My point is, you do need a bit of the altruism; you do need to be able to do this for the greater good and not for something that's going to glorify you as a leader..." [Wendy]

"I decided that this wasn't going to be a one-time thing." [Samantha]

Hannah reflects that this is an investment that impacts not only "a team perspective" but also an "individual's perspective" that integrates disciplinary training with perspective that "comes from the experiences that one has had." For her, cross-disciplinary practice involves "bringing all your aspects of your life together." Logan notes he's been cross-disciplinary "since kindergarten", that "this is not my 'day' personality" but rather his everyday practice. For Anthony, sometimes a cross-disciplinary identity emerges from someone's "part of the innovation cycle" such as a "modeling guy" and sometimes a more general identity emerges: "(the interviewer) said—so what are you…I put engineering sciences as mine because I couldn't decide what I was anymore." When Xavier's colleagues ask how he identifies himself he says, "you know what, it's a good thing you're asking

that…I feel as though maybe I've done my job, you know, as a cross-disciplinary" person. Samantha notes that this new identity has advantages and disadvantages:

"I'm wrestling with this idea of homes now. And how I really feel that you have to have people that you can talk with, and so a cognitive home. But 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. It is a more explosive place. It's like, to use a boundary metaphor, the reactive place on the edge, where you have to make tools and ideas come from all kinds of stuff around, but none of which will be able to describe without the help of other disciplines." [Samantha]

5 CONCLUDING REMARKS

In this paper we present results of a phenomenographical study investigating the critical differences in the ways people experience cross-disciplinary practice in engineering contexts. 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*. As such, results from this study may provide a framework for cross-disciplinary thinking and learning goals associated with enabling cross-disciplinary work.

The analysis revealed four hierarchically related categories of variation (see Figure 1) suggesting an expanding awareness of how (1) complex situations require integrating multiple perspectives and systems thinking across not only disciplinary boundaries but more importantly technological-social-human-cultural boundaries, (2) collaborations involve iterative and self-directed reflective practice in order to yield new knowledge, integrated methodologies, system synergies, and personal learning gains, (3) differences encompass disciplinary training as well as lived experiences, and that a crucial aspect of cross-disciplinary practice involves learning through difference and seeking ways to redefine differences, and (4) engagement in cross-disciplinary practices involves participating as a collaborator on a team, facilitating synergy at the interface, and developing a cross-disciplinary identity as a part of everyday practice. To conclude we present some provocative questions regarding preparing people to effectively engage in cross-disciplinary practice and ways to enable cross-disciplinary work environments.

- What are the limits of the "T person" metaphor for cross-disciplinary practice? This study suggests that developing expertise in another discipline is one of many learning goals and that learning how to recognize differences, collaborate, co-develop knowledge, and broaden a perspective of disciplinary training may play more substantial roles.
- How might disciplinary expertise co-develop with cross-disciplinary expertise? This study suggests that early exposure to cross-disciplinary experiences may facilitate learning within *and across* disciplines by leveraging self-directed learning and epistemological development.
- Can cross-disciplinary practice be successful or lead to innovation without trust, respect, and shared ownership? This study suggests that a key aspect of enabling cross-disciplinary practice involves considerable strategic work to build allegiance and networks, integrate stakeholders, and shared values. It also suggests that challenging disciplinary practice impacts transformative innovation.

6 ACKNOWLEDGEMENTS

We would like to thank our participants as well as Shanna Daly, Denny Davis, David Radcliffe, and Monica Cardella for their contributions. This work as supported by NSF grant EEP-0748005.

REFERENCES

[1] Bordogna, J., E. Fromm, et al. Engineering Education: Innovation through Integration. *Journal of Engineering Education*, 1993, January: 3-8.
[2] Bransford, J. Guest Editorial: Preparing People for Rapidly Changing Environments. *Journal of Engineering Education*, 2007, Jan: 1-3.
[3] National Academy of Engineering (NAE). *Engineering of 2020: Visions of Engineering in the New Century*, 2004 (Washington DC: National Academy of Engineering, National Academy Press).
[4] Bucciarelli, L. L. *Designing engineers*, 1996 (Cambridge: MIT Press).

