Chronological and Ontological Development of Engineering Education as a Field of Scientific Inquiry

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Introduction

In the United States[1], engineering education as an area of interest for curriculum development and pedagogical innovation emerged about 1890 to 1910 and its transition to a more scholarly field of scientific inquiry occurred nearly 100 years later (Continental, 2006; Lohmann, 2005). Learning to become an engineer, historically and today, fundamentally occurs at the baccalaureate level; thus, the literature in engineering education focuses predominantly on undergraduate education. It is only within the last decade or so that the engineering and engineering education communities have taken more interest in precollege education. This history is important because much of the scholarly literature in education and the learning

[1] We will use the chronology of events in the United States as the principal framework to describe the evolution of engineering education as a field of scientific inquiry with references to similar events internationally as appropriate.

sciences focuses on precollege education, an area of less interest to most engineering faculty. Further, few engineering educators receive adequate preparation for their instructional duties during their doctoral training or later as faculty. Thus, the field of engineering education research developed largely around research traditions with which engineering faculty members were familiar. As a result, for most engineering faculty, lack of familiarity with the education and learning sciences literature, reliance on familiar research methodologies which were often ill-suited for educational studies, and complacence with accepting student satisfaction surveys for indicators of efficacy of course changes, generated "a rich tradition of educational innovation, but until the 1980s assessment of innovation was typically of the 'We tried it and liked it and so did the students' variety" (Wankat, Felder, Smith, & Oreovicz, 2002). Catalysts, including major NSF funding for educational research and development beginning in the late 1980s and emergence of the outcomes-based ABET Engineering Criteria led to significant publications in engineering education research in the 1990s. In the last twenty years, engineering education research has begun to emerge as an interdisciplinary research field seeking its own theoretical foundations from a rich array of research traditions in the cognitive sciences, learning sciences, education, and educational research in physics, chemistry, and other scientific disciplines.

The remainder of the paper is divided into three parts. First, we provide a brief chronology of the development of engineering education as a field of study. We then describe the ontological transformation of the field into engineering education research using Fensham's (2004) criteria for defining the field of science education research. The third part briefly discusses projects the near future of the field.

THE CHRONOLOGICAL EVOLUTION OF U.S. ENGINEERING EDUCATION AS A FIELD OF SCIENTIFIC INQUIRY

The nation's first engineering program, civil engineering, was established at the United States Military Academy, which was founded in 1802 to reduce the nation's dependence on foreign engineers and artillerists in times of war (United States Military Academy, 2010). Other parts of the world also began engineering programs during the 1800s and especially the latter half of the century (Continental, 2006). Nonetheless, higher education was largely inaccessible to many Americans until the passage of the Morrill Act[2] in 1862 (Lightcap, 2010), which accelerated the nation's growth throughout the last half of the century fueled by such engineering efforts as the transcontinental railroad, electric power, the telegraph and telephone, and steam and internal combustion engines. The first engineering society, the American Society of Civil Engineers, was established in 1852 (American Society of Civil Engineers, 2010) and the first engineering education society, the Society for the Promotion of Engineering Education (SPEE), was founded in 1893 (American Society for Engineering Education, 1894), now known as the American Society for Engineering Education (ASEE). The growth of similar engineering education societies appears to have occurred mostly after WW II (*Journal of Engineering Education*, 2010). SPEE established the first periodical "devoted to technical education" in 1910, called the *Bulletin* (American Society for Engineering Education, 1910), which nearly a century later evolved into the discipline-based (engineering) education research journal, *Journal of Engineering Education* (*Journal of Engineering Education*, 2010; Lohmann, 2003).

[2] The Morrill Act (often called the Land Grant Act) gave each U.S. senator and representative 30,000 acres of land, which was to be used to provide for colleges in each of the states. The colleges were to educate citizens in agriculture, home economics, mechanical arts (i.e., engineering), and other professions practical for the times.

