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Michael C. Loui

Purdue University, mloui@purdue.edu

Maura Borrego

University of Texas at Austin, maura.borrego@austin.utexas.edu

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Engineering Education Research

Michael C. Loui, *Purdue University*

Maura Borrego, *University of Texas at Austin*

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0 Introduction

In this chapter, in the **Foundations** section of this book, we review the history, infrastructure, **theories, methodologies**, and key **empirical findings** from engineering education research. This chapter could benefit computing education researchers because computing and engineering have many similarities. Undergraduate programs in computing and engineering prepare professionals to apply mathematics and science to solve practical problems by designing artifacts such as software and skyscrapers. Both computing and engineering programs have difficulty recruiting and retaining diverse groups of students. Instruction in both computing and engineering is growing in K-12 (pre-college) education, in both formal and informal settings, especially through integration with instruction in mathematics and science. Both computing and engineering have incorporated discipline-based education research (DBER) activities, similar to physics education research, biology education research, and others.

Computing education researchers may be particularly interested in the strategies and policies that have enabled the growth of engineering education research. Although the American Society for Engineering Education (ASEE) was founded more than 100 years ago, modern engineering education research began to coalesce around 2003, when the *Journal of Engineering Education* changed its mission to focus exclusively on research, and when engineering education departments and doctoral programs emerged at multiple universities in the United States. These changes resulted from a shift to outcomes-based criteria for engineering accreditation that had begun in 1997. The emphasis on outcomes prompted engineering faculty members in the U.S. to identify course learning objectives and to gather evidence of student learning. During this period, the U.S. National Science Foundation funded several engineering education coalitions,

each with a group of universities. Some coalitions focused on assessment, which laid the foundation for increasingly scholarly investigations of engineering student learning and retention (Froyd & Borrego, 2014).

Research projects in engineering education require expertise both in engineering and in social sciences. Since the inception of engineering education research, these projects have been conducted through interdisciplinary collaborations of researchers with different areas of expertise (Borrego & Newswander, 2008). As a consequence, engineering education research has borrowed theories and research methods from social science fields such as education, psychology, sociology, and management rather than developing its own theories and methods. Today engineering education researchers are trained through formal courses and degree programs in which students learn these theories and methods. Although projects are still pursued through collaborations between engineers and social scientists, other projects are conducted by researchers who are trained in engineering education.

Currently engineering education research is supported by professional societies, annual conferences, scholarly journals. The societies, conferences, and journals in engineering education parallel and overlap those in computing education. The Association for Computing Machinery (ACM) supports education and research in computing, and the ASEE and other engineering education societies around the world support education and research in engineering. The ACM publishes the *ACM Transactions on Computing Education* journal, and the ASEE publishes the *Journal of Engineering Education*. The IEEE publishes the *IEEE Transactions on Education*, which includes research articles in both computing education and electrical engineering education. The annual Frontiers in Education Conference covers both computing education and engineering education research.

1 Engineering education as a scholarly field

Formal education in engineering began in France with the establishment of the École Polytechnique in 1794. In the United States, the U.S. Military Academy at West Point began offering engineering programs in the early 1800s. The four-year curriculum at West Point was based on the École's (Davis, 1998, pp. 18-19). Engineering education expanded greatly with the passage of the Morrill Act in 1862, which led to the founding of land-grant colleges and universities to teach agriculture and engineering. By the end of the nineteenth century, a group of academic engineering leaders founded the Society for the Promotion of Engineering Education (SPEE) in 1893. This organization is now known as the American Society for Engineering Education (ASEE) (Froyd & Lohmann, 2014). Other organizations devoted to engineering education were established in the twentieth century: the Internationale Gesellschaft für Ingenieurpädagogik in 1972, the Société Européenne pour la Formation des Ingénieurs in 1973, the Australasian Association of Engineering Education in 1989 (Froyd & Lohmann, 2014). Today many nations have engineering education associations, and they belong to the International Federation of Engineering Education Societies (www.ifees.net). Although engineering education is a worldwide endeavor, this chapter focuses on scholarship in

engineering education in the United States, because it is the setting with which we are most familiar.

In 1910, SPEE began publishing the first periodical devoted to engineering education. Originally titled the *Bulletin of the Society for the Promotion of Engineering Education*, and later simply *Engineering Education*, this magazine published opinion pieces, reports on engineering enrollments, and descriptions of pedagogical practices in classrooms and laboratories. By the 1980s, *Engineering Education* regularly published research studies in the "Findings" section. A few of the more scholarly articles in *Engineering Education* became highly influential (e.g., Stice, 1976; Stice, 1987). Scholarly papers on classroom innovations were presented at ASEE Annual Conferences and at the annual Frontiers in Education Conference, which began in 1971 (<http://fie-conference.org/>).

In 1986, a report of the U.S. National Science Board called for the application of scholarship to strengthen undergraduate education in science, engineering, and mathematics. This report prompted the U.S. National Science Foundation to allocate substantial funding for grants to improve education programs in all fields of science and engineering (Froyd & Lohmann, 2014). To obtain these grants, proposals required "serious assessment planning" (Wankat et al., 2002).

The assessment of student outcomes was incorporated into the guidelines for accreditation of engineering programs. Because engineering is a profession, engineering programs in colleges and universities seek formal accreditation as a certification of their quality. To obtain a professional license, an engineer must have earned a baccalaureate degree from an accredited program. After the U.S. Department of Education (1988) began requiring that accreditation agencies ask institutions for assessments of educational quality, the Accreditation Board for Engineering and Technology (now simply "ABET") adopted new criteria and procedures in 1997. Called Engineering Criteria 2000 (EC 2000), these criteria required programs to assess their own effectiveness in achieving student outcomes (Prados, Peterson, & Lattuca, 2005). These outcomes included both technical skills, such as design and problem solving, and professional skills (sometimes called "soft skills"), such as communication and teamwork. About the same time, Engineers Australia, the accrediting agency for Australia, also adopted outcomes-based accreditation criteria (Godfrey & Hadgraft, 2009). The U.S., Australia, and other countries are signatories to the Washington Accord, which recognizes the substantial equivalence of the accredited engineering programs in the signatory countries. The Washington Accord defines attributes of engineering graduates that are generally consistent with the outcomes defined by ABET (Passow & Passow, 2017). These outcome-based accreditation requirements prompted engineering faculty members to gather assessment data about student learning. These data could also be used to demonstrate the effectiveness of instructional innovations. The focus on assessment and evidence, coupled with an infusion of funding from the National Science Foundation at this time, accelerated research activity in engineering education (Borrego, 2007).

