Characteristics of Successful Cross-disciplinary Engineering Education Collaborations

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Abstract

This article employs theory to demonstrate the characteristics of successful cross-disciplinary engineering education collaborations. Specifically, we analyzed data from interviews with 24 recent *Journal of Engineering Education* authors from engineer-nonengineer teams. Theoretical frameworks from education and psychology are used to ground the results and contribute to broader research on collaboration across technology and social science disciplines. The data suggest that the way an individual understands and appreciates the nature of knowledge affects the way he/she collaborates with colleagues in different academic disciplines, especially when the disciplines are fundamentally different. Though the literature criticizes engineers for not understanding or respecting other viewpoints, we found that nine engineers and eight nonengineers articulated awareness of their collaborators' perspectives, worked to integrate these into the research, and noted increased satisfaction and quality of work as a result. Recommendations for fostering this type of interdisciplinary integration in engineering education and are offered along with suggestions for future research.

Keywords: epistemology, faculty, interdisciplinary collaboration

I. Introduction

With only a handful of individuals currently trained in both engineering and education traditions, engineering education research currently relies on collaboration between engineers and social scientists (including educational researchers). At the 2006 ASEE annual conference plenary, *Journal of Engineering Education* editor Jack Lohmann stated that in recent years, *JEE*'s acceptance rate has been 20-30% when a social scientist is a member of the author team, but only 2-3% if the authors are all engineers—a difference in acceptance rate of a *full order of magnitude*. Similarly, the National Science Foundation's Engineering Education programs call PD 05-1340[1] states "It is expected that successful proposals will most likely be comprised of multidisciplinary teams of engineers and other fields that bring expertise pertinent to learning research." Even as new PhD graduates trained specifically in engineering education emerge, collaborations that cross disciplinary lines will continue to be a critical component of engineering education research.

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[1] http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=13374&org=NSF&more=Y, accessed 2/22/2007

Despite these and other motivators of cross-disciplinary research, boundaries between academic disciplines still pose problems for those who wish to try their hand at it. These roadblocks include promotion and tenure requirements and department politics on one level, and communication and competing truth claims on another. While a number of publications provide anecdotal evidence of these difficulties, surprisingly few published empirical studies focus on cross-disciplinary collaboration processes (see [1-3] for empirical studies).

Although practical difficulties like differences in terminology are commonly cited in discussions of collaboration, research on disciplinary differences reveals more fundamental variation in the ways individuals in various disciplines discuss problems and value knowledge. The combination of disciplines can also impact how closely collaborators work together; we and others argue that the level of integration for a collaborative project can be a predictor of the quality of the final product [4]. Most people will agree that researchers from other disciplines "see" things differently, but by understanding the underlying differences and how these can expand possibilities for research, would-be collaborators can learn lessons invaluable to cooperation, communication, and ultimate understanding. The Research Agenda for Engineering Education specifically cites engineering epistemology as a key area for future research, and goes so far as to initiate a "call to the nation" to answer the problems of engineering education through research of "the historical, contextual, and philosophical" dimensions of engineering epistemology both in practice and among faculty [5]. In the process of such learning, students, practicing engineers, and faculty are likely to develop higher quality products as a result of more fully integrated perspectives.

Thus, the purpose of this project is to better understand cross-disciplinary collaboration in engineering education research for the purpose of facilitating increased collaboration between engineers and nonengineers. As demonstrated in the results and discussion, this research contributes to both theory and practice in the specific setting of engineering education, as well as the larger body of empirical research on interdisciplinary collaboration and theories of interdisciplinarity and epistemology. The following questions guided this research:

1. What models and procedures do engineer-nonengineer collaborators employ in productive engineering education collaborations? Specifically, how do they find collaborators? What structure do their interactions take? How do they share or divide the workload?
2. Which individual characteristics might be attributable to successful engineering education collaborations? In particular, how do epistemology and a willingness to learn affect collaborative relationships and outcomes?
3. What are the implications for the emerging field of engineering education? What recommendations can be made to engineer and nonengineer researchers planning to collaborate in cross-disciplinary engineering education research?

For the purposes of this study, "successful engineering education collaborations" are defined as those resulting in a *JEE* publication in recent years. As described in the methods section, persuasive sample size had to be balanced with realignment of *JEE* as the cutting-edge engineering education research journal in 1993 and again in 2005 [6, 7]. Two other key terms should also be defined. First, we use “cross-disciplinary” as a general term to describe collaborations involving multiple disciplines; the more specific terms “interdisciplinary” and “multidisciplinary” are defined in the literature review section. In this manuscript, cross-disciplinary encompasses both interdisciplinary and multidisciplinary collaborations. Second, epistemology is defined as the way an individual values and understands knowledge. Specifically, it is “the theory of knowledge and knowing … a branch of philosophy concerned with the nature of knowledge, its possibility, scope, general basis, and justification of belief” [8].

The following section begins with a theoretical grounding for the idea that successful interdisciplinary research is the result of an open approach to learning and valuing other disciplinary perspectives. Then, we explain the methods employed in this empirical study. The methods section also includes the coding tree used in analyzing the data, which provides an organizing framework for the results section which follows. Finally, we end this paper with a brief discussion of implications and recommendations for further research and practice.

II. Theoretical Framework: Truly Interdisciplinary Collaboration as Integration of Epistemologies

A. Multidisciplinary Collaboration and Truly Interdisciplinary Collaboration

Cross-disciplinary collaborations can be enacted through either (1) multidisciplinary approaches or (2) truly interdisciplinary approaches. Figure 1 demonstrates the differences between strictly multi- versus truly interdisciplinary modes of collaboration. In a multidisciplinary approach to research, collaborators come together to work on a problem, each bringing his or her own expertise and unique contribution. There is limited exchange of information in this approach, only two (or more) experts coming together to contribute an expected product to the outcome [2, 9]. While the product of a multidisciplinary collaboration may be considered excellent research, collaborators leave the project without having learned much about the other discipline(s). Each researcher continues on his or her own independent trajectory, unchanged by the experience. This appears to be the more common approach to cross-disciplinary research [3, 10]. In contrast, in a truly interdisciplinary approach to collaboration, researchers from different disciplines work in a more integrated way to solve a problem together. Rather than each contributing separate pieces to the solution, the collaborators work closely together, combining their knowledge from their own disciplines to work toward a solution [2, 9]. At the end of a truly interdisciplinary collaboration, each collaborator is changed by the experience.

