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Innovation through Propagation: Future Directions for Engineering Education Research

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INTRODUCTION

This special issue includes three commissioned papers on the future directions in engineering education research, each with an emphasis on propagation of results. They have been developed by carefully selected writing teams; each team was assisted by a consultant who read and critiqued each draft as the papers evolved. The three papers cover respectively:

- Learning inside the classroom,
- Improving and diversifying the pathways, and
- The role of technology.

These papers were developed as part of an extensive process that involved three Delphi exercises and a special interactive session at the 2015 Annual ASEE National Conference to identify key issues and appropriate writing team members. Work-in-process papers were presented and critiqued at a second interactive special session at the 2016 Annual ASEE National Conference. In all, over 200 members of the broader engineering education community have contributed to the process.

Because of the importance these papers potentially have on the broader engineering education community, they have gone through an extensive peer review process once they were submitted to *Advances*. In particular, each paper was reviewed by considerably more reviewers than the usual unsolicited paper submitted to the *Journal*. We anticipate that the papers will be widely read, commented on, and referenced in future papers and research proposals.

Key words: Delphi Method, engineering educational innovation, STEM propagation.

BACKGROUND

Despite a series of blue ribbon reports and white papers addressing the U.S.'s deteriorating competitive position and consequently a need to increase the quality and output of STEM graduates, the overwhelming evidence suggests that much remains to be accomplished. (See Figure 1 for a graphical overview of these studies.) Among the STEM fields, engineering has been especially singled out. Compared to other developed countries where over 15% of college graduates are engineers, just five percent of U.S. college graduates are engineering majors, and, what had been until recently, a small but growing portion of those are international students. Thus, a national concern is not only how to increase the quantity of engineering graduates, but equally important, how to improve the quality with foci on both pathways to and through college, as well as improved learning issues. As a result, through a National Science Foundation EArly-concept for Exploratory Research (EAGER) grant, funding was obtained to commission a set of papers that would be based on input from the larger engineering education community in order to layout potential research to improve propagation of engineering related innovations. These papers, which comprise this volume address learning and assessment, technology, and having a diverse set of pathways for future students. In addition, all three also focus on propagating proven results across the field.

Where Are We? What Have Recent National Reports Told Us?

Over a decade and a half ago, a National Academy of Engineering study declared that "Leadership in innovation is essential to U.S. prosperity and security . . . [However,] U.S. leadership in technological innovation seems certain to be seriously eroded unless current trends are reversed" (NAE, 2004a). An NSF-commissioned study by the American Society of Engineering Education also concurred "U.S. engineers lead the world in innovation," but "this great national resource is at serious risk because America has an engineering deficit" (Douglas, et. al., 2004). Thomas Friedman's characterization of an increasingly flat world sounded a similar warning that "The Chinese and the Indians are not racing us to the bottom. They are racing us to the top" (Friedman, 2005). Indeed, at least the Chinese now appear to have caught up and may be on their way to surpassing us (Moritz, 2018; Kang and Rapapport, 2018).

Further, as we entered the new millennium, researchers began to recognize that engineers' roles were changing in what has become a tightly connected global environment. Now 21st century engineers must address complex problems in collaborative, interdisciplinary contexts. These new roles call for ". . . a new type of engineer, an entrepreneurial engineer, who needs a broad range of skills and knowledge, above and beyond a strong science and engineering background. . ." (Jonassen, Strobel & Lee, 2006, p. 139).

In 2004-2005, the NSF-funded Engineering Education Research (EER) Colloquies led to the organization of EER around five priority areas: engineering epistemologies, learning mechanisms, learning systems, diversity and inclusiveness, and assessment that merged disciplinary knowledge and learning science (The Steering Committee of the National Engineering Education Research Colloquies, 2006a and 2006b). To some, this marked the emergence of rigorous engineering education research (Lohman and Froyd, 2011).

