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

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ABSTRACT

In this paper, we report and expand on research questions designed to improve undergraduate engineering education. These questions are based on a yearlong process that included a three-step Delphi study and a subsequent two-day workshop. The Delphi study, conducted during winter and spring of 2015, engaged subject matter experts from engineering education research and engineering academic administration. It resulted in the formation of three writing teams, one each for the critical areas of improving student learning in undergraduate engineering education, improving and diversifying pathways of engineering students to increase retention, and using technology to enhance learning and engagement in engineering. Participants in the two-day workshop, held in October 2015, were chosen for their expertise in one or more of the three areas, such that the workshop could explore priorities for research that would address each of these areas. Using results from the Delphi study and the workshop, the writing teams worked to synthesize and expand on the research questions to guide future work. This paper addresses the first area: improving student learning in undergraduate engineering education.

Comprehensive, systemic, and systematic improvement of student learning in the undergraduate engineering education system will require change across numerous elements in the system. The Delphi study and the subsequent workshop clustered major issues related to these numerous elements into four themes: (1) change the organizational culture, (2) research effective assessment practices, (3) promote adoption of research-based teaching practices, and (4) characterize successful faculty development. For each of the four themes, we present a rationale to support selection of the theme and offer categories to organize the research questions. We expect these questions 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.

Key words: Institutional Change, Instruction, Assessment.

INTRODUCTION

Recommendations in two reports from the American Society of Engineering Education (ASEE) addressed *who* and *what* needs to change as we work to improve learning in undergraduate engineering education (Jamieson & Lohmann, 2009; 2012), and many other calls to action have motivated the engineering education research community to develop plans for systemic improvements in engineering education (e.g., Malcom & Feder, 2016; National Academy of Engineering, 2004, 2005; President's Council of Advisors on Science and Technology (PCAST), 2012). In the spirit of addressing the engineering education research community as it works to achieve this systemic change, we offer some potentially promising directions for improving student learning in undergraduate engineering education. We organize the research questions around four themes, based on results of a yearlong process that included a three-step Delphi study and a two-day workshop (Besterfield-Sacre & Shuman, 2016; Finelli, Froyd, & Shuman, 2016). Those themes include: (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. We hope that the questions we offer here will be of interest to scholars in engineering education research, engineering instructors, and engineering education administrators alike.

Figure 1 illustrates how we organize the four themes (shown as four dark blue, enumerated bubbles) as they relate to student learning. We depict the overarching influence of organizational culture as a large cloud. Teaching and assessment occur within the organizational culture of an institution of higher education, and this culture influences everything about the institution, including decisions that scholars, instructors, and administrators make about which research efforts to pursue, which teaching and assessment practices to adopt, and which faculty development opportunities to provide. Changing the organizational culture is the first theme around which we highlight the need for future research (shown as the dark blue bubble labelled 1 in Figure 1).

The blue and green triangle in Figure 1 illustrates how teaching and assessment work together to improve student learning within the culture of an institution of higher education. It visually represents

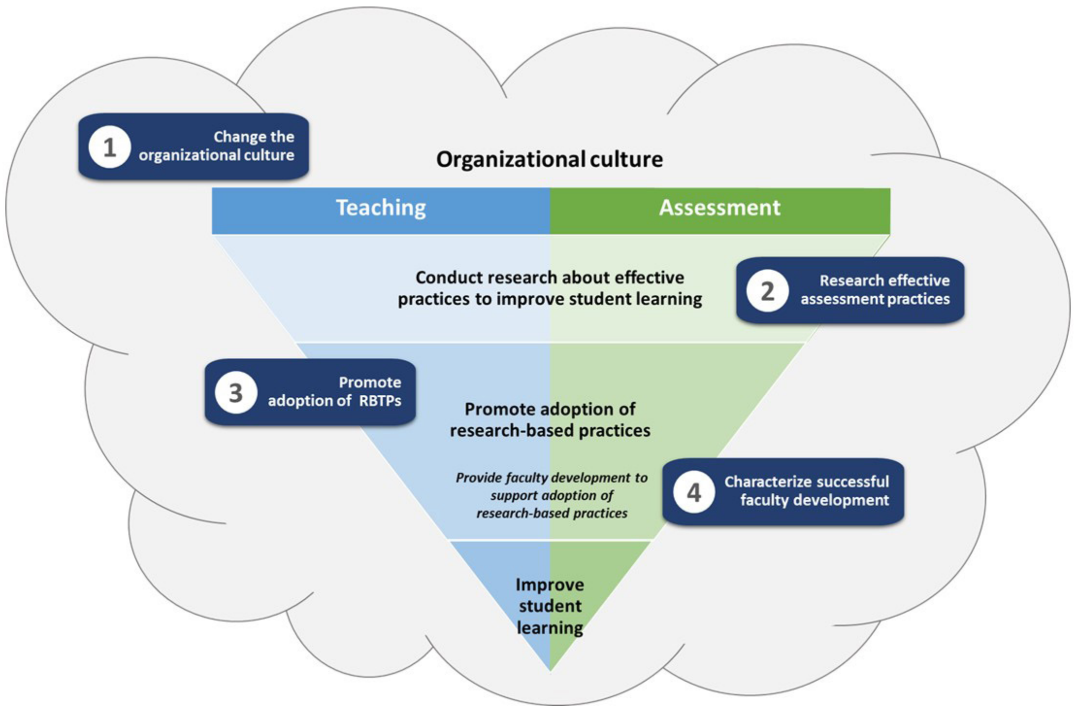

Figure 1. The organization of our four themes for future research to improve student learning in undergraduate engineering education.

the need for a research base about effective practices for both teaching and assessment and a way to promote instructors' adoption of those research-based practices to improve student learning. Of course, boundaries between teaching and assessment are vague, but we think the visual division of Figure 1 may be useful because teaching and assessment are often distinct. The evidence base for effective teaching practices is significantly deeper than that for effective assessment practices, and the level of adoption of those practices is even more varied. Table 2 of the report from the PCAST (2012) reflects this imbalance. It lists 14 practices that have been demonstrated to enhance learning, 12 of which are teaching practices and only two of which are assessment practices. We suggest that rather than reflecting the relative importance of these practices, this difference reflects the fact that research about effective assessment practices considerably lags research about effective teaching practices. Figure 1 emphasizes the need for more research about effective assessment practices (shown as the dark blue bubble labelled 2 in Figure 1).