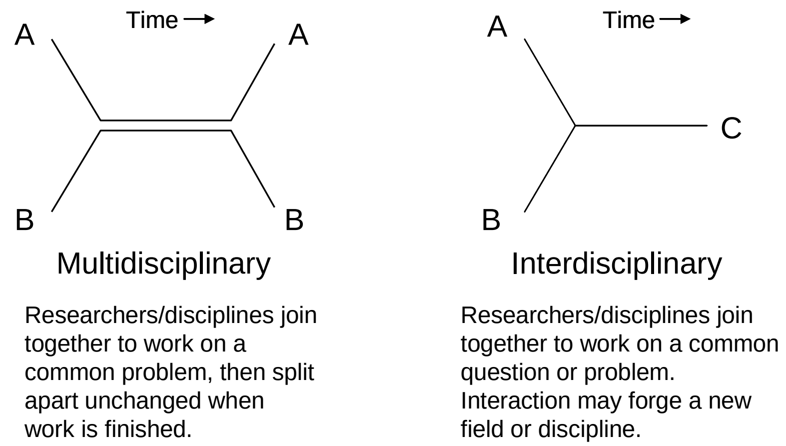

Figure 1. Difference between multidisciplinary and truly interdisciplinary research collaborations, reproduced from [9].

B. Collaborating With Engineers: Approaches and Roadblocks

Truly interdisciplinary collaborations require some effort on the part of the collaborators to understand and appreciate the contributions presented by various disciplinary frameworks. This is not always easy when fundamental differences are involved but not obvious. Biglan [11] provides a framework for understanding why and how engineering research is different from that in education and other social science fields. High consensus disciplines like traditional engineering and the sciences feature a strict level of agreement upon standards with which to validate truth. As a result, the criteria for success in these disciplines are clear and implicit knowledge to all. In low consensus disciplines like the humanities and social sciences, research thrives on controversy and contributions are seen as part of a broad conversation rather than as claims to absolute truth [11]. In engineering education, which relies on the collaboration of engineers with educators and social scientists, these differences in understanding and approaching a research problem present both difficulty and opportunity.

Specific studies have compared collaboration styles in high- and low-consensus disciplines. Lodahl and Gordon [12] found that the high consensus and well-defined terminology in fields such as chemistry and physics enabled a multidisciplinary division of labor. For example, specific types of instrument-based analyses can be requested, performed and reported with limited discussion or interaction among team members. Lodahl and Gordon also believe that collaboration is often more truly interdisciplinary in low-consensus social science and humanities disciplines because these disciplines require that researchers work more closely to agree on methods and interpretations. As a new discipline featuring lower consensus, engineering education shares more characteristics with social sciences than with traditional engineering [13] and is likely to benefit significantly from truly interdisciplinary rather than strictly multidisciplinary approaches to collaboration [14].

However, a review of interdisciplinary literature suggests that engineers are often uncomfortable with or unlikely to participate in truly interdisciplinary work. Klein [2], for example, criticizes traditional engineers for building bridges across disciplines in a more multidisciplinary way than a truly interdisciplinary way. Borrego [15] similarly found that engineers are more likely to rely on the expertise of others than seek to understand specific aspects of a project themselves. This reliance on trust without understanding suggests that engineering collaborators are not fully involved in the details of others' work. Often, engineers euphemistically refer to this process of reliance on an educational expert as "trust," offering explanations like, "I'm trusting them to do their part, because I am too busy" [15].

While this method of strictly divided labor works reasonably well in traditional engineering, it may not be the best approach for engineering education. Engineers have been criticized by others as being particularly unlikely to consider other perspectives as required for truly interdisciplinary work as a symptom of their positivist [16] or post-positivist [17] orientation. Positivism relies on a particular method of truth validation that emphasizes the importance of quantitative data and statistical analysis and does not allow for multiple epistemologies in the same way as social science research. Specifically, Klein [2] believes that engineers "do not tend to engage in critical reflection on problem choice, the epistemology of the disciplines being used, or the logic of disciplinary structure." Similarly, Muis and Haerle [18] argue that engineers enact post-positivism as instrumentalism, breaking up the work and dividing the tasks among "experts" as described above. If engineers are indeed as positivist as these studies indicate, with no interest in considering other disciplinary perspectives, they could be undermining attempts at truly interdisciplinary collaborations and disabling the progress of engineering education and perhaps engineering as well.

C. Epistemology

A researcher's attempts at cross-disciplinary collaborations are necessarily rooted in his or her epistemology. Simply stated, a person's epistemology is her way of knowing and understanding the world. As a deep-seated view of knowledge, epistemology dictates which research questions, methods, and purposes a person considers to be legitimate. Epistemology is related to discipline, and problems occur when collaborators assume that one's specific epistemology applies to other disciplines. Since epistemological differences are expected to be most significant when high consensus/low consensus lines are crossed, the potential implications for engineering education collaborations are substantial.

In order to overcome the barriers confronted by different ways of knowing and valuing truth in engineering education collaborations, one must first (1) be able to identify his or her own epistemological framework and be aware of the strengths and weaknesses inherent to it. For an engineer, this means realizing that the methods used in engineering are not the only ways to accumulate understanding. For example, while the natural world often allows us to uncover universal truth, the social world may involve multiple realities dependent on context. After realizing that different ways of knowing exist, a person must (2) learn enough about them to respect them. The final step is (3) integration of a new epistemology into the collaboration. The result of this process, we argue, is a truly interdisciplinary approach to research.

D. Promoting Interdisciplinarity in the Engineering Education Context

In a review of literature, Lattuca et al. [19] used two case studies to explore the types of learning that truly interdisciplinary courses might promote. They cite Davis' [20] arguments that in an information society, students need to cope with multiple perspectives to address problems as a system and solve them comprehensively, and that truly interdisciplinary courses can help develop comprehensive perspectives. Specifically, they say:

> Students must also be able to see, evaluate, and select from among differing perspectives that bear on a problem…Despite differing assumptions about the sources of epistemological beliefs [home environments, pre-college schooling, and major fields], researchers agree that pedagogy can promote the development of sophisticated views of knowledge—and should therefore challenge students to learn to recognize, evaluate, and choose among multiple perspectives [19].