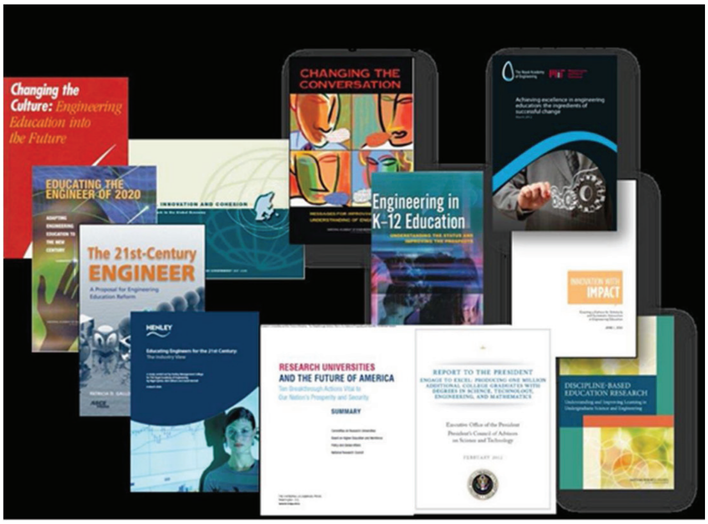

Figure 1. Recent National Reports.

Fast forward ten years – two studies again examined issues in engineering education. In the first, the ASEE under NSF support, initiated "*Transforming Undergraduate Education in Engineering*" that aims to clearly define the qualities engineering graduates should possess and to promote the curricula, pedagogy, and academic culture changes needed to instill those qualities in the future engineers (ASEE, 2013). The authors envisioned a T-shaped graduate, who would bring broad knowledge across domains and the ability to collaborate within a diverse workforce while possessing deep expertise within a single domain.

In the second study, the National Research Council (NRC) produced *Discipline-Based Education Research (DBER): Understanding and Improving Learning in Undergraduate Science and Engineering* (NRC, 2012), which contains an extensive volume of insights, references, and recommendations; it calls for (among its many recommendations): Research exploring similarities and differences among different student populations; longitudinal studies to better understand the acquisition of important concepts and factors influencing retention; more studies and better instruments to measure outcomes beyond tests and course performance; and interdisciplinary studies of cross-cutting concepts and cognitive processes. The DBER report provides further impetus for improving the pipeline and diversity as well as research on learning and retention of learning. However, the DBER goes one step further in enumerating principal areas of inquiry that address the need for research on the propagation of engineering education research into practices, including: the extent to which engineering faculty adopt evidence-based practices, the values that departmental, college, and university cultures place on teaching and learning compared with traditional disciplinary research, as well as the balance that Ph.D. programs strike between disciplinary research and the development of teaching and learning knowledge and skills (NRC, 2012).

The NRC study notes that a true pocket of propagation of STEM education research does exist - the NSF-supported Center for the Integration of Research, Teaching, and Learning (CIRTL), which started with a core network of 22 research active universities, and after 13 years now has 38 members that provide professional development opportunities for doctoral students and post-doctoral scholars in science, technology, engineering, and mathematics. Research suggests that those participants involved in CIRTL will develop a greater sense of the value of teaching as part of their careers; a wider range of approaches to analyzing teaching problems; and an enhanced ability to encourage student learning (Austin, et al, 2008). There are indications that participants feel better prepared for undergraduate teaching, have a greater sense of self-efficacy about teaching, and value opportunities to interact with others with similar interests regarding teaching through the CIRTL learning communities (Austin, 2011). However, more research is needed if national needs are to be met in engineering education (NRC, 2012).

More recent major reports have focused on the integration of the humanities and arts (Skorton and Bear, 2018), introducing data science for undergraduates (National Academies, 2018), women's participation and retention (ASEE, 2017), global state of the art in engineering education (Graham, 2018), role of assessment of intrapersonal and interpersonal competencies (Herman and Hilton, 2017), integrating ethics into the curriculum (Center for Engineering Ethics, NAE, 2016), and integrating discovery based research into the undergraduate curriculum (National Academies, 2015).

Three Key Areas for Engineering Education Research

We have focused on three key areas for the propagation of research in engineering education:

- Learning inside the classroom,
- Improving and diversifying the pathways, and
- The role of technology.

We have recently witnessed the introduction of new forms of pedagogy including the blended and flipped classroom (See *AEE*, Fall 2016, vol. 5,3) and gamification in complement with rapid changes in teaching based technologies, which are changing the perspectives by which education can be delivered (Yuan and Powell, 2014). Consequently technology is now at the forefront of engineering education, with examples of true personalized learning already appearing (Alli, et al, 2016; Blumenstyk, 2018; Feldstein and Hill, 2015; Kapp, 2016; Lieberman, 2017; Riland, 2017).

