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Bridging from Research to Teaching in Undergraduate Engineering Design Education*

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Our goal is to promote a research-informed approach to engineering design education. Over the past eight years, we have conducted a number of studies in order to understand how engineering students do design. Some of our current efforts focus on integrating research and practice in engineering design education. Because of the complexity of real educational practice, we are working on multiple strategies to bridge the research-to-teaching gap. These include: 1) the creation of instructional activities based on our research results and 2) a workshop model to engage design educators with research on engineering student design behavior. In this paper, we present a framework for thinking about the link between research and teaching, provide detailed descriptions of the two strategies mentioned above, and discuss the effectiveness, viability, and reproducibility of these strategies.

INTRODUCTION

THE OVERARCHING question we address in this paper is how design educators can use research on engineering design learning in their teaching. As an example, consider an engineering educator currently teaching a freshman design course. What would make it possible for the educator to make use of potentially applicable research such as research on student design processes [1–3] and research on students' conceptions and misconceptions about design [4]? How could we help the educator use such research to introduce design ideas or concepts to students, gain insights to facilitate student progress (e.g. how to proceed in the design process), and engage students by having them think about effective design practices? One answer is that research on engineering design learning and knowing can help design educators articulate reasonable learning objectives, understand students' growth relative to learning objectives, imagine activities that can be implemented to promote learning, and identify effective assessment measures [5].

Our interest in this question stems from a desire to promote a research-informed approach to design education, with an emphasis on research into engineering design ability and the acquisition of such ability. In this approach, research findings and teaching practice do not exist in isolation. Rather, research and teaching are in constant communication—teaching informing research needs and educators using research results to inform their teaching activity. We see a research-informed approach as one of several strategies for promoting change in engineering design education [6]. A research-informed approach may also be appealing in the context of engineering education, because it runs parallel with a change model that is familiar to engineering educators—research and development.

In this paper, we discuss existing work in our research-informed approach and point to the research-to-teaching piece as a specific area for attention. We then describe a way to distinguish among research-to-teaching strategies and discuss our experiences with two specific strategies: research-based instructional activities and research-to-teaching workshops. We close with a discussion of what we have learned about the effectiveness, viability, and reproducibility of these strategies.

BACKGROUND ON RESEARCH AND TEACHING IN DESIGN EDUCATION

In a research-informed approach to teaching engineering design, teaching activity is informed by existing research on engineering student learning. Fig. 1 presents this model, highlighting the important role of the research on engineering student learning in the left node of the figure and the teaching of engineering design in the right node (C. J. Atman, Director for the Center for Engineering Learning and Teaching, http://depts.washington.edu/celtweb/). The figure also illustrates two kinds of cross-talk: instances of teaching giving rise to research (bottom arrow) and instances of research informing teaching practice (top arrow). The remainder of this section highlights existing work in three of these areas

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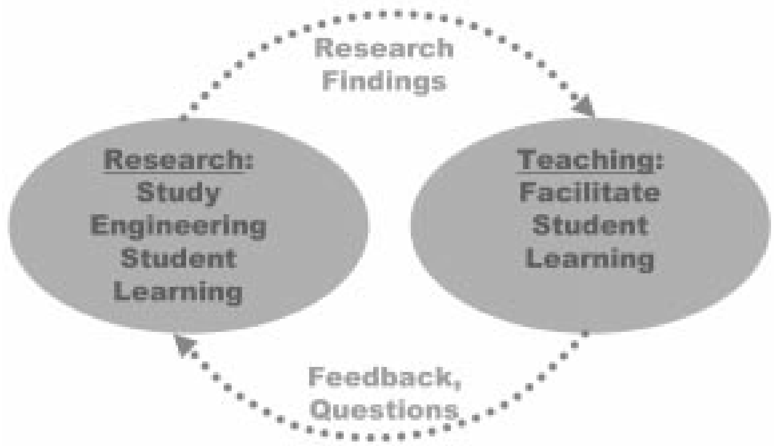

Fig. 1. Bridging research to teaching.

and provides a backdrop for the next section, which focuses specifically on the use of research to inform teaching practice.

Appraising the current state: teaching

The goal of design teaching (see Fig. 1, right node) is to help engineering students become effective designers. The engineering community has experimented with a wide variety of strategies for teaching design [7]. Students have long been exposed to design at the senior level [8] and are also frequently exposed to design at the freshman level [9]. Some faculty weave design into core engineering courses, such as courses on structures [10] and courses on engineering mechanics [11]. Active conversations about teaching design are occurring in venues that bring together engineers, architects, product designers, and graphic designers from around the world (e.g. the International Conference on Engineering Design, the Design Thinking Research Symposiums, the Mudd Design Workshops, Design Studies, Design Issues).