In 1993, the magazine *Engineering Education* was replaced by two periodicals: a magazine titled *ASEE Prism*, and a "scholarly professional journal" titled *Journal of Engineering Education*

(JEE). During the 1990s, articles published in JEE primarily reported the results of scholarship of teaching and learning (SoTL) studies. These studies aimed to improve student learning in classrooms and instructional laboratories. SoTL studies in engineering typically used surveys of students, end-of-course ratings, and grades as assessment data (Wankat et al., 2002).

In 2003, JEE changed its mission "to serve as an archival record of scholarly research in engineering education." (Lohmann, 2003). In 2005, the first of four Engineering Education Research Colloquies was held. By 2006, researchers began calling for "rigorous research" in engineering education (Streveler & Smith, 2006). This research would aim not to improve teaching and learning in individual classrooms, the goal of SoTL studies, but instead to build general knowledge that addressed fundamental questions about how students learn. This research would be grounded in an appropriate theory, and it would be conducted using rigorous methods (Streveler & Smith, 2006). In 2008, ASEE created a new journal, *Advances in Engineering Education*, to publish applications of engineering education research and SoTL studies, which would no longer be published in JEE (Shuman, Besterfield-Sacre, & Litzinger, 2013).

The change in the mission of JEE marked a milestone in the development of engineering education research as a species of discipline-based education research (DBER), along with physics education research and chemistry education research. DBER addresses fundamental questions about education in particular academic disciplines, typically at the undergraduate level. DBER draws on more general research in the learning sciences, but is grounded in the epistemology, priorities, and culture of a particular discipline (Singer, Nielsen, & Schweingruber, 2012, p. 9). As a consequence, DBER projects require deep expertise in the target discipline.

Engineering education research examines both undergraduate education and pre-college (K-12) education. While teachers in elementary and secondary schools have always used engineering and technology as contexts for lessons in mathematics and science (Sneider & Purzer, 2014), pre-college curricula have been developed specifically to teach engineering concepts and skills, with an emphasis on engineering design. Two of the largest curricular efforts are Engineering is Elementary for students in elementary schools and Project Lead the Way for students in middle and high schools (Brophy et al., 2008). Since the 1990s, national standards for science education in the United States have increased attention on incorporating engineering and technology. In 2013, the Next Generation Science Standards called explicitly for integrated instruction in science, technology, engineering, and mathematics (STEM) (Sneider & Purzer, 2014). A consensus report of the National Academy of Engineering and the National Research Council emphasized the need for research on the potential benefits of an integrated approach to STEM instruction (Katehi, Pearson, & Feder, 2009).

2 The structure of engineering education research today

Research in engineering education is supported through the same structures as research in older academic disciplines: university departments, doctoral programs, research centers,

academic journals, specialized conferences, and groups within professional societies (Borrego and Bernhard, 2011). In this section, we describe each of these structures.

The first two departments of engineering education were established at U.S. universities in 2004 (Benson et al., 2010). As of 2017, there are six such departments in the U.S. All six arose from academic units that had previously been responsible for teaching engineering programs for first-year undergraduates, but then expanded their missions to include research and doctoral programs. A few other U.S. universities without engineering education departments now offer PhD degrees in engineering education. Outside the United States, there are doctoral programs in engineering education in Sweden, Denmark, and Malaysia. In fact, in Europe, PhD degrees in engineering education have been awarded as early as 1929 (Borrego & Bernhard, 2011). Several universities around the world offer doctoral programs in STEM education, usually within a college of education rather than a college of engineering, but in collaboration with engineering faculty members (Engineering Education Community Resource, 2017). At universities without doctoral programs in engineering education, engineering education research is also conducted at teaching and learning centers (Litzinger, 2010), in research centers (Benson et al., 2010; Borrego & Bernhard, 2011), and by individuals in traditional engineering departments.

Engineering education researchers publish articles in peer-reviewed academic journals.

Journals that focus on specific engineering disciplines include

Chemical Engineering Education

IEEE Transactions on Education (electrical and computer engineering)

International Journal of Electrical Engineering Education

International Journal of Mechanical Engineering Education

Journal of Professional Issues in Engineering Education and Practice (civil engineering)

Journals that cover all engineering disciplines include

Advances in Engineering Education

Australasian Journal of Engineering Education

European Journal of Engineering Education

International Journal of Engineering Education

Journal of Engineering Education

Journal of Pre-College Engineering Education Research

Online Journal for Global Engineering Education

Engineering education research also appears in journals devoted to all of STEM education (Borrego & Bernhard, 2011).

Some journals are published by professional societies. These societies also sponsor annual conferences. The American Society for Engineering Education (ASEE) and the Société Européenne pour la Formation des Ingénieurs (SEFI, European Society for Engineering Education) each hold an annual conference. The proceedings of the ASEE Annual Conference are available via open access at the website peer.asee.org. The IEEE Education Society, the IEEE Computer Society, and the ASEE Educational Research and Methods Division jointly sponsor the annual Frontiers in Education Conference (fie-conference.org). The proceedings of this conference are available through the IEEE Xplore Digital Library (ieeexplore.ieee.org). The

International Federation of Engineering Education Societies holds the World Engineering Education Forum each year in a different country. The Research in Engineering Education Symposium is a biennial international conference that also travels to different countries.

As the field of engineering education research has grown in diverse ways in different countries, drawing on ideas from multiple disciplines, it is sometimes difficult for researchers to locate related work. To help researchers communicate with each other, a taxonomy for engineering education research has been developed (Finelli, Borrego, & Rasoulifar, 2015). This taxonomy is currently maintained at the University of Michigan, and a small group of volunteers is dedicated to maintaining and updating the taxonomy. The *Journal of Engineering Education* and the *IEEE Transactions on Education* now require authors to use at least some keywords from the taxonomy to describe their articles.