For the first half of the twentieth century, U.S. engineering and engineering education was characterized by its practical arts. This focus changed abruptly when the world observed the power of science and its applications during WW II. When coupled with creation of NSF in 1950 (National Science Foundation, 2010), and several other programs within existing Federal agencies, Federal funding largely transformed the American higher education system into research-based institutions of higher learning, especially in science and engineering. This was reinforced in 1955 when ASEE issued a landmark study commonly called the Grinter Report (1994). It outlined a more research-oriented and science-based curriculum that still exists today in the vast majority of U.S. engineering programs.

In 1986, the National Science Board (NSB) issued a much needed wake-up call about the state of U.S. engineering, mathematics, and science education (National Science Board, 1986). Its report provided a number of recommendations and made clear that one among them played a critical role: "The recommendations of this report make renewed demands on the academic community—especially that its best *scholarship* be applied to the manifold activities needed to strengthen undergraduate science, engineering, and mathematics education in the United States" (National Science Board, 1986, p. 1, emphasis added). It was instrumental in reviving the NSF's role to "initiate and support science and engineering education programs at all levels and in all the various fields of science and engineering" (National Science Foundation, 2010). The report was also among those that sparked a vigorous national dialogue on the role of scholarship in improving the quality of U.S. higher education. For example, the highly influential 1990 report, "Scholarship Reconsidered: Priorities of the Professoriate," by Ernest Boyer of the Carnegie Foundation, offered a new taxonomy and terminology to describe academia's multifaceted forms of scholarship (Boyer, 1990). In engineering, the introduction of EC2000 by ABET in the 1990s was a major driver to improve the quality of engineering education (ABET, 1995). Its outcomes-focused, evidenced-based cycle of observation, evaluation, and improvement characterized many aspects of a scholarly approach to educational innovation.

The dialogue and decisions made in the 1990s paved the way for engineering education to become a field of scientific inquiry as it became increasingly clear that the intuition-based approaches of the past were not producing the quantity and quality of engineering talent needed to address society's challenges (Continental, 2006; National Academy of Engineering, 2004; National Research Council, 2005; National Science Foundation, 1992) and that more scholarly and systematic approaches based on the learning sciences were needed (Gabriele, 2005; Haghighi, 2005; National Research Council, 1999, 2002). Consequently, embryonic and globally diverse communities began to emerge and collaborate such that by the mid-2000s engineering education as a scientific field of inquiry (research) had passed the "tipping point" both within the United States and elsewhere (Borrego & Bernhard, 2011; Jesiek, Borrego, & Beddoes, 2010). Integrating and expanding these communities was a major point of discussion in a recent NSF-funded ASEE study, *Creating a Culture for Scholarly and Systematic Innovation in Engineering Education* (American Society for Engineering Education, 2009).

In the next section, we describe the current state of engineering education research, much of it having been created within the last decade or so.

An Ontological Description of The State of Engineering Education Research

Peter Fensham (2004) recently published a framework with which to judge the evolution and maturity of science education research. It involves three categories of criteria: structural, research, and outcome, as summarized in Table 1. We believe this framework is appropriate for organizing and critiquing the evolution and maturity of engineering education research. For a chronological description of the development of engineering education and engineering education, the authors (together will support of others in the engineering education research community [please see Acknowledgement] have compiled a timeline in Appendix I.

Structural Criteria

1) Academic Recognition: There are about twenty centers involved in engineering education research of which most were established in the last decade (Center for the Advancement of Scholarship in Engineering Education, 2010). The departments of Engineering Education at

Table 1. Fensham's (2004) Criteria for Defining the Field of Science Education Research

Category	Criteria	Exemplars of Criteria
Structural	Academic Recognition	Full faculty appointments in the area of research
	Research Journals	Successful journals for reporting quality research
	Professional Associations	Healthy national and international professional associations
	Research Conferences	Regular conferences for the direct exchange of research that enable researchers to meet in person
Research	Scientific Knowledge	Knowledge of science content required to conduct the research
	Asking Questions	Asking distinctive research questions not addressed by other fields
	Conceptual and Theoretical Development	Theoretical models with predictive or explanatory power
	Research	Invention, development, or at least adaptation of