In general, it is clear that there are many ways for educators to engage their students in design learning. It is also evident that educators have many questions about how to better teach design and enhance student learning [7]. For educators to make effective decisions among teaching strategies, they need the appropriate information (such as information about student learning of design).

Appraising the current state: research on design learning

Research on the learning and doing of engineering design can and should inform the teaching of engineering design. Of particular interest is research on how engineering students learn design and what engineering students should know in order to be effective designers. Research on the design activities of practicing engineers is also of particular interest. Fortunately, there is a growing body of such research. For example, Cross [12] presents a comprehensive summary of research using verbal protocol analysis. In our lab, we have been involved in research that has used verbal protocol analysis to comprehensively document and understand engineering student design processes. In all, we have conducted six studies building on three datasets [2, 13]. From these studies, we have: a) described how freshmen and senior engineering students differ in their approaches to design problem-solving, b) measured differences in design activity across levels of design experience and final solution quality, c) correlated design performance with various design behaviors (e.g. information-gathering behaviors, iteration, generating solutions, and evaluating solutions), and d) developed a set of measures that can be used to assess student design processes. While it remains important to promote research on the doing and learning of engineering design, it is clear that there is an existing body of work which educators can use.

Appraising the current state: teaching informing research

Research on the learning of engineering design can address a variety of questions. Some questions (such as many of the questions underlying the research just described) are theoretically motivated. At the same time, it is also important to pay attention to questions that arise from teaching practice (e.g. what learning is going on in the classroom, and what learning difficulties students experience). For example, Goldschmidt [14] became interested in students' interpretations of design feedback provided during design crits (critical review sessions between design students and their design instructor). She subsequently conducted a study focused on the comprehensive set of messages exchanged during one of these design sessions and the identification of the messages the instructor and the students each perceived as critical. She learned that there was a very small overlap between what the student saw as important and what the instructor saw as important. Such research can have important implications for how design educators provide feedback and help students interpret feedback.

Insights from teaching practice also inform research by helping to prioritize research directions and efforts. For example, the challenges of knowing how to assess design learning suggest the importance of studying student design processes as a basis for designing valid assessment instruments. As another example, a survey of the current state of design education provides insight into research needs such as what challenges students face in learning communication skills in design teams and how team communication practices correlate with design processes and products [15].

Appraising the current state: research informing teaching

In the preceding sections, we described three of the four elements associated with a research-informed approach to teaching. The linchpin of the research-informed approach to teaching (see Fig. 1) is the bridge from research into teaching. If the activities in a coupled research and teaching system do not ultimately reflect back on teaching, then it is reasonable to expect that student learning will not improve. Furthermore, there is reason to believe this link represents a challenge. For example, a recent citation analysis of papers on design education over the past five years suggests that educators are not referencing the available research [15]. In that analysis, the authors discovered that most citations dealt with publications by other educators rather than researchers, and that many educators experience similar difficulties with teaching and assessing design.

STRATEGIES FOR BRIDGING FROM RESEARCH TO TEACHING

Our current challenge is to identify strategies for linking research more directly with the teaching of engineering design. Although research can inform teaching in myriad ways—by providing information about how to teach better and how to help students learn better—strategies for supporting this link are not trivial. Kennedy [16] hypothesized four reasons for a perceived lack of connection between research and practice: the research is not sufficiently persuasive because the study lacks rigor or authoritative results for practitioners, the research has not been relevant to practice in terms of addressing educators' questions or constraints, ideas from research have not been expressed in ways that are comprehensible or accessible to educators, and the education system itself is too intractable or, conversely, too unstable to engage in systematic change.

In the engineering education community, existing strategies for supporting the research-to-teaching link include running workshops, creating research-informed curricular models, developing assessment models and instruments, and collaborating with education researchers. Of these, workshops are a prevalent strategy. Often, workshops help educators identify instructional principles that they can follow in their own classrooms in order to address student learning difficulties described in research findings. While such workshops can generate immense enthusiasm for new teaching approaches, there has been concern about their effectiveness for impacting change in engineering classrooms. Some reasons why there may be limited effectiveness include the following:

- *Underestimates of the amount of work required to implement effective practices*: the leap between general principles of teaching effectiveness and an educator's classroom practice can be considerable.
- *Underestimates of the need to directly connect educators with the research foundation*: establishing credibility of research is critical.
- *Limited recognition of the diversity of educators' needs and interests*: educators range in experience (research and teaching), teaching philosophy, willingness and ability to adapt models to their circumstances, and the challenges they face helping students learn.
- *Limited support for adapting models in diverse contexts*: educators often redesign models or tools for their specific needs, which, depending on the resources provided, can promote or detract from effective implementation.