3 Theories in engineering education research

In education research, theories can inform the design of empirical studies and the interpretation of the collected data. Theories can explain observed phenomena and predict future events. Tying education research to a theory helps establish the generalizability or transferability of studies conducted in one specific setting. Engineering education research borrows theories of learning, motivation, and identity development from other academic disciplines, notably cognitive science, education, learning sciences, psychology, and sociology. These theories were introduced to engineering education researchers by Svinicki (2010), in her primer *Guidebook on Conceptual Frameworks for Research in Engineering Education*. The *Guidebook*, in turn, was based on an earlier book by Svinicki (2004) and the *How People Learn* framework (National Research Council, 2000). Occasionally engineering education research uses theories from other DBER areas. For instance, the Lesh translational model was developed by mathematics education researchers and used in an engineering education study (Moore et al., 2013).

3.1 Identity and professional formation

Identity is a popular lens for studying the persistence of students in several STEM fields, including engineering (Tonso, 2007; Tonso, 2014). Students who identify with engineering, or who view their own identities as consistent with engineering, are more likely to select engineering as a career and to persist through engineering programs (Matusovich, Streveler, & Miller, 2010; Patrick & Borrego, 2016).

In a seminal qualitative study, Carlone and Johnson (2007) found that science identity depends on performance, recognition, and competence. Subsequent quantitative studies of mathematics and physics identities among high school and undergraduate students have identified performance/competence, interest, and recognition as separate constructs, which can be used to predict identity and major choices as outcomes (e.g., Hazari, 2010). This work has been extended to explore engineering identity (Godwin et al., 2016; Prybutok et al., 2016).

In general, students choose to major in engineering because they intend to pursue professional careers as engineers. Social Cognitive Career Theory (SCCT) is a popular theory that describes the primary influences on students as they choose careers. According to SCCT, students' decisions about careers are influenced by their personal attributes and by contextual factors that might support or hinder them from achieving their career goals. Personal attributes include self-efficacy beliefs, outcome expectations, interests, and goals. (Self-efficacy is described in section 3.3 below.) Contextual factors include the availability of role models, encouragement from family members, and funding for college expenses. Atadero, Rambo-Hernandez, and Balgopal (2015) used SCCT to analyze outcomes from introducing design projects in one section of a statics course. They found that, as predicted by SCCT, students in the projects section connected their engineering self-efficacy and their positive outcome expectations with their goal of becoming an engineer.

3.2 Cognition

Engineering education research borrows theories of learning from psychology. Two major kinds of learning theories are behavioral and cognitive. Whereas the behavioral approach to learning emphasizes only the observed behaviors of students, the cognitive approach focuses on the internal workings of students' minds. The most prevalent cognitive theory in engineering education is *constructivism*, which states that students create their own mental models of concepts and phenomena, based on their prior experiences. According to constructivism, instructors should help students modify these initial mental models so that they align better with accepted scientific conceptions. Research on students' mental models of concepts in engineering thermodynamics revealed several misconceptions. In particular, students have difficulty distinguishing equilibrium from steady-state (Streveler et al., 2014).

A specific cognitive theory, *cognitive load theory* (Sweller, van Merriënboer, & Paas, 1998), categorizes the kinds of difficulties that students experience in learning a subject. In this theory, *intrinsic cognitive load* refers to difficulties that are inherent to the subject, *extraneous cognitive load* refers to difficulties that are induced by the instructional presentation, and *germane cognitive load* refers to the effort required to construct a *schema*, which is the mental model that organizes the student's knowledge about the topic. Good instructional design can minimize extraneous cognitive load and increase germane cognitive load (Sweller, van Merriënboer, & Paas, 1998). Cognitive load theory has been used to explain how students' level of prior knowledge affects their learning in a multimedia presentation on electric circuits (Johnson et al., 2013).

Engineering education researchers have studied cognitive differences between experts and novices, particularly in studies of design. Researchers have found that experts organize knowledge differently from novices. This organization enables experts to recall information, recognize patterns, and solve problems more efficiently than novices. Researchers have examined differences between experts and novices in unstructured design activities (Atman et al., 2007) and in solving textbook problems (Larkin et al., 1980; Chi, Feltovich, & Glaser, 1981).

To explain expert-novice differences in engineering design, researchers have used the theory of *adaptive expertise* (McKenna, 2014). This theory posits two dimensions of expertise: *efficiency* and *innovation*. Efficiency refers to the ability to apply domain-specific knowledge with speed and accuracy. Innovation refers to the ability to identify problems and to generate ideas to achieve ambitious goals. In this theory, *novices* exhibit low efficiency and low innovation, *routine experts* exhibit high efficiency and low innovation, and *adaptive experts* exhibit high efficiency and high innovation.

3.3 Self-beliefs and motivation

Engineering education researchers have used theories of motivation, previously developed by psychologists, to investigate the role of student motivation in engineering education. Motivation theories explain the reasons that individuals initiate and sustain behaviors. In the context of engineering education, these theories can explain students' behaviors with academic tasks and their persistence through an engineering program. In this section, we review popular motivation theories in engineering education research: self-efficacy, expectancy-value theory, self-determination theory, mindsets, and goal orientation theory. This section is particularly long as a reflection of the emphasis on motivation and persistence in engineering education research.

Defined by Bandura (1977), *self-efficacy* is an individual's belief in their ability to complete a task to achieve a desired goal. Self-efficacy combines confidence, an emotion, with a justification for that confidence. Self-efficacy is context-dependent. Bandura (1977) identified four sources of self-efficacy: mastery experience, vicarious experience, verbal persuasion, and physiological states. Students have a *mastery experience* when they perceive success or failure in their efforts to achieve a learning objective. Students have a *vicarious experience* when they see other students succeed or fail. *Verbal persuasion* consists of feedback from peers and teachers such as praise or criticism. *Physiological states* are the emotions that students feel: emotions such as joy and anxiety can affect students' self-efficacy beliefs. Hutchison-Green, Follman, and Bodner (2008) showed that the self-efficacy of first-year engineering students is strongly influenced by comparisons of their academic performance with other students, a form of vicarious experience. Mamaril et al. (2016) developed an instrument to measure the self-efficacy of students in academic engineering tasks.