Consequently, there is growing recognition that research is needed on how best to use new technologies and pedagogical approaches (Bates, 2013) that is equal to the focus on learning and the pathway issues. Many exciting engineering education innovations have been produced over the past few decades; however, as Rogers indicates in his *Theory of the Innovation-Decision Process* (2004), a lack of knowledge of how to implement the innovation correctly as well as a lack of underlying basic principles can lead to discontinuance of a proven innovation. These findings argue for shifting the conversation from "what works" and the connected evidence for those practices to putting proven practices into place efficiently (NRC, 2012).

Our Objectives

Our overarching objective has been to produce three forward thinking papers framed by input from the broader engineering education research community that point out needed future directions for research to promote and propagate documented innovations. In doing this, we asked the community and author teams to address four major questions:

1. **What accomplishments have been produced to date?** What new innovations have occurred over the past one to almost two decades that have lasting value in engineering education?
2. **To what extent have innovations been propagated?** Have meta-analyses of certain funded innovations across the key areas gleaned useful understanding of how propagation has or has not occurred?
3. **What remains to be done?** What are the gaps in the research? What are potential root causes as to why the particular innovations have not proliferated across engineering schools?
4. **How best can future work be propagated?** What type of research agenda is needed over the next five to ten years to facilitate innovations in engineering education spreading across different types of engineering schools, engineering disciplines and engineering coursework? What evidence is required to document a successful innovation?

METHODOLOGY

We addressed these questions through a series of interactive strategies that involved both engineering education researchers and administrators. The strategies were designed to achieve both peer credibility and involvement. A major component of the process was the use of the Delphi process to identify issues and writing teams. In all, three rounds of the Delphi were used coupled with interactive input from the larger community. The Delphi process (Linstone and Turnoff, 2002) provides an interactive communication structure between researchers and subject matter experts (SMEs) to develop themes, needs, and directions about a topic. Participants remain anonymous, and responses are reported in aggregate, allowing for a free exchange of ideas among the group.

Participants know other SMEs exist, but do not know their names or affiliations. For all rounds, responses were collected via Qualtrics survey software.

First, we empowered a planning committee consisting of three engineering education experts – Alan Chevelle, Tom Litzinger and Michael Loui - to assist in determining a broad spectrum of subject matter experts to engage in the first Delphi study. That study (Round 1) would more explicitly identify the issues and needs to be addressed, as well as possible writing team members.

To assist in identifying SMEs, a broad list of 797 potential participants was assembled including authors who had published in *Advances in Engineering Education* and the *Journal of Engineering Education* over the past decade; all Principal Investigators with either a REE or RIGEE project; and all participants in the National Academy of Engineering's Frontiers of Engineering Education symposiums. Participants in the project's three Delphi studies would be drawn from this initial pool of potential SMEs.

Together with the planning committee members, each of the 797 individuals was categorized (i.e., do not know person/cannot make a judgement; do not invite; potential SME; or definitely invite as SME). Those judged to be potential or definitely invite SMEs were then subdivided into one of the three focus areas based on their background. The result of this initial effort was a reduced pool of 187 SMEs divided into four areas and categorized according to their potential contribution as follows.

- Learning inside and outside of the classroom (60)
- Improving and diversifying the pipeline and pathways (43)
- The role of technology (22)
- Change and culture in education (18)
- Other (44)

We then chose to invite as SMEs the first 30 individuals in the "Learning" cluster, the first 30 in the "Pathways" cluster, and all of the "Technology" cluster. We also invited all of the "Change" cluster, but reallocated these SMEs across the first three pools. The "Other" cluster was then eliminated.

Of the 100 invited SMEs to participate in the three Delphi Studies, 18 of the "Learning," 10 of the "Pathways" and 13 of the "Technology" responded and participated. For Round 1, two questions were asked (depending on the SME's subject area):

- What are the most critical unresolved issues facing engineering education research and its propagation *related to*
  - Learning inside and outside of the classroom?
  - Improving and diversifying the pipeline and pathways?
  - The role of technology?
- Who are the most appropriate individuals to address these issues?