In the context of our research-informed model, specifically the challenge of research informing teaching (see Fig. 1, top arrow), workshops such as the example described above often lie in the center of the arrow represented in the figure. Such workshops are not closely tied to the research (since participants may rarely see the research) and are not closely tied to teaching (since participants will still need to find ways to apply the instructional principles in the context of their own teaching).

The contribution of the two research-to-teaching strategies described in this paper can be highlighted against this backdrop. These two strategies are interesting, because they have the potential to depart from the limitations described above. Specifically, the two strategies that we describe in this paper lie at the extremes of the research-to-teaching arrow (see Fig. 1). These strategies are different from the type of workshops described above, in that one is closely anchored to teaching while the other is closely anchored to research.

- The first strategy, creating instructional activities based on research tasks and results, provides a way for educators to bring the research (not research implications but the research specifically) directly into their classroom. This strategy seems particularly promising for educators with little time but clear interest. In this case, the educator would learn about the research through the activity that he/she conducts with his/her students.
- The second strategy, research-to-teaching workshops, brings educators directly into contact

Table 1. An illustration of the space of potential research-based instructional activities (an X represents an instance of an instructional activity discussed in this paper)

	Instructional Activity Type			
Research	Students discuss the research	Students complete research task	Students complete an assessment based on the research . . .	. . .
Information gathering		×		
Communication in design teams	×			
. . .				

with the research. Participants explore research papers during the workshop in order to understand the findings and brainstorm how they could use the research to inform their own teaching. This model seems well suited for skeptics—educators who are unwilling to make use of research until they develop an understanding of that research for themselves. Additionally, the implementation challenge is much less ambiguous than in the traditional instructional principles workshop in that the instructional design is clearly the complete responsibility of the educator.

Over the past two years, we have been experimenting with these two strategies. Through these successful early experiments, we have gained crucial insight into our approaches as well as insight relative to questions of effectiveness, viability, and reproducibility. The next section provides more detail on these two strategies and examples of their use. Finally, the discussion section summarizes what we have learned regarding the effectiveness, viability, and reproducibility of these strategies.

OUR RESEARCH-TO-TEACHING WORK

In this section, we provide examples of our research-to-teaching efforts, focusing on our research-based instructional activities and research-to-teaching workshops. Specifically, we describe each approach by highlighting its primary characteristics, identifying the type of challenges the approach is meant to address, and illustrating insights gained through our experiences with each approach.

Research-based instructional activities

As discussed earlier, design researchers are uncovering important issues about designer behavior, designer attitudes, and designer knowledge. Such research involves a range of methodologies, theoretical perspectives, and data sources. For example, researchers have characterized iteration in design activity using verbal protocols collected during design episodes and used the characterization to identify iterative behaviors linked to design success [3]. Each of the various elements of such research (e.g. the research methods, the raw data, and the synthesized results) represents a potentially powerful tool that educators can use to engage students in learning about design.

Through our research-based instructional activities, we aim to enable design educators to use this research as a basis for classroom activities. We imagine that there are a number of ways for transforming research on engineering student learning into instructional activities. For example, an instructor could have students complete a variation of a task used in a research experiment, analyze the students' data in class, compare the results to the published research results, and discuss implications. Alternately, an instructor could present research data and/or research results from one of the research studies and engage students in a discussion about effective design practices. Table 1 suggests the space of such instructional activities, by illustrating the space using a small number of instructional activities and research areas. Each cell represents a potential research-based instructional activity.

To illustrate these ideas, we are exploring the development of example activities and studying the use of these activities in actual classrooms. To date, we have worked on research-based activities in the areas of information gathering, problem scoping, and team communication. In the next two subsections, we describe two examples, focusing on our development and evaluation processes. The examples (represented by the 'X's in Table 1) draw respectively on data concerning information gathering by individual designers and communication behavior in design teams.

An activity to illustrate information gathering

The research that serves as a basis for the information-gathering activity is part of a study of student design behavior [17]. Students were given three hours to design a playground for a fictitious neighborhood and were allowed to ask for information. The research data includes a record of the types of information students requested. This data was then analyzed relative to a series of categories (e.g. budget, liability, neighborhood opinions, material costs) representing a broad interpretation of the information needed to design a playground. The results portray the percentage of the students (both freshmen and seniors) who requested information for each of these categories (see Fig. 2).