Expectancy-value theory (EVT) was developed by Wigfield and Eccles (2000) and their colleagues to understand the motivations for students' academic behaviors. This theory posits that an individual's motivation for a task is determined by their competence beliefs and value beliefs about the task. *Competence* beliefs, which resemble self-efficacy, comprise the individual's expectations for success in completing the task. *Value beliefs* comprise the individual's beliefs about how well the task matches their desires and goals. EVT specifies four categories of values. *Attainment* value is the perception of the importance of the task for the individual's self-concept. *Intrinsic or interest* value is the individual's interest in the task itself. *Utility* value is the perception of how the task might help the individual achieve some goal other than the task. *Cost* value is the perception of the time, effort, and psychological impact required by the task. Using EVT, Peters and Daly (2013) identified the costs considered by engineering

students who pursued doctoral degrees after five or more years of work outside the academy. Matusovich, Streveler, and Miller (2010) used EVT to understand students' motivations to enroll in and persist through undergraduate engineering programs.

Intrinsic motivation has been the focus of other studies in engineering education, which used self-determination theory (SDT). Developed by Ryan and Deci (2000), SDT states that an individual's intrinsic motivation is driven by three basic psychological needs: competence, autonomy, and relatedness. *Competence* is the desire to master a skill or to be effective in achieving a goal. *Autonomy* is the condition of having control to make decisions. *Relatedness* is the urge to connect with other people. Besides defining three elements of intrinsic motivation, SDT also specifies a range of extrinsic motivations. Trenshaw et al. (2016) used SDT to examine the outcomes of a core engineering course that was redesigned to promote intrinsic motivation. Kajfez and Matusovich (2017) studied the factors that affected the competence, autonomy, and relatedness of graduate teaching assistants who taught first-year engineering courses at five different universities.

Student motivation can be affected by students' beliefs about intelligence. Dweck (1999) and her collaborators studied the differences in the beliefs of students when they faced difficult academic challenges, specifically, mathematical problems. They classified students into two groups, incremental self-theorists and entity self-theorists, based on their beliefs about intelligence. Students with the *incremental* theory (now called the *growth mindset*) believe that intelligence can improve with effort. Students with the *entity* theory (now called the *fixed mindset*) believe that intelligence cannot be changed: they believe in innate talents—you have it or you don't. When faced with difficult mathematical problems, incremental theorists believe that they can solve the problems with more knowledge or effort, whereas entity theorists attribute difficulty to a lack of intelligence in themselves. Further, students with a growth mindset adopt *mastery goal orientations*, in which they strive to master an academic subject, but students with a fixed mindset adopt *performance goal orientations*, in which they aim only to earn a grade or to perform better than peers. Stump, Husman, and Corby (2014) showed that engineering students with incremental beliefs (i.e., a growth mindset) tended to report that they engaged in collaborative learning and knowledge-building behaviors, such as connecting new ideas with previous knowledge and constructing personal understandings of new material. By contrast, engineering students who held entity beliefs were less likely to engage in knowledge-building behaviors. Reid and Ferguson (2011) found that engineering students drifted from incremental beliefs toward entity beliefs during the first year of undergraduate studies. Reid and Ferguson presented no data beyond one year, however.

3.4 Summary

In this section, we have highlighted some theories that engineering education researchers have borrowed from other disciplines. The research practices in adopting and applying these theories have evolved since the beginning of the "rigorous research" movement around 2006. Initially researchers merely named and cited the theories that guided their studies. Nowadays researchers are expected to justify their choices of theories, to explain why they rejected

alternative theories, and to integrate the chosen theories into the design of their studies and the interpretation of their results. Some contemporary researchers in engineering education have begun to develop theoretical and conceptual frameworks specifically for engineering. For example, Canney and Bielefeldt (2015) created the Professional Social Responsibility Development Model as a conceptual framework for describing how engineers develop their understandings of the social responsibilities of professionals. As another example, Walther, Miller, and Sochacka (2017) drew on intellectual traditions in social work to propose a theoretical model of empathy in engineering as a teachable skill, a practice orientation, and a professional way of being. We expect the trend toward sophistication in the use and development of theories to continue.

4 Methodologies in engineering education research

In engineering education research, empirical studies predominate over theoretical studies, particularly in the United States. To conduct empirical studies, engineering education researchers now use a wide range of quantitative methods, qualitative methods, mixed methods, and synthesis methodologies (Borrego, Douglas, & Amelink, 2009).

In the U.S., quantitative methods are historically the most popular. Quantitative studies primarily involve survey research. To argue for the validity and reliability of their surveys, researchers often cite the article by Douglas and Purzer (2015) on validity and the article by Allen et al. (2008) on coefficient alpha. Some researchers develop survey instruments; see section 5.5 below. Quantitative researchers also conduct experimental and quasi-experimental studies to compare the effectiveness of different pedagogies. Some researchers have conducted single-institution correlational studies of student transcript data, but for the most part, engineering education researchers have not taken advantage of national databases such as the Integrated Postsecondary Data System (IPEDS) maintained by the U.S. Department of Education. One notable exception is the stream of research that uses the MIDFIELD database, which now includes transcript data from engineering students at 113 institutions (Ohland et al., 2016).

While qualitative methods have been popular in engineering education research in Europe and Australia, they have recently become widespread in the United States too. Case and Light (2011) used studies in engineering education to illustrate different approaches to qualitative research: action research, case study, discourse analysis, ethnography, grounded theory, narrative analysis, and phenomenography. Bernhard and Baillie (2016) provided an extensive review of research quality criteria in engineering education and other DBER disciplines. This review included the popular Q³ framework developed by Walther and his colleagues (Walther & Sochacka, 2014; Walther, Sochacka, & Kellam, 2013).