If students are to engage in truly interdisciplinary work as Lattuca suggests, faculty must develop truly interdisciplinary approaches. The NSF is aware of the need for this kind of training and has made a goal of increasing cross-disciplinary collaborations, especially in engineering education. Their strategic plan states that they will "emphasize investigations that cross disciplinary boundaries and require a systems approach to address complex problems" [21]. Furthermore, they express the belief that "[d]iscovery increasingly requires the expertise of individuals with different perspectives—from different disciplines and often from different nations—working together to accommodate the extraordinary complexity of today's science and engineering challenges" [21]. The "extraordinary complexities" referred to by the NSF strategic plan are only intensified by discipline-specific epistemologies and the inability (or unwillingness) of one discipline to appreciate the concerns of another. Perhaps, then, the type of learning or changing of perspectives suggested by the NSF and in the definition of truly interdisciplinary collaboration may be achieved through thoughtful consideration of multiple epistemologies.

E. Cognitive Flexibility as Tool for Truly Interdisciplinary Collaboration

If epistemology varies across academic disciplines, a truly interdisciplinary collaborator must necessarily be able to change his or her epistemic "lens" to suit various contexts. This idea of cognitive flexibility is detailed by Spiro et al. [22] as a means of adjusting ways of knowing and thinking contextually. The theory of cognitive flexibility emphasizes cognitive training as the main facilitator of—or roadblock to—a researcher's ability to accommodate or shift epistemologies according to context. Examples of engineering education situations requiring this kind of flexibility include presenting results to education research and engineering faculty audiences, or addressing the validity concerns of various collaborators and reviewers. Because exposure to a variety of complex problems increases cognitive flexibility, research, particularly in engineering education, is an ideal gymnasium for cognition. By bringing together the efforts of engineers, social scientists, and others, engineering education research represents the ideal complex problem because, as previously stated, the ways of knowing and of valuing knowledge can be particularly divergent across these two domains. Thus, engaging in engineering education research may foster cognitive flexibility, with benefits to both the immediate project and the researchers involved.

III. Methods

A. Participant Selection and Data Collection

To explore the issues described above with respect to cross-disciplinary collaboration in engineering education, 32 engineer-nonengineer *Journal of Engineering Education* coauthor pairs were identified for a recent four year sampling period. (The exact date range and systematic selection rules are not reported to protect the identities of participants.) Human subjects research (IRB) approval was secured, and each participant was interviewed either in person at the 2006 ASEE annual conference or over the telephone. Five potential participants declined to participate. Three other potential participants could not be located after they had left the organization listed on their articles. A total of 24 participants were interviewed, broken down as 14 engineers and 10 nonengineers representing 15 distinct pairs. Not all members of each collaborative team were interviewed. For this reason, the sample includes six unpaired interviews. Engineering participants represented five different engineering disciplines with high representation from chemical and electrical engineering. Nonengineers represented education, psychology, educational psychology, instructional technology, humanities, public policy, and campus teaching and learning centers. The term "social scientists" is used interchangeably with "nonengineers" to refer to all of the nonengineers in this study.

In their interviews, participants described their past experiences collaborating across engineering and nonengineering disciplines. The interview protocol was semi-structured to allow for clarification of how the partnership(s) was initiated, how work was distributed, lessons learned for future collaborations, and comparison to other collaborations within the home discipline. Two forms of member checking [23] were used to verify findings. First, the researcher summarized statements made by the participants within the interviews to ensure clarity and understanding. Second, this manuscript was sent to all interviewed participants to preview and comment on before submitting for peer review.

B. Data Analysis

Constant comparative method [24] was employed to thoroughly and systematically analyze the interviews to arrive at the conclusions. First, a simple set of codes was established and applied to categorize brief passages in the data. Examples of codes are listed in Figure 2. An open coding approach was used, in which codes were developed based on the concepts emphasized by participants through their comments and questions, using their own language whenever possible. After the codes were created and applied, a second researcher independently checked the codes and applied them to the entire data set. Discrepancies were used to refine the definitions of the codes, and passages with the refined codes were checked and recoded if necessary.

The frequency and clustering of codes were then used to draw conclusions about the cross-disciplinary collaboration experiences. Specifically, each participant was identified as preferring either a multidisciplinary or truly interdisciplinary approach to engineering education collaboration. Initial categorization was based on the relative number of comments coded as multidisciplinary or truly interdisciplinary in nature. Then, each categorization was verified by both researchers rereading the entire interview. The results section describes the preferences of the engineers and nonengineers as well as match or mismatch between coauthor pairs. In other areas, codes were first organized into categories, with special attention paid to the background of the participant and the perceptions of that participant's coauthor. The data from each category were used to develop themes addressing the research questions. It is this systematic rigor in analyzing data that distinguishes qualitative research from anecdotal information and other superficial analyses [25]. The resulting coding tree is presented in Figure 2. It follows a structure suggested by Anfara and coworkers [26], and provides structure to the results sections which follow.