In the instructional activity we designed based on this research, students complete a streamlined version of the experimental task [18]. Students are told that they have agreed to design a playground for the local community and that, because they are busy professionals, they will need to have a colleague collect any necessary information. The students are given approximately 10 minutes to create a list of the types of information they will need in order to proceed with the design activity. Next, the students are asked to prepare for the analysis of this data by exchanging papers. The instructor goes over each of the information categories, explaining the category and asking the students to code any items on the list that are related to the category under discussion. At the end of the process, the instructor revisits each of the coding categories and uses a show of hands to determine how many of the students identified an information need related to that category. The instructor then plots each result as a percentage on a graph that already displays the percentage of freshmen and seniors in the research study who requested information for each of the categories. The activity culminates with the students and instructor discussing the results. For example, the instructor can choose to highlight places where the students did better and worse than the study participants, and can also focus on categories of particular interest (e.g. liability). The entire exercise can be completed in about 30 minutes in the classroom.

We have tested this instructional activity by using it in a mid-size senior-level industrial engineering course on professional practice issues (for more information on this class, see [19]). The activity was carried out in the manner described above. Figure 2 shows the results. In the figure, the sixteen information categories from the research study are represented along the x-axis. The y-axis represents the percentage of subjects requesting information from that category. The two curves with gray lines represent the results for the freshmen and seniors in the original study. The remaining curve represents the results from the students engaged in the classroom activity.

As can be seen from the figure, the students in the class outperformed their peer group (represented by the research results) in a small number of areas. For example, 58% of the students in the class included human factors issues (e.g. the size of children who will use the playground), as compared with 3% of freshman and 19% of seniors in the research study. This result is reassuring, since human considerations are an important aspect of industrial engineering. In general, the class results paralleled the major trends in the research data. There was notable variation across categories (e.g. a small number of students mentioned liability, while a large number mentioned budget). Additionally, there was no category that was addressed by all students. In the class, the results were used as the basis for a discussion about the role and responsibilities of an engineer. This discussion brought at least one student misconception to the surface. Specifically, during the discussion of the maintenance category results and why so few students had addressed this issue (only 33% of students mentioned maintenance), one student responded that he did not think he was responsible for maintenance. This is the type of comment that can be followed with a deeper discussion of the idea of designing for

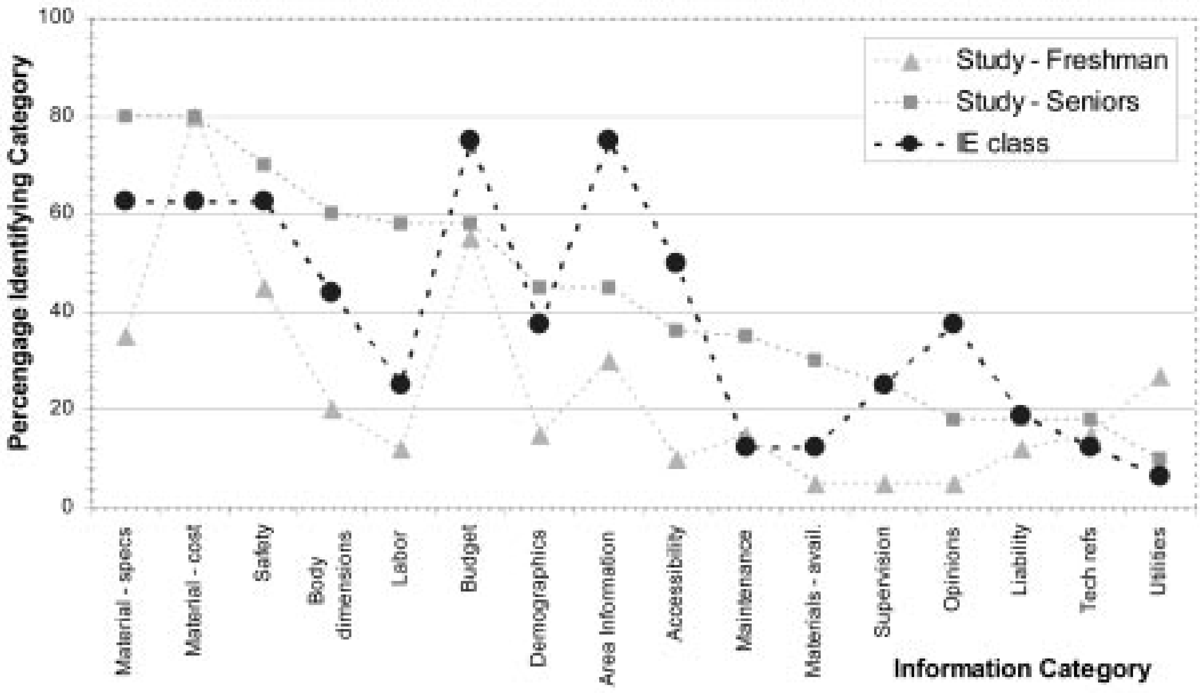

Fig. 2. Instructional activity results.