In mixed methods research, quantitative and qualitative approaches are thoughtfully and logically integrated (Creswell & Plano Clark, 2007). Borrego, Douglas, and Amelink (2008) discussed how these criteria and study designs apply in engineering education using examples of studies previously published in *Journal of Engineering Education*. Crede and Borrego (2010)

expanded this analysis to include seven different journals, and analyzed how 16 studies had applied mixed methods to engineering education research.

Another category of research approaches that is rapidly gaining popularity in engineering education research is *systematic literature reviews*, which synthesize what is known in a particular research area using primary studies. Unlike narrative reviews, which are the most common kind of literature reviews, systematic reviews adopt detailed procedures for collecting and analyzing primary studies. Unlike meta-analyses, which use only quantitative methods to synthesize only quantitative studies, systematic reviews may use quantitative, qualitative, or mixed methods to synthesize quantitative, qualitative, and mixed methods studies (Borrego, Foster, & Froyd, 2014). Borrego, Foster, and Froyd (2015) reviewed systematic reviews of interest to STEM educators.

5 Some empirical results in engineering education research

In this section, we describe a selection of key empirical results in engineering education research. Although early research in engineering education focused on the effectiveness of classroom pedagogies to teach design and problem solving skills, research today considers a much broader variety of research questions. Engineering education research can be divided into five categories (The research agenda for the new discipline of engineering education, 2006):

Engineering epistemologies. In this category are research questions on how students and instructors think about concepts, theories, and principles. For example, how do students interpret diagrams and representations of physical situations? How do engineering instructors understand the purpose and use of mathematical models?

Engineering learning mechanisms. In this category are research questions on how and why different methods of teaching can foster student learning in classrooms and laboratories. For instance, for what reasons does cooperative learning promote problem solving skills?

Engineering learning systems. In this category are research questions about larger issues beyond classrooms. For example, what factors influence engineering instructors to adopt new pedagogies? How do institutional cultures and policies affect systemic changes in engineering education?

Engineering diversity and inclusiveness. In this category are questions about students. For instance, what factors affect the retention of women and minority students in engineering programs? How do engineering students develop self-efficacy and professional identities?

Engineering assessment. To determine how well a teaching method works, we need valid, reliable assessment instruments. This category includes efforts to develop

"concept inventories" for common engineering subjects such as statics, dynamics, circuits, and thermodynamics. Instruments have also been developed to assess the development of professional skills such as teamwork and ethical reasoning.

These five categories define the overall organization of the *Cambridge Handbook of Engineering Education Research* (Johri & Olds, 2014), which provides a comprehensive overview of the field.

5.1 Engineering epistemologies

Engineers and engineering students model physical situations with a variety of representations, including mathematical formulas, abstract sketches, and computational simulations. These simulations enable students to visualize dynamic physical processes. Students must continually translate between these representations as they apply conceptual knowledge to solve engineering problems. For example, Moore et al. (2013) studied the role of representational fluency in conceptual understanding. Nelson et al. (2017) examined how computational simulations can induce student misconceptions.

A robust stream of research has investigated how students learn concepts and change their conceptual understandings; some concepts such as thermodynamic equilibrium seem difficult to learn (Streveler et al., 2014). For many difficult concepts, students' understandings are fragmentary and incoherent (Herman, Zilles, & Loui, 2014). Researchers have also described the general epistemological beliefs of engineering students (Gainsburg, 2015) and engineering faculty members (Montfort, Brown, & Shinew, 2014).

At the pre-college level, researchers have studied the perceptions, beliefs, and attitudes of both students and teachers about engineers and engineering. For example, Capobianco et al. (2011) used the Draw-an-Engineer-Test to investigate how children in grades 1 through 5 understand engineers and engineering. Their most common conceptions were a mechanic who fixes engines or drives vehicles, a laborer who constructs buildings or roads, and a technician who repairs electronics or computers. Rarely did students draw someone who designs technologies. Few boys drew female engineers. Besides students, teachers are an important group to study because almost none have backgrounds in engineering or in engineering education (Hynes et al., 2017). As an example of research on teachers, Hynes (2012) documented the levels of teachers' understandings of different stages of the engineering design process.

5.2 Learning mechanisms

Across science and engineering disciplines, many DBER studies have compared the effectiveness of different instructional methods (Singer, Nielsen, & Schweingruber, 2012). In particular, DBER researchers have examined the impact of introducing student activities into lectures, which are still the predominant instructional method in science and engineering. Both a literature review by Prince (2004) and an extensive meta-analysis by Freeman et al. (2014) have concluded that active learning is superior to didactic lectures in fostering student

understanding across science and engineering. One way to accommodate active learning is through a *flipped classroom* approach, which provides lecture material or other resources as assignments to free up class time for active engagement in learning. Flipped classrooms have been gaining in popularity in engineering since 2012, as documented in recent reviews (Karabulut- Ilgu, Jaramillo Cherez, & Jahren, 2017; Kerr, 2015).

Active learning often occurs in the instructional laboratory. As in science education, the laboratory has been considered an essential component of engineering education since the nineteenth century (Feisel & Rosa, 2005). Despite its importance, there has been little research on the instructional laboratory in engineering (Singer, Nielsen, & Schweingruber, 2012, p. 134).

Among active learning pedagogies, collaborative learning strategies have been investigated extensively in engineering because they provide opportunities for students to learn teamwork skills, which are essential in professional practice. Cooperative learning is a particular form of collaborative learning that requires common goals, positive interdependence between group members, and individual accountability. In a watershed study published in five parts, Felder, Felder, and Dietz (1998) provided some of the first evidence about the effectiveness of active learning for engineering students. A cohort of students who took a series of five courses that used cooperative learning earned higher grades and graduated at higher rates than a comparison cohort who took the same courses that used traditional teaching methods (Felder, Felder, & Dietz, 1998). Menekse et al. (2013) found that interactive pedagogies that involve student collaboration are more powerful than other kinds of active learning pedagogies in promoting student learning. Team design projects are also very common in engineering education. Borrego et al. (2013) reviewed how teams have been used in engineering education, including prior studies of team formation and functioning. Loughry, Ohland, and Woehr (2014) and Willey and Gardner (2010) developed robust tools for managing peer assessment in team projects.