Extensive research on teaching practices has identified a large number of RBTPs, yet widespread adoption of these practices has not occurred (e.g., Froyd, Borrego, Cutler, Henderson, & Prince, 2013; Jamieson & Lohmann, 2012; PCAST, 2012; Stains et al., 2018). Further research on individual and organizational change shows that evidence of efficacy is a necessary, but not sufficient, condition to promote adoption of a new practice. Thus, Figure 1 highlights the need for future research about promoting adoption of RBTPs over identifying additional effective practices (shown as the dark blue bubble labelled 3).

Figure 1 likewise spotlights a proven method of promoting adoption of research-based practices: faculty development for instructors and future instructors. Centers for teaching and learning are numerous, and they offer an important channel for increasing awareness of research-based practices and influencing instructors' decisions to continue or discontinue effective practices or to adopt new ones (Henderson, Dancy, & Niewiadomska-Bugaj, 2012; Finelli, Daly, & Richardson, 2014). Therefore, Figure 1 highlights the need for future research to characterize successful faculty development (shown as the dark blue bubble labelled 4).

In the sections that follow, we first provide an overview of the processes that identified these four themes. We then offer a series of research questions for each theme. The paper concludes with a short summary.

BACKGROUND

A Delphi study, followed by a two-day workshop, engaged over 100 leaders in engineering education to generate both the four themes of this paper and the content of many of the research questions we offer herein.[1] The three-step Delphi study was conducted during winter and spring of 2015 (Besterfield-Sacre & Shuman, 2016), and it engaged subject matter experts (SMEs) from engineering education research and engineering academic administration. The first step of the Delphi study consisted of asking 27 participants to comment, in an open-ended format, on the critical unresolved issues facing engineering education research and hindering diffusion of innovation. Researchers synthesized those responses and created a closed-form instrument which listed issues the SMEs had identified.

In the second step of the Delphi study, 17 SMEs rated the importance of each issue and had an opportunity to suggest additional issues. Following this second step, the researchers conducted an interactive session at the 2015 *ASEE Annual Conference & Exposition* in which they summarized results of the second step of the Delphi study and invited additions and critiques from more than 70 participants.

[1]A similar process took place for the other two critical areas of "improving and diversifying pathways of engineering students to increase retention" (Simmons and Lord, 2019) and "using technology to enhance learning and engagement in engineering" (Koretsky and Magana, 2019). In this paper, we describe the process for the "learning within the classroom" only.

Researchers refined the closed-form instrument one more time and then, during the third and final step of the Delphi study, 16 SMEs reviewed the feedback from the ASEE session participants and again rated the importance of each issue facing engineering education research and its diffusion of innovation. As a result, the researchers had a list of issues the SMEs considered to be priority research areas for improving learning in and out of the classroom. For instance, the SMEs identified the organizational culture of teaching and learning, efficient assessment and evaluation tools for measuring learning, and incentives for instructors to adopt evidence-based teaching methods as key issues.

Following the Delphi study, the authors of this paper were commissioned as a writing team by the leaders of the Delphi study to address the topic of "learning in and out of the classroom" by establishing a set of research questions to guide future work. We combined results from the Delphi study with existing scholarship and with our knowledge of the topic to develop initial thoughts, which we presented at an interactive, two-day workshop in fall 2015. Leading engineering education researchers and administrators selected for their expertise participated, and they were invited to refine the list of issues and research questions. The participants reached general agreement and offered significant input for the current article, which we hope will be useful for a wide variety of audiences, including engineering education scholars and researchers, engineering instructors, and administrators in understanding future directions for engineering education research.

To improve the focus of the paper, we fine-tuned our topic to be "improving student learning in undergraduate engineering education by improving teaching and assessment." We also decided to focus on learning within the classroom only and save learning outside the classroom for another paper. We categorize the research questions around four themes: (1) change the organizational culture; (2) research effective assessment practices, (3) promote adoption of RBTPs, and (4) characterize successful faculty development. The questions this paper presents derive primarily from the three-step Delphi study and the subsequent two-day workshop. However, in some instances (especially related to the first two themes), when there was insufficient detail from the community about a specific issue, we generated additional questions based on existing gaps in the literature.

CHANGE THE ORGANIZATIONAL CULTURE

Improving student learning requires changing instructor practices related to both teaching and assessment. Instructors' decisions about their teaching and assessment practices reflect aspects of the organization (e.g., departments, colleges, universities, and professional societies) in which they are embedded, which together create the *culture* of the organization (Hora, 2012). Many researchers cite organizational culture as a barrier, a focus, a factor to consider, and even an affordance for change initiatives in higher education (Elrod & Kezar, 2017; Henderson, Beach, & Finkelstein, 2011; Kezar & Eckel, 2002; Oleson & Hora, 2014). In addition, several reports and requests for proposals to improve engineering and/or science, technology, engineering, and math (STEM) education, from National Science Foundation (NSF) and from other organizations, cite culture as a factor to be addressed. The list below provides a sampling:

- A description of the NSF's REvolutionizing engineering and computer science Departments (RED, www.nsf.gov/funding/pgm_summ.jsp?pims_id=505105) program stipulates that:
  Departmental cultural barriers to change and to inclusion of students and faculty from different backgrounds must be identified and addressed.
- The report "Progress Toward Achieving Systemic Change," published by the Association of American Universities (AAU) Undergraduate STEM Initiative (www.aau.edu/progress-toward-achieving-systemic-change), announced the launch of a major initiative to improve undergraduate STEM education with the overall objective of:
  …influence[ing] the culture of STEM departments at AAU institutions so that faculty members are encouraged and supported to use teaching practices proven by research to be effective in engaging students in STEM education and in helping students learn.
- The NSF ADVANCE program (ADVANCE: Increasing the Participation and Advancement of Women in Academic Science and Engineering Careers, www.nsf.gov/funding/pgm_summ.jsp?pims_id=5383) describes organizational culture as an impediment to efforts "to develop systemic approaches to increase the participation and advancement of women in academic STEM careers." The program's website states,
  Organizational barriers that inhibit equity may exist in areas such as policy, practice, culture, and organizational climate. For example, practices in academic departments that result in the inequitable allocation of service or teaching assignments may impede research productivity, delay advancement and create a culture of differential treatment and rewards.