maintainability. Overall, the activity went smoothly, it served to engage students, and led to stimulating discussion. More recently, these materials have been used by other educators.

One challenge of using this activity has been weaving it into the right context. Information gathering is a critical part of design but is not typically a specified topic in any given design class. This points to the underlying nature of our instructional activities: that it will be the instructor who recognizes the potential value of a particular activity at a particular point in time. This will be something that we will need to support, and has emerged as a theme in the development of the instructional activity discussed in the next section.

Communication in student design teams

The previous example illustrated the development of an activity based on a specific task and the technique for analyzing the data resulting from the task (i.e. analyzing the data relative to an a-priori set of categories). The second example serves as a clear counterpoint. This example focuses on a six-month project to transform transcriptions of discussions within design teams into instructional activities. In this example, it is the data rather than the task or the analysis technique that serves as the basis for the instructional activity.

There are several reasons to be interested in instructional activities based on transcriptions of design activity. First, there is a strong possibility that students will find transcripts of design episodes intrinsically interesting. Second, this type of data can be used to illustrate subtle design phenomena, such as the ways that team members interact and the ways that designers make use of information. Further, since a great deal of research on design behavior has made use of verbal protocol analysis [12], learning to transform the data from such research into instructional activities can lead to the rapid development of a wide variety of instructional activities.

The activities in this example are based on transcripts of student team communication during design episodes. In the design episodes, teams were asked to design a procedure for testing animal toenail clippers. As part of the study, 18 teams completed this design task. The teams were from community colleges and four-year universities. Additionally, the teams were mixed in terms of student academic level, with the community colleges having teams composed primarily of freshmen and sophomores and the four-year colleges having teams composed primarily of juniors and seniors. For additional information about this study, see Adams *et al.* [20].

The development process for this instructional activity proceeded initially in the same direction as in the previous example: development of a prespecified sequence of steps. This resulted in a prespecified, workshop-like instructional activity that would last about 90 minutes. The heart of the instructional activity was a set of excerpts selected from the transcripts and presented to students as a basis for discussion. Selection of appropriate excerpts proved to be a significant step, particularly given the size of the dataset (the transcripts of the team design episode are each about 25–30 pages long). We ultimately chose six excerpts that represent communication behaviors of interest (both positive and negative).

Our second step in the development process was to obtain feedback from an instructor's perspective. We accomplished this by meeting with a faculty developer who works primarily with engineering faculty and eliciting her feedback on the usability and usefulness of the instructional activity. The faculty developer was enthusiastic about the overall idea, and reported that she could see faculty finding such activities valuable. At the same time, the faculty developer expressed significant concerns about the length of the activity and the size of our documentation. She suggested that the activity be made more modular in order to be usable for engineering faculty.

Armed with this feedback, our third step was to re-evaluate our approach. We realized that the excerpts, which had been an important element of the instructional activity, were actually the key tools that we could provide to faculty. In our second round of design, we focused on creating a format for sharing these excerpts with educators. The resulting one-page format showcases the excerpts and provides discussion questions. Additionally, we revised our remaining materials so that they are supplemental to the excerpts.

Our fourth and most recent step was to gain feedback from a practicing engineering educator. We wanted to understand the educator's perceptions of the materials and to learn how she might make use of such materials in their classrooms. The educator we worked with has experience in teaching design at all levels of the curriculum. Additionally, the instructor frequently uses small instructional activities to engage her students and to focus their attention. As such, this instructor represented exactly the type of instructor who would be likely to use our materials. During our one-hour session, we showed the materials to the instructor and asked her to comment on the materials generally, as well as considering how she might use them in her teaching. This instructor was quite positive about our new format. While she did have constructive criticism (e.g. she suggested that transcripts from teams involved in more technical design activities would be of greater interest to more advanced students), she also stated that she could see herself using these materials in both her freshman and senior design classes. She described exactly how she would use the materials and plans to use them in the future.