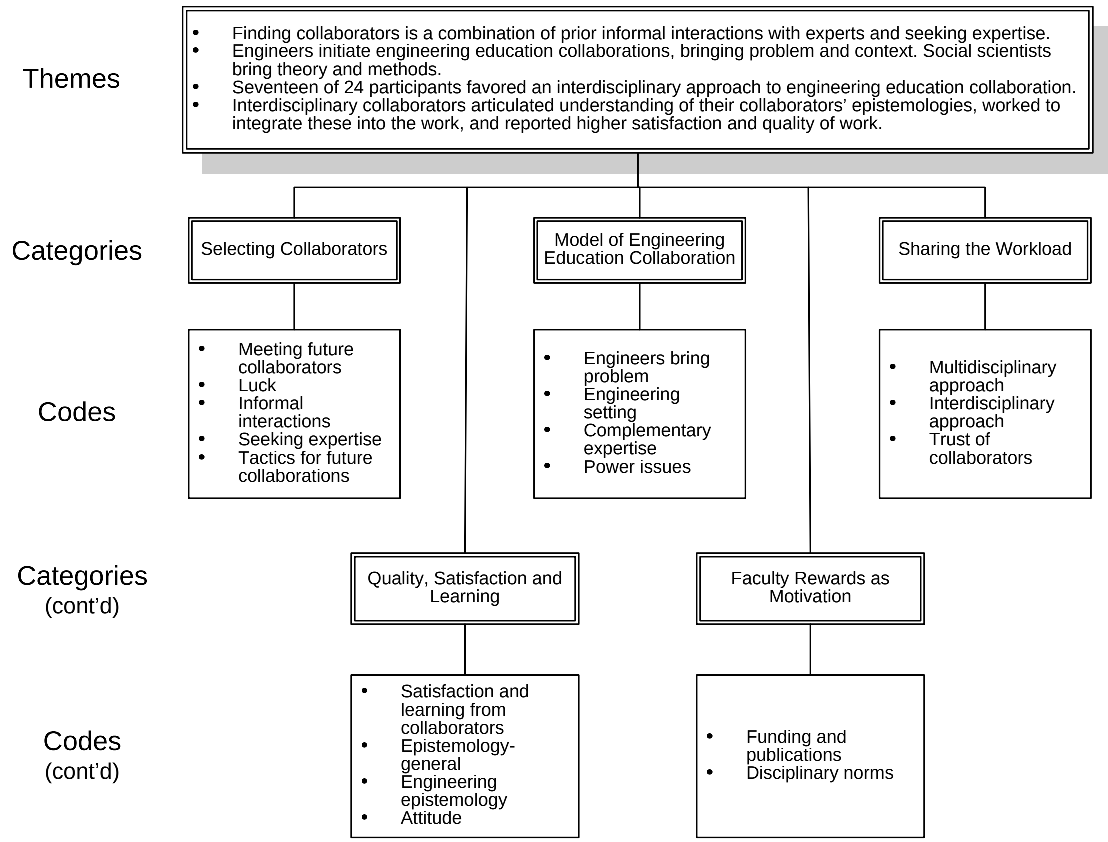

Figure 2. Coding tree resulting from systematic analysis of interview data. Format from [26].

IV. Results

A. Selecting Collaborators

1) Meeting Collaborators

The first step in any collaboration is locating and enlisting a collaborator, which may be more challenging in cross-disciplinary work, as disciplinary boundaries tend to keep engineers and nonengineers on different sides of campus. The data demonstrate that cross-disciplinary collaborators often seek out experts in another field (such as education or psychology) for the specific purpose of a pre-conceived study, and that existing personal and professional relationships with these experts are a source of "serendipity" in moving the project forward. (The concept of serendipity in engineering education research opportunities is also evident in studies of interdisciplinary individuals [27].)

For example, knowing that an assessment component was needed for an existing or planned classroom intervention, participants informally asked current acquaintances, with whom a rapport was already developed, about potential interest. Specific strategies included looking for potential collaborators among friends, family members, neighbors, and church members. Others found future co-authors through professional connections such as co-teaching, committee service, conference attendance, attending lectures and contacting the speaker directly, advisor/advisee or mentor/mentee relationships, serving on review panels, membership in interest groups, and reliance on existing interdepartmental collaborations within an institution. One nonengineer was "amazed at the number of collaborations that come out of putting people in a room together with a semi-structured program" around a specific research area.

Support from the institution was key in facilitating these collaborations across departments and colleges. Although the question was not specifically asked in the interviews, three nonengineering authors mentioned their good fortune at having institutional support for their interdisciplinary collaborations. These persons were able to seek the recommendations of their deans and look to them as examples of cross-disciplinary collaborators. Support from reduced department and college boundaries or advice from deans and other colleagues was a helpful tool for these authors. No matter the particular strategy used, cross-disciplinary collaborative research ultimately begins with the recognition of the need for expertise in an area beyond one's own disciplinary training.

2) Seeking Expertise

Of the 24 authors interviewed, 8 (7 engineers and 1 nonengineer) specifically mentioned that they sought out expertise. One engineer explained it this way: "You can be hard core technology in one discipline by yourself. But you cannot be successful in education alone because there are humans and other complexities [involved]." Other engineers described the decision to seek expertise as motivated by the research question coupled with lack of expertise:

> I knew I wanted to capture what was happening, which we couldn't have done in a survey. I wouldn't even know which questions to ask. So I knew I needed some help with the qualitative work…. I seriously wanted to know about how the students were using the materials. I just didn't know how to measure that.

However, establishing collaborations strictly on the basis of expertise could be problematic if other factors such as work ethic, interest in the research question, and personality are ignored. This was the case for one nonengineer, who expressed displeasure with past collaborations in feeling like the "token" social scientist brought in only to appease the funding agency. This social scientist eventually quit this particular collaboration because "I started to feel like my input on the instructional issues was being ignored. I got the impression that they wanted someone from another department because NSF wanted that." This example demonstrates that expertise alone is insufficient basis for successful cross-disciplinary collaborations—authors also identified professional compatibility as essential.

3) Informal Interactions to Determine Compatibility

The data suggest that compatibility in engineering education collaborations often stems from common interests and work ethic, and informal interactions provide low-risk opportunities for would-be collaborators to get to know one another. These collaborations often grow out of informal discussions. One engineer was surprised to learn that his co-teaching partner “was also searching for research ideas.” Team-teaching partnerships in particular appear to be ready-made for engineering education collaboration because the persons involved are likely to already have a shared research interest in pedagogy and know how to work together. The teaching partner of the engineer above said, “[we] would shoot the breeze during course planning.” Another engineer said of his collaboration “[i]t started out as hallway talk, then we started compiling the data.” Others were more strategic, instigating informal interactions specifically for the purpose of finding collaborators. One engineer says, “I started an interest group on campus” in an effort to find people with similar research interests. No matter their specific genesis, informal beginnings to formal collaborations have the advantage of allowing for familiarity first as a foundation for their work.

4) Tactics for Future Collaborations

Upon reflection of their approach to finding and enlisting collaborators, six authors offered specific thoughts about what they would consider when looking for future collaborators. Some preferred more strategic methods than leaving it to chance as before, emphasizing expertise but also desiring compatibility of work ethic. One engineer said that, given the opportunity to choose a collaborator over again, “I would have asked the dean for someone with experience.” Another engineer elaborated on personal attributes as part of the attraction of a future collaborator and said,

> Personally, I would pick someone I could get along with. You know, so it would be easy to have a discussion. Someone that’s not difficult to work with, who thinks their time is too valuable. That would be [my] first [concern]…Second, I would want them to be active themselves in publishing. I don’t want them to take 12 years to do their part.