[5] McDonnell, J. Feedback to the design: A study of the negotiation of contributions in design conversations between architect and building users. In J. McDonnell and P. Lloyd (eds), *About Designing: Analysing Design Meetings*, 2009, (London: Taylor and Francis Group).
[6] Adams, R. S., J. Turns, and Atman, C.J. Educating effective engineering designers: The role of reflective practice. *Design Studies*, 2003, 24(3): 275-294.
[7] Dorst, K. & Cross, N. Creativity in the design process: co-evolution of problem-solution. *Design Studies*, 2001, 22 (5): 425-437.
[8] Ball, L. and Christensen, B. Analogical reasoning and mental simulation in design: Two strategies linked to uncertainty resolution. In J. McDonnell and P. Lloyd (eds), *About Designing: Analysing Design Meetings*, 2009, (London: Taylor and Francis Group).
[9] Jonassen, D. H., J. Strobel and Lin, C. Everyday Problem Solving in Engineering: Lessons for Engineering Educators. *Journal of Engineering Education*, 2006, 95(2): 139-151.
[10] Committee on Facilitating Interdisciplinary Research (CFIR), Committee on Science, Engineering, and Public Policy. *Facilitating Interdisciplinary Research*, 2005 (Washington, DC: National Academies Press).
[11] Bromme, R. Beyond One's Own Perspective: The Psychology of Cognitive Interdisciplinarity. In P. Weingart and N. Stehr (Eds), *Practising Interdisciplinary*, 2000. (Toronto: University of Toronto Press).
[12] Lattuca, L. *Creating interdisciplinarity: Interdisciplinary research and teaching among college and university faculty*, 2001 (Nashville, Vanderbilt University Press).
[13] Galison, P. (1997). *Image and Logic*, 1997 (The University of Chicago Press: Chicago).
[14] Nersessian, N. J. The Cognitive-Cultural Systems of the Research Laboratory. *Organizational Studies*, 2006, 27(1): 125-145.
[15] Adams, R.S., Mann, L., Jordan, S., and Daly, S. 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).
[16] Marton, F. and Booth, S. *Learning and Awareness*, 1997 (New Jersey: Lawrence Erlbaum Associates).
[17] Bowden, J.A. and Walsh, E. *Phenomenography*, 2000 (Melbourne: RMIT University Press).
[18] Daly, S., *Mann*, L., and Adams, R. A new direction for engineering education research: Unique phenomenographic results that impact big picture understandings. In *Proceedings of the 2008 AaaE Conference*, Yeppoon, Australia, 2008.
[19] Klein, J. T. *Interdisciplinarity: History, theory, and practice*, 1990 (Detroit, Wayne State University).
[20] Klein, J. T. Prospects for transdisciplinarity. *Futures*, 2004, 36: 515-526.
[21] Kline, S. J. *Conceptual Foundations for Multidisciplinary Thinking*, 1995 (Stanford University Press).
[22] Adams, R. S., Mann, L., Forin, T., and Daly, S. *Ways of Experiencing Cross-Disciplinary Practice in Engineering Contexts*. Presented at Research on Engineering Education Symposium, Davos, Switzerland, 2008.
[23] Bowden, J.A. & Green, P. Doing Developmental Phenomenography, 2005 (RMIT University Press: Melbourne).
[24] Mann, L. M. W., D. Radcliffe, and Dall'Alba, G. Using Phenomenography to Investigate Different Ways of Experiencing Sustainable Design. In *Proceedings of the ASEE Annual Conference & Exposition*, Honolulu, Hawaii, 2007.

Robin S. Adams (Assistant Professor at Purdue University in the School of Engineering Education) holds degrees in ME, MSE, and Education (http://xdisciplinary-thinking-practice.blogspot.com/).

Llewellyn Mann (Lecturer and Foundations Coordinator at Central Queensland University in Rockhampton, Australia) investigates developing 21st century engineering professional skills.

Tiago Forin (doctoral student in Engineering Education at Purdue University) holds BS and MS degrees in Civil Engineering, is an alumni brass performer and President of Purdue's Fencing Club.

Shawn Jordan (doctoral candidate in Engineering Education at Purdue University) investigates geographically distributed design teams and innovation, and founded Purdue's winning Rube Goldberg team.