Overall, we are encouraged by the positive direction of this work. Our work with research on both information gathering and team communication has helped advance our ideas about how to translate research tasks, data, and results into instructional activities. Our sample efforts provide not only specific activities but also roadmaps for developing additional activities. This theme of providing a roadmap is something we also address in the next section, which focuses on our research-to-teaching workshops.

Research-to-teaching workshops

While research findings can provide significant value to design educators, another challenge is bringing educators and the research together. With support from the GE Fund, we have designed a model for a workshop that aims to address this challenge. The goal of these research-to-teaching workshops is to provide opportunities for educators to link teaching challenges with empirical research on student learning. In these workshops, educators discuss teaching challenges and the types of difficulties their students encounter, discover explanations of these student difficulties in the context of existing research, and practice using the research to address learning and teaching challenges. A key to the workshop is having participants *directly* explore the research by reading and discussing journal papers describing the research findings.

This workshop model is one means of addressing the challenges Kennedy [16] hypothesizes when discussing a lack of research-to-teaching connections. For example, rather than provide summative answers on how design should be taught, we use the workshop to provide windows into design learning that help design educators develop their own answers to their own questions. As such, educators and researchers engage in a collaborative process of finding both specific solutions and general strategies on how to connect research and practice.

To ensure our workshop model would be aligned with current research on the effectiveness of workshops, we worked with a faculty development specialist who has expertise in working with engineering educators. Together, we developed appropriate learning objectives and implementation strategies. The structure and flow of the workshop activities were designed to model effective teaching behaviors. In particular, we emphasized active and collaborative learning approaches, synthesis and debriefing activities, and opportunities to practice applying knowledge and strategies. The main activities of the workshop were designed using a jigsaw approach [23–25], a two-phase teaching strategy which focuses on the development and sharing of distributed expertise. During the first phase of a jigsaw activity, learners work in groups to develop expertise in various topics. During the second phase, representatives of the various expertise groups come together in new groups in order to solve a problem using their distributed expertise.

To date, we have conducted two research-to-teaching workshops [24–25]. In the following paragraphs we provide a summary of the first workshop [24], including the flow of activities, the outcomes for participants, and the lessons learned. The three-hour workshop was divided into six phases of activity: introduction, starting the conversation, exploring the research, connecting research to practice, a research-based instructional activity, and wrap-up. The data described below are based on observations taken during the workshop.

1. *Introduction.* We opened the workshop by discussing the workshop goals. Specifically, we had designed the workshop so that participants, by the end, would be able to identify design teaching challenges, recognize some of the empirical design research relevant to those teaching challenges, and develop strategies for using the research to inform design teaching.

2. *Starting the conversation.* During the second phase of the workshop, we wanted participants to meet each other and to begin to share the successes and challenges they encounter in teaching design. Participants designed a name tag that included their specialty in teaching design and then self-organized into small groups (approximately four to six members) based on the information from these name tags. In these groups, the participants discussed two questions: what distinguishes successful and unsuccessful student designers? and what challenges and successes they have faced in helping students be more successful? In response to the first question, some participants suggested that successful student designers are more capable of articulating the qualities of their design solutions in terms of good design principles such as design for sustainability, manufacturing, and life cycle. Participants also commented that unsuccessful student designers tend to have poor project management skills and select too quickly among design alternatives. In addition, participants shared observations on the difficulties students encounter when learning engineering design, such as committing to design alternatives late in the process and not having sufficient time to fully develop a quality solution. In response to the second question, participants identified a number of challenges, including encouraging students to innovate, convincing students that teams are good, having students take more initiative, incorporating theoretical dimensions into student designs, and helping students validate the importance of other engineering courses in the context of their design projects.

3. *Exploring the research.* The goals of this phase were to help participants recognize the variety of research on engineering design behavior relevant to teaching design, identify sources for such research, and connect characteristics of successful and unsuccessful student designers to research findings. Six groups of three to four participants discussed one research paper each and were asked to answer the following questions: 'What is the research question?', 'What are

three main findings?', 'What about the findings surprised you?'

The six research papers used in this phase of the workshop [1, 3, 4, 26–28] covered five themes: team and individual design processes [26], comparisons of design behaviors across experience and performance levels [1, 3], design behaviors of practicing engineers [27], the role of design context in design activity [28], and student conceptions of design [4]. The rationale for selecting the research papers was an important consideration for the design of the workshop. We chose the papers such that each had accessible language, topics relevant to the workshop themes (e.g. challenges in teaching design, student design behaviors, design performance), and representations of empirical data that would be engaging to engineering educators. This last criterion was of critical importance, because it provided a means for workshop participants to quickly engage in the research results and an anchor for participants to use in discussing these research results. Further, we chose papers to represent a variety of sources (e.g. conferences, journals) covering broad research communities of interest (e.g. international, multiple disciplines). We wanted the papers to collectively provide participants with information about where they could find additional research.