The SMEs provided a highly comprehensive set of responses for the first question. Each response was read by two researchers, who first delineated every issue, and then sorted the resultant issues

Table 1. First Delphi Results.

Subject Area	Question 1: Distinct Ideas Suggested	Question 2: Potential Writers
Learning In and Out of the Classroom	28	35
Pathways and Pipelines	16	39
The Role of Technology	18	23

into three exhaustive groups – Learning, Pathways or Technology. Each resultant response was rephrased into an action statement (i.e., verb followed by noun phrase) for consistency. A third researcher reviewed the groupings, regrouped where necessary, and drafted an overview statement for the grouping. Any remaining issues were then arbitrated by the three researchers.

For the second question, initial pools of writers were developed. Table 1 provides a summary of the number of distinct ideas generated per subject area along with potential experts that could write about the particular subject area.

With this information, the second Delphi (Round 2) was conducted. Each of the responding SMEs were then asked to:

1. Rate the degree of importance each item might have on engineering education and its propagation, and
2. Select up to three senior and three junior level individuals who could best address these issues.

For each of the three areas, the top five results for question 1 were selected for presentation to the engineering education community at the 2015 ASEE national conference in Seattle, Washington. The purpose of the special session was to introduce the project to the engineering education community, and obtain feedback regarding the results of the second Delphi. Consequently, everyone on the list of 187 SMEs was invited to the special session. In addition, invitations were sent to various divisions of ASEE (e.g., Educational Research Methods Division). Nearly 100 people attended that session. Attendees learned about the project and the process that led to the special session. Attendees were then presented with the top results selected for each of the three areas, asked to think about their own weighting of these items, then briefly discuss with their colleagues before voting (i.e., the community participated in a large think-pair-share exercise). That is, each attendee was asked to "select the item you think is most important to engineering education research and its propagation." Classroom response systems (i.e., clickers) were used to capture responses. Of the 100 people in attendance at the special session, 74 actively signed in and participated in the voting process. Another four individuals emailed their responses as we ran out of clickers (Besterfield-Sacre and Shuman, 2016).

In light of the special session responses, the data was further analyzed, and a final Delphi (Round 3) was conducted to refine issues and narrow the selection of the writing teams. Writing teams were invited; and each team received a small contract and an assigned consultant, who would provide additional input while serving as a first reader. Those writing teams whose final papers are part of this issue were:

- Learning inside the classroom – Jeff Froyd and Cindy Finelli; Tom Litzinger (consultant);
- Improving and diversifying pathways – Susan Lord and Dennis Simmons; Michael Loui (consultant); and
- The role of technology – Milo Koretsky and Ale Magana; Alan Cheville (consultant).

A series of conference calls were conducted with the teams to outline the requirements for the paper and review results from the three Delphi rounds and the ASEE session. The writing teams used these results combined with their own literature review and input from the consultants to develop a set of issues to address with a larger body of experts.

To present their ideas, the writing teams met with the larger body of SMEs, selected from participates of the Delphi, in Pittsburgh for a 1.5 day workshop. The workshop's objective was to: Provide to the writing teams additional insights and wisdom as to the important engineering education issues and how they could best be propagated (i.e., What research is needed for propagation? What research is needed on how best to propagate?).

The workshop resulted in agreement and a strategic, in-depth understanding of the issues, as well as tactical recommendations for how research on these issues might best proceed. Participants worked both across all three foci as well as in small groups addressing one of the three areas. The workshop also provided an opportunity for the writing teams to vet their interpretation of the key issues, and revise them from the resultant input. For example, the "Learning inside and outside the classroom" team narrowed the scope to "Learning *inside* the classroom" given, in part, to feedback from the SME's that attended the workshop. It was felt by workshop participants and the writing group that "outside the classroom" incorporated an entirely new scope for the work and would be a paper in itself.

"Outside the classroom" experiential learning includes such co-curricular activities as international learning/study abroad, internships and cooperative learning, learning through student clubs and competitions, as well as learning through makerspaces. These experiential learning examples are certainly viable and contribute highly to student learning, but are supported by a different literature as well as different SME expertise.