Collectively, authors noted expertise, work ethic, and personality as key factors they would evaluate in finding new collaborators. These suggestions align with our other findings that compatibility of personality and work ethic, as well as complementary expertise are also imperative to the success of engineering education collaborations.

B. Model of Cross-Disciplinary Collaboration in Engineering Education

Building on the fact that in all but one of 15 cases, the engineer initiated the collaboration, the interview data suggested a possible model of collaboration in engineering education. This model is depicted in Figure 3. In the case of many of the pairs several factors were apparent:

1. The engineering faculty member recognizes a problem, often in the engineering classroom.
2. The engineer provides the problem statement, context, and motivation to improve the educational experience for students.
3. The nonengineer (often education or other social science researcher) provides structure by applying theory and methods relevant to the problem at hand.

It must be noted that Figure 3 is not the only possible model for cross-disciplinary collaboration; it represents the process as it has operated in the recent past. The following sections discuss the findings related to the three steps mentioned above with specific data from the interviews to illustrate this model of cross-disciplinary engineering education collaboration in action.

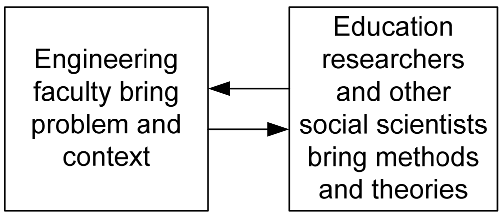

Figure 3. Model of engineering education collaboration (between two or more people).

1) Engineers Recognize a Problem

Engineering education collaborations are most often borne out of problems identified by engineers, as depicted in Figure 3. A nonengineer offers an example of how this happens:

> [The engineers] had a problem with the freshman course in engineering. They wanted to attract more women, more minorities, and more students overall to engineering. …The idea was to get students to understand what engineers do in the real world. We decided to redesign the course.

Often nonengineers are only waiting for an engineer to suggest collaboration and application for their expertise. Many nonengineers are simply too unfamiliar with the engineering setting to instigate engineering education research. A nonengineer said,

> I know too little about engineering education to supply my own problem. I am more passively waiting for them to ask me to join them. I may have a new idea about [instructional] technology, but I am not sure of its applicability to engineering. I don't generate my own research questions.

Another nonengineer expressed a similar method of finding engineering collaborators: "I wait for them to come to me." Because researchers outside of engineering are sometimes reluctant to make the first step in forging cross-disciplinary teams, it is necessary for engineers to take a proactive role in forming cross-disciplinary research partnerships. Making this model explicit can help give engineering faculty the confidence to initiate collaborations by contacting complementary experts.

2) Engineering Setting

Because engineers generally supply the problem (e.g., in the form of a freshman design course), the research tends to take place in an engineering setting with engineers working from a teaching point of view. Engineers provide deep understanding and concern for the setting which contributes to data interpretation and ensures the results will be put into practice. For collaborators from outside engineering, working in unfamiliar territory provides both difficulties and opportunities. One nonengineer said that "[k]nowing the disciplinary context is half the battle" in engineering education collaboration. Another nonengineer expressed a lack of knowledge about engineering as a discipline. He said, "I didn't think that engineers drove trains or anything, but I wasn't that far off." Lack of initial understanding of the context of the research problem can be a psychological barrier for nonengineers. However, the interview data suggests that where there is a will, there is a way. An engineer said of his nonengineering collaborators, "[t]hey are interested, too. They are looking for contexts. … They have their own theories they want to test, and to extend them." The engineering classroom context allows for practical application of social science theory, resulting in a generally rewarding experience for all involved. Furthermore, it presents opportunities for learning on the part of the nonengineer. One said, "[in engineering education collaboration] I've learned more about undergraduates and educating engineers…this gave me a chance to know a different population."

3) Nonengineering Theories and Methods Complement

While engineers provide the problem and context and ensure the results are applicable, nonengineers provide structure to the project in the form of methods and theories. This was the experience of many of the collaborators interviewed for this study. One nonengineer says that it is more desirable to collaborate with someone outside of his discipline because:

> [M]y contribution in engineering is more unique. In [my discipline], we all have the same training, so someone might know a little more or less than me, but the knowledge is about the same. It's easier to communicate [in own discipline], but [in engineering] they value my contribution better.

Another nonengineer says that in cross-disciplinary collaboration,

> We each have a different substance and process, but if we have enough interest in the same thing and talk about it, that's when it gets interesting… When you are complementary and can bring different skills, sometimes that's enough.

The data clearly demonstrate a belief among authors that collaborators with complementary expertise can bring valuable contributions to engineering education research. One engineer believes that "[i]f you get too many people of the same type together, you have too many opinions on how to do the work, and the team gets bogged down in decisions." The general opinion appears to be that teams made up of researchers from different disciplines do not have this problem, and in fact, new perspectives lend important insight. One engineer expressed relief at recognizing that working with nonengineers would allow access to their expertise. This person said, "eventually we decided you could just collaborate with them. We didn't have to become them."

4) Potential Ownership and Expertise Issues

Because engineering education research often takes place in an engineering setting, with the engineers bringing the problem and relying on others for specific expertise, ownership of the ideas and the end product can be unclear. In just one of the teams interviewed, this arose as an issue. Questions of who was "in charge" led to limitations in the ways by which various collaborators could contribute. The nonengineer expressed that "there were ownership issues. Not explicit ownership issues, but I think they were located in that tension. [The engineering collaborator] had the purse, it was his idea, his design." Furthermore, s/he said, "[i]t was [the engineer's] baby. It was awkward because it was [the engineer's] idea …We're both very strong-willed." An engineer in another pair also assumed that the engineering initiator has the upper-hand in the research. He said, "as the PI, I was in the driver's seat." It must be noted, however, that power issues were directly mentioned in only one case out of a represented 15 pairs of successful collaborators.