Overall, the papers stimulated intense discussion. Most groups were successful in identifying the research question and main findings; however, in some instances participants noted that extracting findings was difficult. When groups reported on what surprised them, intriguing themes emerged. Many noted that the findings were not surprising, in that they validated or explained some of their own beliefs and experiences. As such, participants noted that sharing the research with students would help justify classroom activities or project goals that students tend to question. In some cases, participants were surprised at the extent to which researchers identified implications on where to help students most, and, in other cases, participants noted that they preferred letting the data speak for itself. Some participants noted that the tone or writing style of some of the papers may lead them to question the quality of the research. In general, participants found that the paper titles were surprisingly self-explanatory and, as such, they felt they would be successful with reviewing titles in a journal and identifying research of interest to them.

As preparation for the next phase of the workshop, participants brainstormed ways an educator might use the results of these research studies to inform their teaching of design. Initial thoughts included: asking students to perform the research task and compare their responses to the study group, engaging students in a discussion of successful design behaviors by showing data from both successful and unsuccessful designers, and using data as a basis for helping students develop strategies for moving design projects forward.

4. *Connecting research to practice*. This phase of the workshop represented the second step in the jigsaw approach. Specifically, we had participants form three new groups of six to eight participants, with each group having someone knowledgeable about each of the research papers discussed previously. This distribution of expertise created opportunities for all participants to learn something about all research papers included in the workshop. The goals of this phase were for participants to identify general strategies for using research to inform teaching and to practice applying their knowledge of design research in the context of an educational setting. Groups were given one of three scenarios and were asked to: 1) identify three examples of how the previously discussed research could be used in the context of the scenario and 2) provide two examples of new research that would be valuable in the context of the scenario. The design of the scenarios was informed by a literature review of the current state of design education [7]. Findings from the review were used to identify common points in the curriculum where design is taught (e.g. the context of the scenario) and common challenges in teaching and/or assessing design in these contexts. The three scenarios were: designing a freshman design course, attending to process in a senior capstone course, and adding design to a content course.

The group focused on the *freshman* scenario was told they had been asked to develop a new freshman design course and, as a first step, identify ways they might use the research on design in this situation. One specific suggestion was to develop pre- and post-assessment instruments based on the study task Newstetter [4] used to investigate students' evolving conceptions of design. A more general suggestion was to use the research to identify problems that freshmen experience and develop instructional activities based on the research. For example, since research suggests that freshmen may tend to narrowly define design problems [3], an educator could design an instructional activity to engage freshmen in identifying requirements for a design problem from multiple perspectives.

The group focused on the *senior capstone* scenario was asked to take the role of an instructor of a capstone design course in mechanical engineering who is revising the course to place more emphasis on the design process. In this group, one suggestion was to use the research to identify points in the design process where providing a mini-lecture or just-in-time lecture on a particular issue would be appropriate. For example, the participants noted that the Adams paper [3] provided insights into where in time it would be useful to encourage students to revisit their understanding of the problem or re-evaluate the quality of their solutions. At these points the instructor could lead a classroom discussion or provide information that may not have appeared relevant to the students when they began their design process.

The group focused on the *content course* scenario was asked to take the role of an instructor of a course on structures who has decided to add a design project. Further, the group was asked to identify strategies for using research on design to address two key challenges: keeping the complexity of the project manageable and keeping the students focused on the content of the course (rather than the solution to the design product). One idea raised by the group was to use research that suggests students have difficulty defining design problems (e.g. [1]) to create an instructional activity. Such an activity might provide students with an ambiguous problem and ask them to list the questions they would need to answer before beginning to think about solutions. In this way, students would be focusing on understanding the underlying principles for a given system rather than on designing a solution.

Overall, the groups identified the following strategies for connecting the research to the teaching situations presented in the scenarios:

- Use data to identify, explain, validate, and reinforce known effective practices
- Use data as illustrative cases of successful strategies or expert behaviors
- Use research tasks as pre- and post-assessments
- Use research as a vehicle for defining and discussing design continuously throughout coursework (e.g. ask students what design is and give feedback from the research)
- Use data to create instructional activities, with the research informing both the timing and the content of the activities
- Use findings to define course or learning objectives

5. *A research-based instructional activity.* The goal of this phase was for participants to experience connecting research and practice by participating in a sample instructional activity. The plan was to have the participants engage in the information-gathering instructional activity described earlier in the paper. Because the workshop discussion ran longer than expected, we decided to describe the activity and have participants discuss how they could envision its use in their specific contexts. We were contacted after the workshop by one participant who planned to explore the activity in his classes.