A popular form of active learning in engineering is problem-based learning (PBL) (Kolmos & de Graaff, 2014). In PBL, an instructor starts with an actual or realistic problem. The problem is structured to motivate students to learn fundamental concepts and principles in engineering. For example, if the problem is to improve the efficiency of a heating and ventilation system for an office building, then students must learn and apply relevant principles of thermodynamics and heat transfer. PBL focuses on the process of learning rather than on developing and prototyping a product. Studies show that PBL increases student motivation; enhances the long-term retention of knowledge; and improves the development of transferable process skills such as communication, teamwork, and project management; and (Kolmos & de Graaff, 2014, pp. 153-154).

Some problems for PBL are design problems, in which students must design a device, process, or system to meet a specification. All undergraduate engineering programs include instruction in design, both to meet accreditation requirements and to prepare students for professional practice. In the U.S., design courses are prevalent in the first and last year of undergraduate education (Froyd, 2005). Researchers have used a variety of methods to investigate instruction

in engineering design in a variety of settings, including first-year and capstone courses (Atman et al., 2014). For instance, using verbal protocol analysis, Atman et al. (2007) found that in solving a design problem, experts spent more time than novices on scoping the problem and gathering relevant information. Crismond and Adams (2012) similarly distinguished between beginning designers and informed designers in their synthesis of the literature on teaching and learning engineering design.

In pre-college settings, design is the primary goal of engineering literacy: students should gain the ability to apply the engineering design process to solve problems and to achieve human goals (Snider & Purzer, 2014). In addition, design problems can provide a context for science instruction. Wendell and Rogers (2013) showed that in elementary schools, design problems can improve students' understandings of science concepts. Chao et al. (2017) investigated the role of design tools in the development of students' science knowledge.

5.3 Learning systems

The category of "Learning systems" includes research on institutional change. As in other DBER fields, in engineering education, there is growing interest in examining instructional change, specifically, what motivates engineering instructors to adopt evidence-based instructional practices to support student learning. Although the effectiveness of these practices, such as active learning, has been confirmed by decades of research (Freeman et al., 2014; Prince, 2004), only a minority of faculty have adopted these practices (Froyd et al., 2013). While there is a long history of research on engineering faculty development (Felder & Brent, 2010), only recently has engineering education research focused on quantifying and increasing the adoption rates of evidence-based instructional practices. Early change initiatives focused on developing course-based interventions and using assessment evidence to convince others to adopt the interventions (Clark et al., 2004). More recent studies have focused on academic policies and reward systems that may encourage or inhibit the adoption of evidence-based practice.

In April 2014, a special issue of the *Journal of Engineering Education* (vol. 103, no. 2) focused on "The Complexities of Transforming Engineering Higher Education." Most articles in this issue used a model developed by physics education and institutional change researchers Henderson, Beach, and Finkelstein (2011). This model categorizes change strategies along two dimensions. One dimension, *intended outcome*, ranges from *prescribed* to *emergent*. The other dimension, *aspects of the system to be changed*, ranges from *individuals* to *environments and structures*. Consequently, the model defines four quadrants: prescribed for individuals; emergent for individuals; prescribed for environments; and emergent for environments.

The special issue had six regular articles. Borrego and Henderson (2014) provided specific examples of theories that might guide a change initiative in each quadrant of the model. Besterfield-Sacre et al. (2014) used the model to categorize survey responses in a project sponsored by ASEE that focused on instructional change. Jamison, Kolmos, and Holgaard (2014) used a historical analysis to develop a model to help educators transform engineering education in today's complex settings. Matusovich et al. (2014) and Finelli, Daly, and

Richardson (2014) applied the expectancy-value theory of motivation to understand the attitudes of engineering faculty toward instructional change. Holloway et al. (2014) described a statistical analysis that revealed a significant gender bias in the engineering admissions process, which they traced to a policy on the use of standardized test scores in admissions decisions. After this policy was changed, the representation of women among engineering students increased significantly.

These studies have shown that institutional change is complex, and that effective change requires a scholarly approach. In the next few years, we expect more publications on learning systems and institutional change in engineering education, resulting from projects funded by the National Science Foundation in the Revolutionizing Engineering and Computer Science Departments program (National Science Foundation, 2015). More generally, the Accelerating Systemic Change in STEM Higher Education Network connects individuals and resources in its mission to build knowledge about STEM change (ascnhighered.org).

5.4 Understanding students

Engineering education was once characterized as a "leaky pipeline." At the undergraduate level in the U.S., most students who do not finish engineering degrees leave during the first or second year. Overall, data from the Multiple-Institution Database for Investigating Engineering Longitudinal Development (MIDFIELD) indicate that among those who start as first-year students in engineering, only 57% persist in engineering to the eighth semester (Ohland et al., 2008); nearly all of these students earn engineering degrees within six years of entry (Ohland et al., 2012). Within the MIDFIELD data set, the persistence rates vary by institution from 37% to 66% (Ohland et al., 2008). These persistence rates for engineering are similar to other majors, but one important difference is that few students transfer into engineering to augment the number of graduates (Ohland et al., 2008). Students are discouraged from transferring into engineering from other majors because most engineering programs require long sequences of technical courses, each a prerequisite for the next.

MIDFIELD data have also helped demonstrate that many students who choose to leave engineering have grade point averages as high as students who stay (Ohland et al., 2004; Tseng, Chen, & Sheppard, 2011). Numerous studies have identified reasons for attrition from undergraduate engineering programs, such as excessive coursework and diminished interest (Seymour & Hewitt, 1997), poor teaching and advising (Marra et al., 2012), and lack of confidence in mathematics and science skills (Eris et al., 2010).

Many research studies have documented cultural barriers to the recruitment of women and minorities to engineering and to the retention of these underrepresented groups in engineering programs (Lichtenstein et al., 2014, p. 321). For example, through the story of a female, multi-minority engineering student with a low socioeconomic status background, Foor, Walden, and Trytten (2007) elicited the ways in which the student felt unwelcome in her engineering program. More recent research in this area, particularly on racial/ethnic minorities, focuses on the assets that students bring to classrooms rather than treating students or their backgrounds as deficits

to be overcome (e.g., Martin, Simmons, & Yu, 2013; Samuelson & Litzler, 2016; Wilson-Lopez et al., 2016).