C. Sharing the Workload

The interview data indicate different approaches to sharing the workload in research collaborations, which are also corroborated by the literature [2, 9]. Each participant appeared to prefer one of two main approaches:

1) those who separated the work and let each "expert" perform his or her own tasks, what we call *multidisciplinarity*; and
2) those who demonstrated *true interdisciplinarity* and were more willing to understand and critically evaluate all of the aspects of a research project.

Most often a team's feelings toward collaboration ("multidisciplinary" versus "true interdisciplinary") were matched (n= 6 out of 10 pairs in which both collaborators were interviewed). That the majority of the pairs had similar ways of approaching collaboration leads to two possible conclusions. Either the researchers purposefully sought out like-minded partners for collaboration, or one person's style of collaborating eventually changed other. This speculation goes beyond the scope of this article because from this data set, it is impossible to determine if attitudinal alignment was initially present as a basis of the collaboration or developed over time. In fact, many collaborators simply cannot remember these kinds of details after the work has been successfully published.

1) **Multidisciplinary Approach**

A little over one-quarter of the collaborators interviewed for this study seemed to be most interested in strictly dividing the labor in a multidisciplinary approach (n=7 out of 24). One engineer put it this way: "With a cross-disciplinary collaboration, it's easier to divide the work. You need to know a little about what the others can contribute, but then you can leave the work up to them." All of the authors who preferred the multidisciplinary approach expressed that labor division made sense because of the complementary expertise of the collaborators. One nonengineer simply recounts that his collaborator said "it would take too long to learn" what he needed to know to understand the nonengineering perspective, and so the easy answer was to divide the labor with each knowing little about what the other was up to.

Statements like these suggest a model of multidisciplinary collaboration in engineering education in which the engineering and social science faculty each contribute to the final product, but in which exchange between the collaborators is minimal. As shown in Figure 4 and described in the literature [9], this results in an end product which may appear pieced-together with an obvious seam and lacking complete integration, often described colloquially as "stapling sections together" or "throwing it over the fence." While these publications were not analyzed for coherence, the relative citation rates (Web of Science Citation Index data) of the *JEE* articles used to select interview participants provide some indication of quality. Each of the 15 articles was deemed to be either multidisciplinary or interdisciplinary based on the interview data from the coauthors as described in Section II.B. On average, multidisciplinary articles (n = 4) have been cited 0.05 times per year since publication (i.e., data were normalized to account for year of publication), while the articles written by interdisciplinary teams (n = 10) have been cited 0.3 times per year—nearly a full order of magnitude difference. While alternative explanations such as popularity of topics might explain this difference, the claim that truly interdisciplinary publications are of higher quality is an interesting hypothesis to be tested in the future.

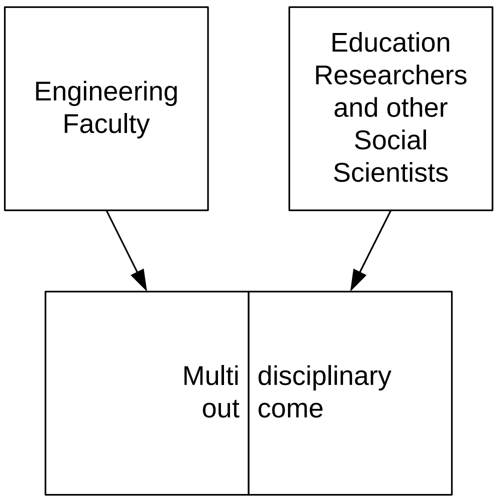

Figure 4. Multidisciplinary engineering education collaboration results in product that is not fully integrated.

2) **Interdisciplinary Approach**

While most collaborators acknowledged different ways of thinking across disciplines, those who took a truly interdisciplinary approach (n = 17 of 24 persons, including 9 engineers and 8 nonengineers) used complementary expertise to expand their personal development as well as their research productivity. In fact, half of them specifically stated that they saw differences in ways of thinking as opportunities for stretching their own limits of cognition. For example, one nonengineer looked at collaborating with engineers as an opportunity to increase her own knowledge base. She said:

> I value empirical evidence [as a social scientist]. Engineers are very quantitative. I have to introduce qualitative methods as a broadening of what's been done and what's been valued. It really goes to the heart of the discipline and challenges it.

Like this person, others interviewed understood that adding viewpoints—even seemingly contradictory points of view—led to a "broadening" rather than a limitation of the capacity of the research. An engineer explained, "Before I worked with them I didn't realize there was anything other than the engineering way, the hard analytical mindset. I realized there are other ways of solving problems that were also legitimate." Others described the interaction as key to the findings of their research. One nonengineer described it this way:

> I like the interaction, the idea that one can learn from people in different intellectual traditions… Research teams create divisions of labor. It shouldn't be "you develop the theory, you extend the theory to testable hypotheses, and you take the data." It may start out with those pieces, but eventually you spend time debating. The idea is that a team adds value to what any one individual could accomplish. And I just don't understand why you would do it otherwise.

Others similarly described their interdisciplinary approach as "very collaborative, very reciprocal," based on "respect," and synergistic. One engineer simply says of the advantages of this approach, "you might miss things if the work is too separate."

These statements and others made by the authors who supported a truly interdisciplinary approach suggest an alternative model of truly interdisciplinary research collaboration in engineering education, depicted in Figure 5. In this model, like the multidisciplinary model in Figure 4, engineers and social scientists each contribute their own expertise. However, unlike the previous model, in a truly interdisciplinary approach engineers and nonengineers also communicate with and learn from each other. Furthermore, the researchers themselves learn from the collaborative outcome of their project, resulting in a reciprocal cycle of learning and contribution. The end result of a true interdisciplinary collaboration is a cohesive product with which both collaborators were intimately connected.

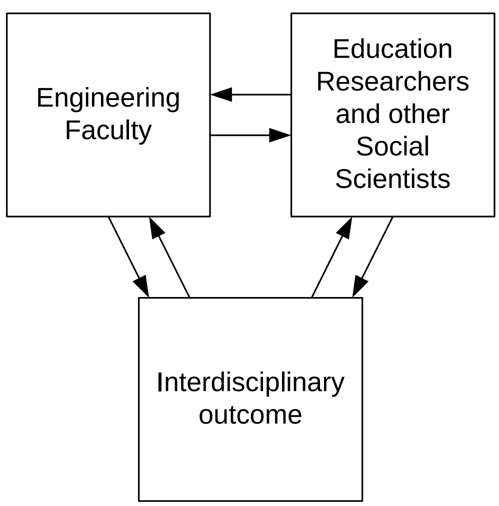

Figure 5. Truly interdisciplinary collaboration in engineering education results in a more integrated product, as well as changes perspectives of the researchers.