These examples reflect a strong impetus to change organizational cultures to support initiatives to improve student learning in undergraduate engineering education. However, the nature of necessary changes and effective plans to achieve desired cultural change remain unclear. To address this gap, research on changing organizational culture needs actionable descriptions of organizational culture so that research can be anchored in shared understandings of the term. Although this overall topic was raised as an important issue facing engineering education research and hindering diffusion of innovation, insufficient progress was made on this topic during the Delphi study and the subsequent two-day workshop. Thus, in this section, we present a review of the literature about organizational culture, and we use that as a basis to highlight research priorities to change the organizational culture (the dark blue bubble labelled 1 in Figure 1).

Understand Organizational Culture

During the two-day workshop, participants shared ideas about how culture could be related to improving student learning. Sometimes participants mentioned the reward systems at institutions of higher education and the lack of support for teaching in these reward systems, but participants did not deeply explore connections between organizational culture and reward systems. Having a clear understanding of *organizational culture* is an important first step to changing the culture, but it is difficult to obtain such an understanding (Jahoda, 2012; Kroeber & Kluckhohn, 1952). To address this problem, we offer three touchstones as a foundation that we hope will contribute to the eventual emergence of a consensus definition of organizational culture.

The first touchstone is that organizational culture is the "accumulated shared learning of [an organization] as it solves its problems of external adaptation and internal integration" (Schein, 2017, p. 6). Schein describes accumulated shared learning as having three levels:

- *Artifacts:* tangible structures and processes, e.g., architecture, published criteria for tenure and promotion, dress code, and office jokes.
- *Espoused values:* the organization's stated values and rules of behavior. They are how the members represent the organization both to themselves and to others, often in official philosophies and public statements of identity. Examples of espoused values include employee professionalism or a "family first" mantra. Trouble may arise if the values leaders espouse do not align with the deeper tacit assumptions of the culture.
- *Shared basic assumptions*: deeply embedded, taken-for-granted behaviors that are usually subconscious, but that constitute the essence of culture. Unlike artifacts and espoused values that can often be recognized by people who are not part of the culture, shared basic assumptions are typically so well integrated into the office dynamic that even members of the organization do not recognize them.

Schein suggests that calls for changing the culture of an organization are calls for changing the associated implicit, shared assumptions.

Bergquist and Pawlak (2008) offer the second touchstone for organizational culture, six facets of culture in the academy:

- *Collegial culture*: reasoned discourse, discipline, and faculty governance aligned with traditional norms of higher education.
- *Managerial culture*: business model, organizational effectiveness, organizational efficiency, administration, learning outcomes, teaching load, budgets, performance review, and accountability.
- *Developmental culture*: faculty development, curriculum development, institutional research, and organizational development.

- *Advocacy culture*: faculty unions, collective bargaining, academic freedom, and instructor priorities.
- *Virtual culture*: online courses and virtual universities.
- *Tangible culture*: bricks, mortar, and residential students.

The third touchstone is that various elements of an organization uniquely contribute to its culture. Tierney's (1988) framework presents six elements to characterize organizational culture:

- *Environment*: individuals and organizations outside the organization that interact with the organization and influence its priorities and resources.
- *Mission*: institutional mission that provides values, priorities, rationale, and criteria that guide decisions within the organization.
- *Socialization*: processes through which new members become acculturated and learn how to survive and/or excel in the organization.
- *Information*: ideas about what is information and how members expect to send and receive information.
- *Strategy*: processes through which decisions are made within the organization and ways organizational leaders communicate expectations for involvement in these.
- *Leadership*: expectations of the organization for its leaders, both formal and informal.

Our three touchstones may allow an organizational change agent to describe either an existing or an envisioned organizational culture by: (1) articulating the often unspoken, but frequently enacted, assumptions that are believed to contribute to initial success of the institution (Schein, 2017); (2) describing the extent to which each of the six facets of culture align with the history and current operation of the unit (Bergquist & Pawlak, 2008); and (3) considering how an envisioned change might require changing the six elements of organizational culture (Tierney, 1988). Descriptions of both the existing and the envisioned culture are needed for organizational cultural change, since any planned change requires both acknowledging the existing culture and envisioning a different one (Van de Ven & Poole, 1995; Weick & Quinn, 1999). However, our three touchstones may not be adequate for describing either existing or envisioned organizational cultures. Simpler descriptions of organizational culture may be needed because the complexity associated with our three touchstones may burden organizational change agents or there may be aspects of organizational culture that are not encompassed by the touchstones. With these ideas in mind, we offer a set of research questions to understand organizational culture better:

- How do researchers conceptualize organizational culture?
- How can organizational culture be described, articulated, and evaluated in ways that facilitate conversations about changing the culture?
- To what extent do the three touchstones of organizational culture we offer support descriptions of existing and envisioned cultures needed for planned organizational cultural change?

- In addition to or in place of the three touchstones, what descriptions of organizational culture will foster shared meaning and constructive dialog about cultural change?
- What metrics could be used to describe organizational culture?
- How can members of the engineering education community use the touchstones to describe envisioned organizational cultures that would support improved student learning in undergraduate engineering education?

Ascertain When Change is Needed

In addition to needed descriptions of organizational change, another issue that was insufficiently addressed during the Delphi study and the two-day workshop was the ability to ascertain when cultural change was needed. Some initiatives to improve student learning may require cultural change, however, others may not require concomitant, supportive cultural changes. For example, Schein (2017) shares an example of leaders who were convinced their organization needed to change its culture to accomplish its goal of sharing functions across a decentralized administration. However, after clarifying the cultures of the organization's different divisions and describing the relationship between them, the change agents decided cultural change was not needed. This example highlights the need to determine whether realizing the envisioned goals of improving student learning actually requires cultural change. The research questions below relate to making this determination in seeking to improve student learning:

- How might organizational culture be hindering initiatives to improve student learning?
- What methods can be developed to determine whether organizational cultural change will help achieve proposed goals?
- When is a change in organizational culture necessary (and when is it unnecessary) for promoting the goals of a proposed change process?
- How can one determine the extent to which cultural change aligns with the goals of an institutional change process?
- How have ongoing change initiatives, such as the NSF RED program and AAU Undergraduate STEM Initiative, described the envisioned change in organizational culture?