In addition, "improving and diversifying the pathways" was originally called "improving and diversifying the pipeline." Workshop participants and the current literature point to "pipeline" as a tired metaphor used in STEM education, with a negative connotation for individuals leaving (or leaking out) of STEM programs. In contrast, "pathways" provides for multiple routes and avenues to attain a STEM (here, engineering) degree. Hence, it is a more inclusive and correct term for the intentions of the workshop participants and writing team.

The writing teams each produced a draft Work-In-Progress paper that was submitted, reviewed and revised for the 2016 ASEE National Conference as part of a second special interactive session. In a similar manner to the 2015 ASEE National Conference, a broad range of participants were invited to attend this session in which the writing teams provided their identified key issues via work-in-process papers to the engineering education community. At the interactive session each writing team presented its work via five minute lightning talks, which then turned into a world café approach enabling each writing team to have small group discussions with participants. A total of six small group (two for each subject area) discussions were held with groups rotating after ten minutes. After two rotations (i.e., three café sessions), all session participants had the opportunity to discuss with the authors their thoughts and ideas regarding each of the three focus areas. In this manner, the writing teams received feedback from the engineering education community regarding the specific issues being addressed. This enabled the writing teams to strengthen their papers while ensuring that they were addressing issues of concern to the larger community.

CONCLUSION

The completed papers were submitted to *Advances in Engineering Education*. Each paper underwent an extensive peer review. As noted in the Introduction Section, this was done in recognition of the potential importance of these papers. Consequently, each paper was sent to a broad spectrum of reviewers that included the attendees at the invited workshop, since they were familiar with the project and the evolution of the papers.

Improving Student Learning in Undergraduate Engineering Education by Improving Teaching and Assessment

Jeff Froyd and Cindy Finelli have addressed what they believe is needed if there are to be comprehensive, systemic, and systematic improvements in undergraduate engineering student learning. This will require change across numerous elements in the education system. Their paper was informed by the three Delphi studies and the subsequent workshops that have enabled major issues to be clustered into four themes: (1) change the organizational culture, (2) research effective assessment practices, (3) promote adoption of research-based teaching practices (RBTPs), and (4) characterize successful faculty development. For each theme, Froyd and Finelli present a rationale to support its selection and organize the needed research questions. As noted in their paper, the expectation is that it will "catalyze scholars to generate new areas of research, will inspire engineering instructors to pursue ideas for improving teaching and assessment in their classrooms, and will galvanize administrators to apply insights to change institutional policies, teaching and assessment activities, faculty development initiatives, and, ultimately, their organizational cultures."

Removing Invisible Barriers and Changing Mindsets to Improve and Diversify Pathways in Engineering

Susan Lord and Denise Simmons propose that "supporting diverse students in engineering education is considered a critically unsolved issue facing engineering education research." They believe that the field not only suffers from a lack of diversity, but continues to struggle to recruit and retain underrepresented students. They believe that this is due in large part to structural barriers that prevent equitable participation. The paper examines these barriers, in particular, racism and sexism, that underrepresented engineering students experience and propose realistic interventions. In calling for action to improve and diversify educational pathways, the authors call for rethinking research and instruction mindsets. They present examples that have worked well. They end by "call[ing] for the engineering education community to work together in changing the culture of engineering education highlighting the key role of the allies."

Using Technology to Enhance Learning and Engagement in Engineering

Milo Koretsky and Ale Magana explore how information, communications, and computational technology (computer technology for short), influence the teaching and subsequent learning of undergraduate engineering. Their goal is to contribute to promoting research, adoption, and policy for propagating the effective use of computer technology in engineering education while avoiding potential pitfalls that technology can create. In this manner they seek to inform action and generate conversation among various constituencies within the broad engineering education community. Their paper addresses the role of technology in learning engineering, including both technologies specifically designed for learning (learning innovations) and domain-specific technologies for engineering practice (computational tools). The paper includes discussion of the needed professional development to prepare faculty to use technology effectively in the classroom. The paper concludes with the broader ways technology interacts with engineering students and faculty at the systems level, both the good and the bad.

We encourage you to read these papers and send comments directly to the authors. We invite well-written responses for possible inclusion in *Advances in Engineering Education*. Those should be submitted via the usual mechanism: https://mc.manuscriptcentral.com/advances.

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