As this was a retrospective study, authors were much more likely to focus their descriptions on the most memorable aspects of their collaborations. Clearly, this was in the ways that the project and the individuals' understanding were expanded through interdisciplinary collaboration. Though authors were asked specifically who was responsible for which aspects of the work, they did not provide much detail. In some cases, graduate students did most of the work under the direction of a faculty team which met often. Some engineers did secondary statistical analysis of quantitative data, but authors offered no examples in which engineers actually coded qualitative data. More frequently, the research team met often to design studies, instruments, and interventions jointly, and to discuss the data after they had been collected and initially analyzed.

3) Trusting Collaborators in both Multidisciplinary and Interdisciplinary Collaborations

Regardless of whether the approach to collaboration was multi- or interdisciplinary, trust was a critical issue for many participants in terms of the shared workload. Interestingly, participants in both approaches used it as justification. For example, a multidisciplinary engineer said of his collaborator, "I have to trust him because he's the expert." This engineer described how work was divided: "I contribute an understanding of how we teach engineering, and also I develop the materials. [Collaborator] and his students give us the ability to interpret." In situations where collaborators relied on trust as a justification for divided labor and a multidisciplinary approach, dissatisfaction was quick to follow if credit was not evenly distributed. One engineer explains, "You put all this work in the first year, then you aren't invited back for the rewrite. Thanks for leaving me out the year it gets funded."

Trust is also a foundation for interdisciplinary collaborations. One nonengineer reported that his collaborator had said of his role as statistician for the project, "I totally trust you because this is totally over my head." In this specific interdisciplinary case, trust was followed by a respect for the nonengineering contribution, as well as an understanding of its importance. Examples such as this demonstrate that trust in the expertise of a collaborator is not necessarily a negative thing. In fact, trust and respect are reported by authors as foundational to truly interdisciplinary collaboration. The data suggest that trust can work as a building block to strong interdisciplinary outcomes as long as collaborators use it as a foundation for reciprocal learning and respect rather than as an excuse to distance oneself from or take credit for another's work.

D. Learning and Satisfaction

According to the authors interviewed, learning and satisfaction follow hand-in-hand in collaborations, particularly those characterized as truly interdisciplinary. One nonengineer said, "I like the interaction, the idea that one can learn from people in different intellectual traditions." Her engineering collaborator expressed a similar point of view, saying, "I think [working across disciplines is] better than working [only] with engineers. [In cross-disciplinary collaboration] we are able to find overlap in our interest, and there is chemistry there." Furthermore, some respondents felt that the benefits of cross-disciplinary collaboration also extended to the researchers' increased understandings of their own academic disciplines. Summarizing a specific example, one nonengineer explained: "I need to think through my side to try to communicate to others."

Altogether, 19 of the 24 authors specifically addressed epistemology or ways of knowing or valuing knowledge in other disciplines. Some expressed frustration at difficulties in communicating ideas, but more prevalent were feelings that different points of view presented new ways of examining a problem. In general, participants in interdisciplinary collaborations were more articulate in describing the various epistemologies they encountered and how working to understand them enriched the project. One interdisciplinary nonengineer said,

> It's so interesting to me. I could never think of working in one department again. The same issue would be researched differently in different disciplines. They bring different knowledge, tools, values, and evidence we seek.

An engineer said that there was a "richness" to the discussions with her collaborator, saying, "I learned a whole lot." Another engineer said of his collaborator, "She had a way of thinking about [the problem] that we hadn't thought of before, in terms of value… It's a different way of thinking. It really changed the way we think about complex decisions." Cumulatively, the data indicate that those who approached engineering education collaborations in a truly interdisciplinary manner were satisfied with the opportunities allowed by different ways of knowing and thinking, and were looking forward to more of these in the future.

In contrast, those who practiced a multidisciplinary approach appeared to have little awareness or appreciation of the validity of other epistemologies. For example, one engineer said of a social science approach to research, "I just find it to be so gray….I just don't find it very convincing in the end." These types of comments could stem from engineering or positivist epistemology. Seven nonengineering collaborators (and even one engineer) appeared to have had negative views of engineer's ways of knowing and valuing knowledge, echoing the criticisms in the literature. A nonengineer said that "As a group, engineers and scientists are among the least introspective people. They don't think about why they are doing what they are doing. …Their values are so ingrained; they think everyone feels this way." Others stated that all PhDs and engineering faculty in particular think they should be able to do any kind of research unaided by collaborators.

Fortunately, this stereotype of engineers as blind to the value of other epistemologies was not the norm demonstrated in this study. In fact, according to the interview data, most engineers and nonengineers were able to interact in a truly interdisciplinary way, both understanding and valuing the epistemologies of the other. Because dissatisfaction was not the case in most of these published co-author pairs, the disciplinary "norms" complained of by a few—if they exist at all—are not an insurmountable obstacle to truly interdisciplinary engineering education collaborations. As evidenced by the above example and elsewhere in the interview data, an openness toward learning and a truly interdisciplinary approach can overcome many difficulties presented by differences in epistemology.

E. Faculty Rewards

More practically than the epistemology issues described above, faculty rewards in various disciplines play a role as motivation or disincentive to pursue cross-disciplinary research. In the past, funding agencies have driven cross-disciplinary approaches, as one author explains, NSF funding "adds credibility to the notion that different backgrounds make magic." The "magic" implied by the participant means different things to different researchers. One nonengineer said: "I went for this project because I smelled a publication," admitting that "it's all the same to me, as long as there is a publication or grant involved." An engineer similarly stated that engineering education collaboration fit into an existing plan for promotion and tenure, saying, “I made a conscious decision that if I was going to pursue teaching work, I would have to do fundable, publishable work.”