Since engineering is a profession, academic engineering programs seek not only to teach students engineering knowledge but also to acculturate students into the profession. In other words, through engineering programs, successful students become engineers themselves. Numerous studies have investigated how this sense of professional identity develops (Stevens et al., 2008; Tonso, 2014). For example, using the expectancy-value theory of motivation, Matusovich, Streveler, and Miller (2010) determined that attainment values played a crucial role in students' decisions to enter engineering. As a consequence, if engineering programs emphasize attainment values, students will more closely identify with engineering, and they will be more likely to complete engineering degrees.

The development of engineering identity provides a source of motivation for students. Other sources of motivation were identified by the Academic Pathways of People Learning Engineering Survey (APPLES) project (Sheppard et al., 2014). In this study, the researchers used the metaphor of a "pathway" rather than a "pipeline" to characterize students' journeys into engineering. Based on 2,143 responses from students at 21 diverse institutions, the APPLES study found two important sources of motivation: intrinsic psychological motivation and financial motivation (Sheppard et al., 2014). Self-efficacy also plays an important role in engineering student motivation (Hutchison-Green, Follman, & Bodner, 2008).

5.5 Assessment

To determine whether students have achieved intended learning objectives, both instructors and researchers need assessment instruments that measure students' knowledge accurately. As a consequence, to support both instruction and research, discipline-based education researchers have devoted considerable effort to developing and validating assessment instruments for fundamental disciplinary knowledge.

Physics education researchers developed the Force Concept Inventory (FCI) instrument (Hestenes, Wells, & Swackhamer, 1992), which measures students' understanding of the force concept, as taught in a high school physics course and in a first-year college physics course. The FCI comprises multiple-choice questions that require no calculation to answer. Each incorrect choice reflects a common student misconception about force. Using the FCI, Hake (1998) showed that interactive-engagement pedagogies are superior to traditional pedagogies in fostering students' conceptual understanding of force.

Inspired by the success of the FCI, engineering education researchers have developed concept inventory instruments for core engineering subjects: statics (Steif & Dantzler, 2005), dynamics (Gray et al., 2005), thermal and transport processes (Streveler et al., 2011), thermodynamics (Firetto et al., 2016), materials engineering (Krause, Decker, & Griffin, 2003), and digital logic (Herman, Zilles, & Loui, 2014), among other subjects. To illustrate these efforts, we summarize the development and validation of the Digital Logic Concept Inventory (DLCI). First, the

researchers identified the most important and difficult concepts in a first course in digital logic through a Delphi process, which seeks consensus by a panel of subject matter experts through multiple rounds of polling. For the DLCI, the researchers asked a panel of experts on teaching digital logic to propose core concepts and to rate the importance and difficulty of each concept (Goldman et al., 2010). Second, the researchers selected digital logic problems that highlighted the most important, difficult concepts, and they asked students to verbalize their thoughts as they solved these problems. These "think-aloud" interviews enabled the researchers to identify common student misconceptions. Third, the researchers created multiple-choice questions and incorrect answers that reflected these misconceptions. They tested the resulting DLCI with hundreds of students at multiple institutions and analyzed the results (Herman, Zilles, & Loui, 2014).

While strong conceptual knowledge provides a basis for technical skills, such as design and problem solving, ABET's EC 2000 accreditation criteria state clearly that engineering programs must develop not only students' technical skills but also their professional skills, such as communication and teamwork. To compare the effectiveness of different methods for teaching professional skills, researchers need valid and reliable assessment instruments for them. Engineering education researchers have thus developed instruments to assess skills in teamwork (Ohland et al., 2012), leadership (Ahn et al., 2014), entrepreneurship (Duval-Couetil, Reed-Rhoads, & Haghighi, 2010), ethical reasoning (Borenstein et al., 2010; Zhu et al., 2014), and many others (Douglas et al., 2016). Engineering education researchers also use more general instruments developed for undergraduate students in any major, including the Collegiate Learning Assessment (Klein et al., 2007), which measures analytical reasoning and critical thinking, the Motivated Strategies for Learning Questionnaire (Pintrich et al., 1993), which measures student motivation and learning strategies, and the National Survey of Student Engagement (Kuh, 2009).

In many situations, qualitative or mixed methods approaches to assessment may be appropriate as well. For example, researchers may not yet know enough about a new or emergent phenomenon to develop survey items. Qualitative methods are particularly helpful for investigating "how" and "why" research questions, in contrast to "what" questions best addressed through quantitative approaches (Borrego, Douglas, & Amelink, 2009). Leydens, Moskal, and Pavelich (2004) described several qualitative assessment methods including interviews, focus groups, and observations, and how they can be used in undergraduate engineering education settings.

In summary, computing education researchers who require assessments could use or adapt the assessment instruments that were previously developed for engineering education. To identify appropriate extant instruments that measure a construct such as self-efficacy, and to determine whether those instruments are valid for a specific setting in computing education, researchers can work with an expert in educational measurement. Checking the validity of an instrument on a new population could be a valuable example of replication research (Benson & Borrego, 2015).

6 A comparison of computing education research with engineering education research

In this section, we compare computing education research with engineering education research. Their similarities and differences reflect the differences between computing and engineering as academic fields. On the surface, both computing and engineering are technical fields in which teams of practitioners apply mathematical and scientific knowledge to design technologies that meet human needs. Undergraduate programs in both computing and engineering have chains of prerequisite courses from fundamental mathematics to required disciplinary courses to advanced technical electives. Whereas programs in engineering are offered at about 400 colleges and universities in the United States, programs in computing are offered at more than 1,000 tertiary institutions (Tims, Zweben, & Timanovsky, 2017). So although some computer science departments are located within colleges of engineering at universities, the majority are not affiliated with engineering. Furthermore, in the U.S., only 284 bachelor's degree programs in computer science, 34 in information technology, and 25 in software engineering are accredited by ABET (as of September 30, 2017). By comparison, 343 bachelor's degree programs in mechanical engineering, 331 in electrical engineering, and 259 in civil engineering are accredited by ABET (as of September 30, 2017). Because few computing programs are accredited, computing has not had the expectation for regular, ongoing assessment of student learning outcomes that has been characteristic of engineering since the 1990s. The emphasis on outcomes assessment for accreditation has strongly influenced engineering education research (e.g., Passow & Passow, 2017).