Clarify the Relationships Between Organizational Culture and Teaching and Assessment Practices

The current change literature in higher education provides mostly generalized statements about the needed conditions to promote change: a willing president or strong leadership, a collaborative process, and rewards (Roberts, Wergin, & Adam, 1993; Taylor & Koch, 1996). This broad perspective may not be particularly helpful in specific cases, and in many instances the ideas of "achieving buy-in" or "communicating effectively" can seem empty to institutional leaders and higher education scholars (Kezar & Eckel, 2002, p. 435).

Kezar and Eckel (2002, p. 435) acknowledge the need for more specific, organizationally nuanced work on change within an institution of higher education, asking, "Can this strategy be used at every institution and in the same way?" In their study of how culture influenced change strategies in six institutions, these authors showed ways that the change process acknowledged the existing organizational culture and used it to their advantage. Others have similarly showed the importance of connecting change strategies with the local context (Bergquist & Pawlak, 2008; Finelli et al., 2014; Henderson et al., 2011). Here we pose two related research questions:

- How can organizational change processes to improve student learning be made compatible with existing cultures in higher education?
- How can change agents use existing organizational cultures to achieve the goals of a change process to improve student learning?

Identify Strategies and Tactics to Change Organizational Culture

Synthesizing results from their systematic review of literature on change in higher education, Henderson et al. (2011) lay out four quadrants for change initiatives in higher education. The fourth quadrant, *Shared Vision*, is most applicable for changing organizational culture. Within this quadrant, Borrego and Henderson (2014) identify two key change strategies: learning organizations and complexity leadership theory. They summarize learning organizations as those in which "a leader works to develop an organizational culture that supports knowledge creation" (Borrego & Henderson, 2014, p. 227), so they suggest that implementation of this strategy requires organizational cultural change. Complexity leadership theory recognizes three types of leadership (Uhl-Bien, Marion, & McKelvey, 2007):

- *Administrative leadership* focused on hierarchy (e.g., organization charts), alignment, and control;
- *Enabling leadership* focused on leadership to facilitate creative problem solving, adaptability, and learning; and
- *Adaptive leadership* focused on generative dynamic that underlies emergent change activities.

Articles on complexity leadership theory rarely reference organizational culture or organizational cultural change. And unfortunately, none of the examples that Borrego and Henderson (2014) offer for either learning organizations or complexity leadership theory involve planned changes in the organizational culture. Our literature review found no solid strategies for planned organizational cultural change, and therefore we offer the following research questions:

- What strategies and tactics are effective in changing an organizational culture?
- What research methodologies support study of strategies and tactics with respect to organizational cultural change?

RESEARCH EFFECTIVE ASSESSMENT PRACTICES

Effective assessment of student learning through practices such as evaluating students with respect to established expectations and providing feedback to students about their performance on assessment tasks can improve student learning in undergraduate engineering education. There is, however, insufficient research about effective assessment practices and their relationships to improving student learning. Therefore, the Delphi study identified a second theme for improving student learning in undergraduate engineering education that is related to conducting research on effective assessment practices. In this section, we define "assessment of student learning," offer a rationale for conducting more research about effective assessment practices, and outline a series of research questions about effective assessment practices (the dark blue bubble labelled 2 in Figure 1). For this research theme, the Delphi study and the subsequent two-day workshop did yield several useful research questions, but those efforts were partially hindered by disparate frameworks and perspectives, so we supplement those with questions that address some gaps in the literature.

To many engineering educators, even the basic definition of assessment of student learning is unclear. For instance, the terms summative assessment, formative assessment, grading, and feedback are sometimes used synonymously, though they convey distinctly different ideas. We consider formative and summative assessment to be two ends of a *purpose-of-assessment* spectrum. Formative assessment focuses on *improving* the learner's performance. It can be used to collect information on student progress toward course learning outcomes or to adjust the pace of instruction or type of learning activities. Summative assessment focuses on *evaluating* the learner's performance. It is generally used to assign grades. In practice, almost any assessment falls somewhere along the spectrum. Homework might be the epitome of formative assessment, but many instructors grade it believing that students will not do homework unless it counts toward their course grade. Thus it becomes, partially, a form of summative assessment. At the other end of the spectrum, final exams primarily act as summative assessments, but they do have some elements of formative assessment. Learners can use the feedback from the final exam to improve their understanding if they must retake the course or when they prepare for a subsequent course that relies on the content of the final exam.

Grading is different from, but related to, assessment. The results of assessment are typically multidimensional, where each dimension addresses one of the articulated course learning outcomes. In contrast, grading (i.e., the practice of assigning a single letter grade or numerical score for student performance across an entire course) is one-dimensional, yielding a single numerical score or a letter grade, as dictated by institutional policy.

Since we subsequently use both feedback and formative assessment, we will clarify how we use each term. Feedback, to support student learning, must provide "opportunities to close the gap between current and desired performance” (Nicol & Macfarlane-Dick, 2006), and both the quality of feedback instructors provide to students and the way they provide it influence whether and how the learner responds to the feedback. However, feedback is only a part of many formative assessment processes. Formative assessment, with its focus on improving student learning, may or may not provide feedback directly to students. For example, one popular form of formative assessment, the minute paper (Stead, 2005), provides feedback to instructors, but not necessarily to the student.

Our review of the existing literature has identified two reasons that improving assessment, especially formative assessment, is important for improving student learning: (1) formative assessment has been shown to improve student learning, and (2) formative assessment applies retrieval practice that has also been shown to improve student learning. With regards to the first reason, several seminal publications have shown that formative assessment can directly influence student learning (Black & Wiliam, 1998; Hattie & Timperley, 2007; Kingston & Nash, 2011). In their synthesis of 12 meta-analyses (including 196 studies and 6,972 effect sizes) reviewing factors that influence student learning and achievement, Hattie and Timperley (2007) report an average effect size of 0.79 for the influence of *feedback* on learning and achievement. This was twice the average effect size of several factors that influence student learning and achievement, and it placed feedback among the top ten influences on student achievement. This effect size, though less than that for students’ prior cognitive ability (1.04), instructional quantity (0.84), and direct instruction (0.82), is greater than that for students’ disposition to learn (0.61), class environment (0.56), peer tutoring (0.50), and student use of calculators (0.24). Further emphasizing the importance of feedback in supporting student learning is its emphasis in frequently cited lists of principles for good practice. For example, Chickering & Gamson (1987) list “giving prompt feedback” as one of the seven principles of good practice in undergraduate education. Ambrose et al. (2006) list “goal-directed practice coupled with targeted feedback enhances the quality of students’ learning” as one of their seven learning principles. Three of the seven principles of good practice for formative assessment and self-regulated learning (Nicol & MacFarlane-Dick, 2006) directly relate to assessment: help clarify good performance (e.g., set goals, criteria, and expected standards), facilitate development of self-assessment in learning (e.g., encourage reflection), and deliver high quality information to students about their learning (e.g., provide feedback).