Attractive as they may seem to be, funding and publishing in engineering education do not carry the same weight in every discipline. Because engineering education work is inherently cross-disciplinary, each of the traditional disciplines often sees limited value in it. Both engineers and nonengineers alike were sometimes discouraged from entering into engineering education collaborations because, as one faculty member reported his dean of engineering said, “I can’t give you credit for doing this.” Another engineer explained, “This has no bearing whatsoever on my tenure because it’s education.” Still another engineer said that his engineering education collaboration likely didn’t have any effect on his career, but he listed it on his CV anyway because “it was still a scholarly accomplishment.”

The motivations were also often complicated for nonengineers. For someone outside of engineering, publication in engineering journals, which have different expectations of research and writing, also may not count toward promotion or tenure. One nonengineer said that “the major difficulty in working with an engineer was the different role that this work played in our careers.” He continued,

> There was a difference in our understanding of the publication process. The major issue was that for the *Journal of Engineering Education*, you could do a quick and easy publication. For psychology journals, it takes much more time and more studies. It takes a lot of time. … It takes much more to be considered good work in the psychology literature.

It should be noted that this comment was referring to publication decisions made prior to the 2005 realignment of *JEE* as a rigorous research journal. Another nonengineer summed up the sentiments of the group by saying “The disciplines are the structure for faculty rewards,” meaning that differing reward structures and levels of institutional support further complicate cross-disciplinary collaborative efforts.

V. Summary and Implications for Policy and Practice

Twenty-four recent *Journal of Engineering Education* coauthors from cross-disciplinary teams were interviewed to understand the characteristics of successful engineering education collaborations. The result was two major findings: (1) a high degree of interdisciplinarity, learning and satisfaction within cross-disciplinary *JEE* author teams and (2) a model of cross-disciplinary collaboration in engineering education. Though the literature criticizes engineers for being unwilling to understand or accept alternative viewpoints, we found that 17 of 24 *JEE* authors (9 of them engineers) preferred to work closely with their collaborators to integrate multiple epistemologies into a truly interdisciplinary project. These authors explained that the differing perspectives of their collaborators were an opportunity to expand their own learning while enriching the project itself. These interdisciplinary collaborators reported a high degree of satisfaction and quality of work resulting from the collaboration.

A model for cross-disciplinary engineering education collaborations was also presented. In all but one of the 15 teams represented, an engineering faculty member initiated the collaboration by identifying a problem in the engineering context, often a classroom. The engineers used a combination of existing contacts and complementary expertise to find collaborators they knew they would get along with. Many were always on the lookout for networking opportunities and new contacts who could eventually turn into collaborators if the right research problem presented itself. Potential difficulties of differing epistemologies or disciplinary reward systems seem to be surmountable if the collaborators have a common ground of work ethic, interest in the research question, and personality compatibility.

These findings translate to a number of implications for policy and practice, as listed in Table 1. Funding and publications remain an important motivation for faculty research, so funding agencies should continue to support engineering education research with explicit expectations for cross-disciplinary teams. Institutional administrators should ensure that policies allow faculty to share credit for grants and teaching across academic units. Given the importance coauthors placed on informal interactions in forming productive collaborations, agencies and associations at many levels should foster semi-structured, cross-disciplinary meetings. Faculty can increase their awareness of both fundamental epistemological issues and more practical disciplinary reward systems to aid interaction with future collaborators. Engineering faculty in particular should understand that although they may have to make the first move in initiating engineering education collaborations, there are a number of education, social science, and other disciplinary faculty willing to expand their own research into the engineering setting. Furthermore, engineering faculty can seek opportunities to engage various epistemologies in their courses, thereby promoting the cognitive flexibility of students and preemptively preparing them for some of the roadblocks generally attributed to a narrow engineering point of view focused on technical details at the expense of societal impacts. Incorporating other disciplines in the early education of engineers will also increase student awareness of the societal impact of their chosen profession.

Table 1. Implications for Policy and Practice.

Stakeholder	**Recommendations for Fostering Cross-disciplinary Engineering Education Collaborations**
Funding Agencies and Professional Societies	• NSF and other funding agencies should continue to fund engineering education research to add credibility, being explicit about expectations for cross-disciplinary expertise. • A broad range of professional societies, associations, agencies, and administrators can facilitate collaboration with semistructured cross-disciplinary gatherings around important research areas.
University Administrators	• Administrators should reduce barriers between academic units by ensuring institutional policies accommodate shared grants and team teaching credit. • Administrators can also host local meetings around important interdisciplinary research areas.
Faculty	• Faculty should increase awareness of epistemology issues

	underlying cross-disciplinary collaborations, and be up-front with each other about both practical (publishing) and fundamental (research approach) issues. • Engineering faculty need to understand they must initiate most cross-disciplinary engineering education collaborations, but that many nonengineers would make willing partners. • Engineering faculty can increase the cognitive flexibility and social awareness of students by incorporating interdisciplinary pedagogical practices into their courses.

VI. Future Work

Opportunities for future work are plentiful, as this study raises as many questions as it begins to answer. It is likely surprising to at least some readers that the participants in this study did not discuss increased time or energy costs generally associated with cross-disciplinary work. The authors believe this is because participants viewed the costs as outweighed by the benefits of a high-quality product and learning from collaborators. One engineering participant addressed this directly: "If I wanted to be efficient, I wouldn't be doing educational work. For the effort it takes to get one education paper out, I could get more than one technical paper. There is a cost to an educational paper. But there is value for the students." Future investigations might address cost-benefit analysis of interdisciplinary work more directly by considering the time it takes single and multiple discipline teams to move through Tuckman's [28] stages of team development (i.e., forming storming, norming, etc.).

Similarly, a number of participants suggested that the results of interdisciplinary collaboration are of higher quality than those of single-discipline or multidisciplinary efforts. In-depth document analyses coupled with more objective and more extensive citation analysis would serve to address this hypothesis in a more convincing manner.

Finally, this retrospective interview study does not directly address the developmental process of interdisciplinary collaborators, particularly if they change from initially multidisciplinary expectations to interdisciplinary ones. Prior work focusing on novices [15] and comparing novice and expert cross-disciplinary collaborators [29] as well as some of the data in this study suggests that many faculty approach collaborations with multidisciplinary expectations, but that experienced cross-disciplinary collaborators hold more interdisciplinary attitudes. Future studies might focus on following teams through longitudinal studies integrating observational methods with less reliance on self reports.

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