6. *Wrap-up.* The workshop clearly stimulated a great deal of conversation and enthusiasm among participants. By the end of the workshop, we had achieved our objectives: participants had identified and shared design teaching challenges (from research and their own experience), were aware of design research as well as sources and strategies for seeking additional research, and had generated many concrete examples for connecting research and practice in design classrooms.

We also learned that educators are quite interested in design research and enjoyed the interactive nature of the workshop. As stated earlier, we implemented a second workshop at the Frontiers in Education conference [25]. The second iteration was informed by what we learned from the first workshop. For example, participants from the first workshop requested that the organizers provide an overview on research findings. As a result, short summary lectures were included in the workshop. In this second workshop, we used a questionnaire to conduct a more formal evaluation and gained insights that we will use during our subsequent workshop.

As part of funded research activities, we are committed to continuing these research-to-teaching workshops and are creating a website where others (e.g. educators or workshop designers) may use our model. As summarized in this paper (and in our future website), some key design issues for planning this type of research-to-teaching workshop involve selecting research papers and creating scenarios for connecting research to teaching. Additionally, it is valuable to prepare for running the workshop by brainstorming ways to use research in the context of the scenarios in order to facilitate conversations in the participant groups. A framework such as the one introduced in Table 1 could be a useful tool for synthesizing these ideas.

DISCUSSION

In this paper, we have focused on two research-to-teaching strategies: research-based instructional activities and research-to-teaching workshops. Our experiences with these two strategies are encouraging. In the paragraphs below we draw out themes from previous sections that speak to the effectiveness, viability and reproducibility of each strategy.

In terms of effectiveness, we have made progress. For example, our workshop participants have been able to achieve the objectives set forth in the workshop, including identifying ways to use research to inform their teaching practice. Also, our use of the information-gathering instructional activity led to a useful discussion between the students and the instructor. The next step in determining the effectiveness of each strategy is to make use of more formal evaluation approaches. In the case of the research-to-teaching workshops, a more formal evaluation could include interviews and focus groups to investigate what participants gain from the workshop. A more ambitious approach would be to follow up with participants after the workshop to determine the extent to which they have been able to implement the strategies they identified in the workshop, their level of success, and any obstacles encountered. In the case of the instructional activities, more formal evaluation of effectiveness could focus on the impact of the instructional activities on student learning and the ability of an instructor to adapt the materials to their unique instructional circumstances.

In terms of viability, we are encouraged by two findings. First, our efforts to run the workshops and design and implement the instructional activities show that these strategies are both possible. Further, our efforts have helped us see that there is an audience in both cases. The attendance for each workshop met capacity, indicating that there are educators interested in learning more about the underlying research and applying it to their own teaching. In the case of the instructional activities, we are encouraged by students' responsiveness to the information-gathering activity, the requests we have received for the materials to run this activity, and the enthusiastic feedback from an engineering design educator concerning the team communication activities. With this knowledge about viability and increasing information about effectiveness of these strategies, we can expect these strategies to continually improve.

While effectiveness and viability are critical, reproducibility may be the key issue if one is focused on change. We need to make it possible for people other than ourselves to adapt and adopt these strategies. Effectiveness and viability both contribute to reproducibility—we know that the audience is there and that the design principles can promote effectiveness. Other considerations include streamlining the resources needed to implement these strategies and clearly identifying the models underlying the workshops and the instructional activities. The long-range goal is to ensure that these models are exportable. In the case of the workshops, the model is now fairly straightforward and streamlined, and we ourselves have used the model more than once with similar effectiveness. In the case of the instructional activities, we are building a knowledge base on the process and are actively working to expand our work using other research in order to more completely understand their potential.

CONCLUSIONS

Our goal is to promote a research-informed approach to engineering design education in which research on engineering student learning and the teaching of engineering design are highly coupled. In this paper we have focused on a critical element of this approach: the bridge from research to teaching practice. We have provided some insights concerning the complexity of this link and described two strategies we have explored to bridge this link: research-based instructional activities and research-to-teaching workshops. An important feature of these strategies is their positioning along a continuum of research-to-teaching strategies, with the instructional activities closely linked to teaching practice and the research-to-teaching workshops closely linked to original research. As we move forward, these types of research-to-teaching activities will be a central theme in our work.

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