Second, formative assessment gets learners to attempt “recall of information from memory, as occurs when taking a practice test, one of the most potent training techniques known to learning science” (Pan & Rickard, 2018, p. 710). Research showing effectiveness of retrieval as a strategy for learning, that is the testing effect, is extensive, both with respect to the number of studies and the period of time over which these studies have been conducted (Karpicke & Grimaldi, 2012; Roediger & Karpicke, 2006). A meta-analysis of retrieval practice concludes, “benefits of retrieval practice persist across a wide array of educational levels, settings, and testing formats and procedures. Therefore, students should be encouraged and taught how to use retrieval practice during self-directed learning activities, and teachers may incorporate retrieval practice into structured classroom activities" (Adesope, Trevisan, & Sundararajan, 2017, p. 690). Applying these findings, formative assessment uses testing to improve student learning and "generate feedback that can be used to assess learning potential or to promote future learning" (Roediger & Karpicke, 2006).

There are a variety of frameworks, models, and steps describing how to accomplish assessment. Here, we blend those frameworks to define four steps of the assessment process and to group our research questions.

Articulate Desired Student Learning Outcomes

The first step of the assessment process is determining standards and communicating them to students. Chickering and Gamson (1987) refer to this as communicating high expectations, and Nicol and Macfarlane-Dick (2006) call it clarifying good performance. Given the broad array of engineering skills and knowledge embedded in undergraduate engineering curricula, this step can pose a challenge to engineering instructors. Engineering graduates are often expected to be entrepreneurs, system thinkers, project managers, innovators, creative thinkers, designers, critical thinkers, effective communicators, computational thinkers, and leaders, but insufficient work has been published about how students might demonstrate their proficiencies to fulfill these roles.

Research related to this first step is critical to the goal of improving assessment of student learning, and it begins with describing learning outcomes desired of engineering graduates. These descriptions need to be supported across the broad spectrum of stakeholders in engineering education, including scholars, instructors, administrators, alumni, practitioners, and employers. To support this goal, we propose this research question:

- What learning outcomes are widely shared for the areas of: (i) entrepreneurial thinking, (ii) systems thinking, (iii) project management, (iv) innovation and creative thinking, (v) engineering design, (vi) critical thinking, (vii) a wide variety of modes of written and oral communication (beyond just technical design reports and presentations), (vii) a wide variety of modes of interpersonal communication, (ix) computational thinking, and (x) leadership?

Most of these outcomes are self-explanatory, but the terminology "wide variety of modes" of written and oral communication bears some elaboration. Engineering education seeks to instill more than abilities to write or present a technical report on a research or design project to an assembled group of people. Graduates should be able to design and produce different genres (e.g., memos, technical reports, elevator pitches, and emails), and these genres require, as Conrad (2017) notes, distinct rhetorical moves. Programs focused on developing entrepreneurial thinking emphasize elevator pitches, for example, and programs featuring undergraduate research emphasize research papers or reports.

Metrics for some of these outcomes have been identified for students without regard for their disciplines of study. For example, multiple studies have developed instruments to evaluate motivation, intent, and/or interest in entrepreneurship across students in different disciplines of study (Carsrud & Brännback 2011; Jain, 2011; Schlaegel & Koenig, 2014; Zhao, Seibert, & Lumpkin, 2010). However, we have not identified any studies that articulate learning outcomes for entrepreneurial thinking or any of the other areas specifically among engineering students.

A study of student and practitioner writing across disciplines hints at the needed scope in engineering programs. Conrad (2017) found that students in the sole engineering discipline she examined, civil engineering, produced writing that fell far short of standards of practitioner practice. Despite the practice on writing offered in current engineering curricula, it appears that in this discipline, engineering students are not able to write an engineering memo that meets the standards of professional practice.

Design Appropriate Assessment Tasks

The second step in the assessment process is designing appropriate assessment tasks, or what Van Merriënboer and Kirschner call "meaningful whole-task practice tasks" (2017, p. 53). Ideally, these tasks will allow students to demonstrate achievement of the outcomes and will be applicable within the constraints of undergraduate engineering curricula. Development of these tasks would be significant contributions to scholarship in engineering education.

In the following set of research questions, we distinguish between tasks that allow assessment of students' *work products* (e.g., a student's final project in a capstone design course or a lab report for an engineering course) and *process skills*, or what Van Merriënboer and Kirschner (2017) call *constituent skills*. Process skills are used in achieving learning outcomes and may overlap across multiple learning outcomes. They include developing requirements, identifying and describing audience for a product through oral or written communication generating alternative conceptual approaches selecting among competing alternatives preparing an oral presentation to pitch an idea and so on. For this step in the assessment process, we present the following research questions:

- What *work products* can be used to demonstrate achievement of the following student learning outcomes: (i) entrepreneurial thinking, (ii) systems thinking, (iii) project management, (iv) innovation and creative thinking, (v) engineering design, (vi) critical thinking, (vii) a wide variety of modes of written and oral communication (beyond just technical design reports and presentations), (vii) a wide variety of modes of interpersonal communication, (ix) computational thinking, and (x) leadership?

- What *process skills* used across multiple learning outcomes can be identified, and what learning tasks can be designed to facilitate student development with respect to these process skills?
- What work products can be used to demonstrate achievement of the process skills and vice versa?

Develop Processes and Instruments for Evaluating Student Work

Instructors typically use a systematic approach for evaluating student work as they execute the third step of the assessment process. For example, when grading each 20-point problem on a five-problem final exam, one systematic approach might be to deduct one point for each calculation error, five points for a minor methodological error, and 10 points for a major conceptual error. Another approach might be to provide full credit if the student gets the problem correct and offers sufficient supporting documentation, but to give zero points otherwise. These two approaches are quite different, and they might be difficult to implement consistently, but grading rubrics can offer structures or templates for developing scoring schemes. Thus, we offer the following questions:

- What validated rubrics can be used to demonstrate achievement of complex student learning outcomes (e.g., entrepreneurial thinking, project management, communication, or leadership)?
- In what areas are existing rubrics insufficient, and how might better rubrics be developed?