As we have noted earlier, engineering education research in the U.S. is conducted within academic departments of engineering education. These departments, and other universities without such departments, offer doctoral programs in engineering education--a structural feature that makes engineering education PhDs more visible than some other DBER fields. As of this writing, there are no comparable departments of computing education, and no doctoral programs specifically in computing education. Nevertheless, doctoral students in computer science and in education do complete dissertations in computing education research, for example within PhD programs in computer science, informatics, education, and human-centered computing.

Computing education researchers present their work at the annual SIGCSE Technical Symposium, the annual Conference on Innovation and Technology in Computer Science Education (ITiCSE), and the annual International Computing Education Research (ICER) conference, which are sponsored by the Special Interest Group on Computer Science Education (SIGCSE) within the Association for Computing Machinery. These conferences resemble the annual Frontiers in Education Conference sponsored by the IEEE Education Society, the IEEE Computer Society, and the Educational Research and Methods Division of the American Society for Engineering Education (ASEE); the ASEE Annual Conference; and the Annual Conference of the European Society for Engineering Education (SEFI). All of these conferences require peer review of submitted papers, and they produce proceedings. ICER

accepts only research studies with strong theoretical and empirical bases, whereas the other five conferences accept a broader range of papers including research studies, scholarship of teaching and learning studies, and reports of promising practices. In addition to these six major conferences, researchers in both computing education and engineering education present papers at smaller regional conferences.

Despite the similarities in conference publication practices, computing and engineering education researchers differ in their journal publication practices. Following the practices of technical researchers in computer science, computing education researchers publish mostly in conferences, rather than in journals. By contrast, engineering education researchers often present preliminary work at conferences and then polish their manuscripts for subsequent publication in peer-reviewed journals.

Computing education researchers historically favored quantitative methods such as surveys, (quasi-)experiments, and correlational studies. Qualitative research in computing education is gaining in popularity, however [CITE CHAPTER 2.8 IN THIS BOOK]. Although engineering education research in the US previously favored quantitative methods too (Borrego, Froyd, & Knight, 2007), today engineering education researchers embrace qualitative and mixed methods as well (Loui, 2017).

Engineering education research is still struggling to become an internationally integrated field, as publication venues are primarily segregated by region. While U.S. engineering education researchers have conducted large scale, multi-institutional studies such as APPLES (Sheppard et al., 2014) and MIDFIELD (Ohland et al., 2016), there are few international collaborations, particularly involving U.S. researchers. In contrast, computing education researchers have developed a range of multi-institutional multi-national research methodologies that aim for both high statistical power and attention to cultural influences on the results (Fincher et al., 2005). Conferences and collaborations alike frequently combine data, perspectives, and researchers from multiple countries.

Like engineering education researchers, computing education researchers borrow theoretical and conceptual frameworks from the learning sciences and educational psychology [CITE CHAPTERS 2.1 AND 2.7 IN THIS BOOK]. Both computing and engineering education researchers investigate the effectiveness of active and cooperative learning pedagogies, and the barriers to participation by students from underrepresented groups. Just as engineering education researchers study the development of engineering thinking by pre-college students and their teachers, computing education researchers study the development of computational thinking by pre-college students. To assess the effectiveness of computing instruction in high schools in the U.S., computing education researchers have used the Advanced Placement Computer Science Test. By contrast, there is no Advanced Placement test in engineering. The development of such a test has been stymied by disagreements over how and whether to assess design as a central characteristic of engineering. Computing education has a shorter history of developing assessment instruments for college-level instruction than engineering education.

Whereas pre-college engineering education promotes engineering literacy, analogous to scientific and mathematical literacy (Snider & Purzer, 2014), undergraduate engineering education prepares students to become professional engineers. As a consequence, engineering education researchers have studied how engineering students develop professional identities. In contrast, there is little research on student identity development in computing.

Many computing education studies have investigated introductory courses in computer science (CS1). Similarly, engineering education research has devoted significant attention to first-year programs for undergraduates in engineering. This attention follows naturally from the responsibility of engineering education departments to deliver first-year engineering courses.

For computing educators just getting started in computer science education, there are several ways to learn more. Reading this Handbook (and its citations of particular interest) is a good start. It may help to discuss the readings with others, for example by organizing a local or virtual reading group. Courses in education or in psychology offered by colleges and universities would provide a directed reading and discussion structure to computing faculty who audit the course. Presenting one's work at campus teaching and learning events and at computing education conferences, and talking to other authors and speakers, are other ways to learn more. Teaching and learning centers, STEM centers, learning technology centers, and assessment and evaluation centers are another good place to start on college campuses. It also helps to know you aren't alone in struggling with the differences between disciplinary research and discipline-based educational research (DBER) (Borrego, 2007). Computing educators may eventually want to seek out collaborators. Local collaborators might be found in social science departments. It is also possible to recruit collaborators from among the authors of specific prior studies. These potential collaborators may be interested in expanding their data collection to additional students and institutional settings. Some people will be too busy. But many successful collaborations are born of both casual local interactions and cold calls to researchers at other institutions (Borrego & Newswander, 2008).

7 Conclusion

In 2009, Godfrey and Hadgraft declared that engineering education research was “coming of age.” That is, it was reaching a state of maturity. Similarly, with the publication of this handbook, we authors declare that computing education research is coming of age. Just as engineering education researchers have drawn inspiration from other DBER fields such as physics education research and chemistry education research, computing education researchers could adopt ideas and practices from other DBER fields, including engineering education research. Conversely, computing education research has contributed models and methods that could benefit other DBER fields. In summary, as suggested by Henderson et al. (2017), interdisciplinary collaborations between researchers from different DBER communities could facilitate exchanges of ideas and thereby advance the development of education research in every discipline.

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