Implement, Analyze, and Share Assessment Results

In this fourth step of the assessment process, instructors assess student work on tasks designed to evaluate desired student learning outcomes, analyze those assessment data, and share assessment results as student feedback. Faculty workload for the three previous steps of the assessment process is mostly independent of student enrollment in a course. However, it increases roughly in proportion to student enrollment for this step, because the effort to implement and analyze several common assessment processes increases (e.g., partial-credit grading of worked problems, evaluation of oral presentations or written reports, evaluation of laboratory experiences, and grading of design projects). Accordingly, advances in this step of the assessment process must address both the quality of the assessment process and faculty workload required to implement it. A companion paper (Koretsky & Magana, 2019), also based on the Delphi study and two-day workshop, explores future research in instructional technology, the most promising direction for addressing the problem of faculty workload.

With regards to ensuring high quality assessment, reflecting on assessment results is a critical precursor to sharing results with students. For example, was an assessment task too easy or too difficult? Did a written report demonstrate that students had adequately achieved desired conceptual knowledge? Did only a small fraction of students demonstrate achievement of a specific learning outcome? Answers to questions like these allow an instructor to make notes, modify content delivery, and update both assessment and instructional processes.

Earlier, we highlighted the importance of feedback for improving student learning, and here we expand on this point briefly. Extensive research on the role of feedback in student learning has found that both positive and negative feedback significantly influences student learning (e.g., Harks, Rakoczy, Hattie, Besser, & Klieme, 2014; Kluger & DeNisi, 1996; Shute, 2008). Hattie and Timperly's (2007) meta-analysis demonstrates the importance of studying assessment and feedback in their synthesis of 12 meta-analyses (which include a total of 196 studies and 6,972 effect sizes) that provide specific information on feedback in classrooms. Although almost all of these studies were conducted in pre-college classrooms, and few focused exclusively in STEM subjects, they demonstrate that effects of feedback on student learning can vary based on the focus and type of feedback.

Hattie and Timperly (2007) present four foci for feedback: self (e.g., "great effort"); task (e.g., "how well a task is being accomplished or performed"); processing of the task (e.g., "relate[d] to students' strategies for error detection, thus providing oneself with feedback"); and self-regulation (e.g., feedback on "the willingness to invest effort into seeking and dealing with feedback information"). They find that self is the least effective focus, but that feedback focused on self-regulation supports "deep processing and mastery of tasks" while feedback focused on tasks can be useful for both "strategy processing" and "enhancing self-regulation" (p. 91).

Similarly, Shute (2008) identifies 12 types of feedback and shows how effectiveness varies according to type, while Booth et al. (2017) note opportunities for studying effectiveness of feedback including: identifying ways to best individualize feedback during class time, studying non-technology-based types of feedback, and assessing the effects of negative feedback. In addition, influences of feedback depend on task complexity (Kluger & DeNisi, 1996) as well as the complexity of the feedback (Shute, 2008).

These studies provide a framework for a series of research questions related to sharing assessment results with students through feedback:

- How can instructors provide personalized feedback about a complex learning outcome efficiently to a class of students?
- How do different foci and types of feedback influence student development and achievement of various student learning outcomes?
- How do different types of feedback (e.g., self, task, processing of the task, or self-regulation) influence student motivation with respect to complex learning outcomes?

PROMOTE ADOPTION OF RBTPS

Unlike assessment of student learning, where the research on effective practices is limited, the evidence for RBTPs is extensive. Research supports the use of cooperative learning; problem-based learning; peer-led team learning; process-oriented, guided inquiry learning; and project-based learning over lecture-based teaching to increase student learning, engagement, and success in STEM fields. Some of the most frequently cited research includes:

- Crouch and Mazur (2001) review 10 years of evidence showing peer instruction in introductory physics courses taught for non-majors supports "increased student mastery of both conceptual reasoning and quantitative problem solving."
- Under controlled conditions in two large sections of introductory undergraduate physics, Deslauriers, Schelew, and Weiman (2011) write that using RBTPs results in increased student attendance, higher engagement, and more than twice the learning than using traditional lectures.
- Haak, HilleRisLambers, Pitre, and Freeman's (2011) study of students in a college-level introductory biology class finds that "daily and weekly practice with problem-solving, data analysis, and other higher order cognitive skills, improved the performance of all students… and reduced the achievement gap between disadvantaged and non-disadvantaged students."
- Hake's (1998) survey of 6,000 college students in introductory physics courses shows that classroom use of interactive engagement methods promotes conceptual understanding and enhances problem-solving ability.
- Knight and Wood (2005) find "significantly higher learning gains and better conceptual understanding" in large biology courses that incorporated interactive engagement and cooperative work.
- Kvam (2000) shows that active learning methods have a significant impact on knowledge retention for students who scored average or below average on a test in engineering statistics prior to the application of the methods.

In addition, multiple synthetic studies add overwhelming support for RBTP. For instance:

- In their meta-analysis of 39 studies related to small-group learning in postsecondary STEM from 1980-1988, Springer, Stanne, and Donovan (1999) report, "various forms of small-group learning are effective in promoting greater academic achievement, more favorable attitudes toward learning, and increased persistence through STEM courses and programs."
- Johnson, Johnson, and Smith (1998), in their meta-analysis of 305 college studies, find that, "cooperative learning promotes higher individual achievement than do competitive approaches or individualistic ones." They also note, "college students learning cooperatively perceive greater social support from peers and instructors than do students working competitively or individualistically."

- Prince's (2004) review of research about active learning, collaborative learning, cooperative learning, and problem-based learning finds support for all four types of active learning. He cites "extensive and credible evidence" that these methods "promote academic achievement and positive student attitudes."
- Freeman et al.'s (2014) meta-analysis of 225 studies of student performance in undergraduate STEM courses encapsulates this compelling body of research as follows:

  If the experiments analyzed here had been conducted as randomized controlled trials of medical interventions, they may have been stopped for benefit—meaning that enrolling patients in the control condition might be discontinued because the treatment [RBTPs] being tested was clearly more beneficial.

This prior research offers compelling evidence on the effectiveness of RBTPs; however, the literature on change has shown that evidence alone is not sufficient to promote adoption. Therefore, the Delphi study and the two-day workshop focused on identifying priorities to promote widespread adaptation of RBTPs (the dark blue bubble labelled 3 in Figure 1), and they are the primary sources of questions we present here. The research questions fall into four main categories.

Understand What Motivates Instructors to Adopt RBTPs

Despite both the extensive evidence on the efficacy of RBTPs and the prevalence of action-based resources to assist instructors in adopting them (e.g., Ambrose et al., 2010; Felder & Brent, 2016; Finelli, Klinger, & Budny, 2001; Smith, Sheppard, Johnson, & Johnson, 2005; Svinicki & McKeachie, 2014; Wankat & Oreovicz, 1993), adoption of these practices has been slow (e.g., Borrego, Froyd, & Hall, 2010; Friedrich, Sellers, & Burstyn, 2007; Froyd et al., 2013; Handelsman et al., 2004; Jamieson & Lohmann, 2012; National Research Council, 2012; PCAST, 2012; Prince, Borrego, Cutler, Henderson, & Froyd, 2013; Stains et al., 2018). We know, for instance, that although 72% of physics instructors try an RBTP, only 49% report sustained use (Henderson et al., 2012). As a result, many undergraduate engineering classrooms are focused on theory, are lecture-based (Hora, Ferrare, & Oleson, 2012), use a competitive grading system, and emphasize algorithmic problem-solving (Bransford, Darling-Hammond, & Page, 2005; Brawner, Felder, Allen, & Brent, 2002; Claxton & Murrell, 1987). While such classrooms challenge students who learn best in that environment, they provide limited support at best for capable students who learn differently.

Researchers have hypothesized various reasons for the slow diffusion of innovation. For instance, Handelsman et al. (2004) attribute slow adoption to lack of awareness about RBTPs, distrust of the educational data, and apprehension about learning new approaches. However, a survey of engineering department heads found over 80%, on average, were aware of several established RBTPs, but that only about 40% of the departments had adopted these RBTPs (Borrego et al., 2010). Henderson and Dancy (2011) find that instructors are generally aware of RBTPs and are interested in implementing them, but they struggle with situational constraints such as expectations of content coverage, lack of instructor time, departmental norms, student resistance, and limitations about the physical classroom and course structure.

Other researchers have identified both barriers to and enablers to adoption of RBTPs among STEM instructors (Dancy & Henderson, 2010; Finelli et al., 2014; Froyd et al., 2013; Hora, 2011; 2012; Jamieson & Lohmann, 2012; Prince et al., 2013; Reid, 2014). Lack of time has been raised as one of the most salient barriers to adoption of RBTP. Other barriers include fear of student resistance; lack of familiarity with RBTPs; lack of skills and knowledge; lack of resources and support for instructors; resistance to change; characteristics of an instructor's environment; restrictive course syllabi and content structure; institutional policies, especially as related to tenure and promotion; institution type and research emphasis; teaching evaluations; heavy workload; and reward systems. Factors that enable instructors to adopt RBTP have also been suggested (Froyd et al., 2013; Hora, 2012; Prince et al., 2013; Seymour, DeWelde, & Fry, 2011; Sunal et al., 2001). These include collegial and administrative support, the opportunity to engage with others, potential time savings, improvements in student learning, student perceptions of the class, and financial incentives. Blackburn and Lawrence (1995) report that instructors are more likely to devote time and energy to efforts in which they have an interest, have confidence in their abilities to succeed, believe they can make an impact, and have collegial support, as well as to which they perceive their institution's reward structures to be aligned.

Questions remain about engineering education instructors' motivation to adopt, retain, or discontinue RBTPs. Understanding the relationship between factors that promote and barriers that hinder adoption of those approaches and the characteristics of instructors at different stages of the adoption/innovation cycle (Rogers, 2003) provides the basis for several compelling research questions:

- What characterizes instructors who have successfully adopted RBTPs?
- What resources, evidence, faculty development initiatives, changes to instructor evaluation, etc. would dramatically increase adoption of RBTPs?
- What influences instructors' decisions about their behavior, and what would encourage instructors to undertake a transformative experience in their teaching?
- How does motivation to adopt RBTPs vary by career stage, and what initiatives would promote adoption of RBTPs by the next generation of instructors early in their careers?
- How can we incentivize instructors (and the next generation of instructors) to adopt RBTPs and take risks through innovative teaching and/or educational scholarship?

Characterize Misconceptions About Teaching

Instructors often have misconceptions about teaching, such as believing that good teachers are most frequently bad researchers or that using RBTPs means failing to cover course content. Though there is some evidence that these beliefs are indeed misconceptions, there is a need for more research to understand how such misconceptions function. This brief sample of research questions could help in addressing these issues:

- What psychological gaps (denial, lack of motivation, etc.) prevent engineering instructors from truly believing that students will learn better from RBTPs?
- How do instructors develop beliefs and values about teaching approaches in general, about lecture, and about RBTPs?
- What incorrect assumptions and misconceptions do instructors have about efficacy of existing RBTPs and what can be done to overcome those erroneous beliefs?

Effectively Communicate Existing Research Evidence to Instructors

One of the key barriers to adoption of RBTPs is the inaccessible nature of the research findings to instructors. Instructors lack the time to seek out convincing research evidence about RBTPs, and it can be daunting to read a 30-page journal article replete with unfamiliar terminology and lacking easily implementable findings. Thus, we need to learn more about how to communicate the existing research to instructors in a more effective way, as outlined in these research questions:

- In what ways can we best catalog existing research so that instructors are able to access it easily?
- How can we effectively translate educational research for people who are not education scholars and help instructors understand and respect educational research?
- What are effective ways to communicate research results and practice needs between researchers and practitioners?
- What are the most practical recommendations or actionable findings that come from existing research?

Identify and Begin to Fill Gaps in The Research Literature

Though there is ample evidence about the impact of RBTPs on student learning, there is still a need for more discipline-specific research findings and for more nuanced research that better differentiates intervention, audience, and outcome (e.g., what types of active learning work better for whom, under what circumstances, and for which outcomes?). We propose the following series of research questions:

- Which innovative teaching practices need a more convincing evidence base?
- In what ways does the successful use of various RBTPs depend on institutional, disciplinary, and course-based contexts?
- How can in-class experiences affect student outcomes beyond learning?

- How can intelligent use of technology improve the implementation of features of good instruction in terms of efficacy, cost, and scale?
- How might RBTPs support more racial, gender, and socioeconomic diversity in engineering?

CHARACTERIZE SUCCESSFUL FACULTY DEVELOPMENT

Conversations about changing instructors' teaching and assessment practices naturally raise questions about how best to enable such change through successful faculty development. Faculty developers can promote adoption of research-based teaching and assessment practices by providing support for instructors (or future instructors) to reflect on and discuss those practices and by influencing decisions to adopt or to continue to use research-based practices (Finelli et al., 2014; Henderson et al., 2012). Here, we present research questions designed to characterize successful faculty development (the dark blue bubble labelled 4 in Figure 1), most of which resulted from the Delphi study and the two-day workshop.

Identify Attributes of Successful Programs

Many factors influence the efficacy of faculty development, such as the type of program, the intended audience, and the model for delivering it (e.g., Brent & Felder, 2003; Gillespie & Robertson, 2010; Sorcinelli, 2002). There are many types of faculty development programs (Felder, Brent, & Prince, 2011; Finelli et al., 2008; Lee, 2010), including individual consultations, workshops and seminars, classroom observations, and faculty learning communities. In addition, the audience could be general, or it could include instructors at specific career stages (future faculty, adjunct faculty, new faculty, mid-career faculty, or late-career faculty), with particular teaching foci (instructors teaching first-year students, design courses, or large introductory courses), or with common disciplinary interests (mechanical engineering or electrical engineering, for instance). As well, technology and online learning are changing at a fast pace, and online platforms are supporting a change in the way we deliver content. The wide variety of faculty development initiatives gives rise to a series of research questions to identify attributes of successful programs:

- What program types are most effective within different institutional contexts and for instructors (and future instructors) at different developmental stages?
- What are the most promising ways to balance discipline-based faculty development (e.g., engineering- or STEM-specific) with more general faculty development?
- How effective are online and virtual programs for faculty development, what factors contribute to their success, and how can online programs be integrated into face-to-face faculty development efforts to increase success?

Study Different Models of Faculty Development

There are multiple models for providing faculty development, including campus-based centers (or individuals) for teaching and learning, faculty development programs organized on a national scale, networks of faculty or faculty developers, and national-level centers or alliances. Thus, we propose the following series of research questions:

- How should faculty development be addressed and supported at different organizational levels (e.g., departmental, college, institutional, national, and international)?
- What factors would increase the effectiveness of faculty development models?
- How should different models of faculty development be interconnected and supportive of each other, and what are effective ways to leverage national and global organizations in faculty development initiatives?
- What are important considerations that require local models for faculty development and what commonalities exist across different contexts that would allow more generalized faculty development?

Understand What Motivates Instructors to Engage in Faculty Development

One main goal of faculty development is to support adoption of research-based teaching and assessment practices (see Figure 1). However, instructors who participate in faculty development initiatives are often a self-selecting group of early adopters, and finding ways to motivate busy instructors to engage in faculty development can be difficult. The following questions refer to the characteristics of the people involved:

- What characterizes instructors who are motivated to engage in faculty development and those who are not, and how might these characteristics inform future faculty development initiatives?
- How can faculty development efforts be more effective at engaging a wide range of instructors across different types of institutions?
- What factors do instructors perceive as supporting their engagement in faculty development initiatives, and what barriers do instructors perceive?
- How might administrators be more involved in supporting faculty development, and what are barriers and affordances to their involvement?

Assess the Impact of Faculty Development Efforts

Assessing the impact of faculty development can take multiple forms, including tracking number of participants, collecting feedback through satisfaction surveys, conducting interviews and focus groups, and measuring teaching outcomes (e.g., Wright, 2011). Chism and Szabó (1997) propose a three-level framework for assessing faculty development that incorporates user satisfaction, impact on teaching, and impact on student learning. Their survey of faculty development programs at

200 campuses found that 85% assessed the programs through user satisfaction. Fewer than 20% evaluated the program's impact on teaching, and none assessed the impact on student learning.

The following series of research questions responds to this problem:

- What outcomes can be used to evaluate the effectiveness of faculty development initiatives?
- How can we demonstrate the benefits of faculty development initiatives effectively in terms of these outcomes?
- How can we better assess the ways in which participating in faculty development changes teaching or assessment practices?
- What approaches are most effective in assessing the long-term impacts of faculty development and in assessing the impact on student learning?

SUMMARY

Improving student learning in undergraduate engineering education depends on improving both teaching and assessment, and this requires change across numerous elements in a complex, adaptive system. Based on a yearlong process that included a three-step Delphi study, a two-day workshop, and a review of the literature, we offer a series of research questions to address this issue. We group these questions into four main themes: (1) change the organizational culture, (2) research effective assessment practices, (3) promote adoption of RBTPs, and (4) characterize successful faculty development, and we further categorize the questions as shown in Table 1.

Table 1. The themes for future research and categories for the related research questions.

Theme for future research	Categories for the research questions
Change the organizational culture	Understand organizational culture Ascertain when change is needed Clarify the relationships between organizational culture and teaching and assessment practices Identify strategies and tactics to change organizational culture
Research effective assessment practices	Articulate desired student learning outcomes Design appropriate assessment tasks Develop processes and instruments for evaluating student work Implement, analyze, and share assessment results
Promote adoption of RBTPs	Understand what motivates instructors to adopt RBTPs Characterize misconceptions about teaching Effectively communicate research evidence to instructors Identify and begin to fill gaps in the research literature
Characterize successful faculty development	Identify attributes of successful programs Study different models of faculty development Understand what motivates instructors to engage in faculty development Assess the impact of faculty development efforts

We are confident that the research questions provided here will prove useful to many in our community – including engineering education scholars, instructors, and administrators – towards the goal of achieving systemic improvements in student learning in undergraduate engineering education. We hope this paper will catalyze new research efforts as scholars work to address some of the questions we offer. We also hope it will inspire engineering instructors wishing to improve teaching and assessment in their own classrooms. Finally, we hope it will galvanize administrators and other academic leaders in engineering education in effecting change in institutional policies, teaching and assessment activities, and faculty development initiatives and in transforming their own organizational cultures.

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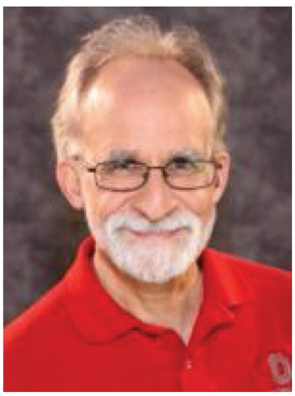

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