	Methodologies	methodologies, techniques, or instruments
	Progression	Researchers are informed by previous studies and build upon or deepen understanding
	Model Publications	Publications that other researchers hold up as models of conduct and presentation of research studies in the field
	Seminal Publications	Publications recognized as important or definitive because they marked new directions or provided new insights
Outcome	Implications for Practice	Outcomes from research that are applications to the practice of science education

Purdue and Virginia Tech, both established in 2004, were the first to provide tenured positions in engineering education.

2) Research Journals: The field has one journal focused exclusively on research, the *Journal of Engineering Education* (JEE), and five whose missions encompass research: *Engineering Studies*, *European Journal of Engineering Education* (EJEE), *International Journal of Engineering Education* (IJEE), *Engineering Education*,, and *Chemical Engineering Education* (Borrego & Bernhard, 2011).[3] Two are listed on Thomson-Reuters citation indices (IJEE and JEE) and three are ranked by the Australian Research Council (EJEE, IJEE, and JEE).

3) Professional Associations and Research Conferences: There are many international engineering education societies including a federation of such societies (International Federation of Engineering Education Societies, 2010). The dominate ones are ASEE, the Australasian Association for Engineering Education (AAEE), and the Société Européenne pour la Formation des Ingénieurs (SEFI). Annual conferences focus on curriculum development; however,

[3] There are other engineering education journals but their primary focus is curriculum development and pedagogical innovation.

increasingly some host engineering education research tracks and some have groups whose focus is engineering education research, notably AAEE, ASEE, and SEFI. An independent research symposium Research on Engineering Education Symposium (REES) was established in 2007 to facilitate a periodic global gathering of researchers in the field (Research in Engineering Education Network, 2010).

4) Funding and Honors: The authors believe there are two additional structural criteria of importance to engineering. Peer-reviewed extramural support has been a critical to U.S. engineering research since WW II. Educational initiatives, however, have been supported mostly within university budgets. In the late 1980s, the NSF established programs for curriculum development and pedagogical innovation whose support mirrored their technical research counterparts, and a number of programs are now available for discipline-based education research. Awards and honors for teaching are ubiquitous but recognitions for engineering education research are nearly non-existent. Two publication awards include ASEE's Wickenden Award for the best paper published annually in JEE and the Outstanding Research Publication Award by Division I (Education in the Professions) of the American Educational Research Association.

Research Criteria

1) Scientific Knowledge and Asking Questions: The NSF-funded Engineering Education Research Colloquies held in 2004-05 were among the more notable efforts to begin to frame a scientific basis for thinking about the research challenges in the field of engineering education (The Steering Committee of the National Engineering Education Research Colloquies, 2006a, 2006b). They produced a taxonomy organized around "five priority research areas (Engineering Epistemologies, Engineering Learning Mechanisms, Engineering Learning Systems, Engineering

Diversity and Inclusiveness, and Engineering Assessment)" that merge disciplinary engineering and learning sciences knowledge. Other efforts have recently emerged in the European community (Borrego & Bernhard, 2011; European and Global Engineering Education Network, 2010). Although the global community has not reached consensus on a taxonomy, it clearly feels a pressing need for such and is working to develop it (Borrego & Bernhard, 2011).

2) Conceptual and Theoretical Development and Research Methodologies: These two areas form the intellectual core of any disciplinary-based educational research field. Currently, conceptual and theoretical frameworks and research methodologies in engineering education research show considerable similarity to those of educational research in general; a condition that reveals its lack of maturity. Like other educational research fields, one foundation is research in the learning sciences, with its vast literature base and different theoretical frameworks (Greeno, Collins, & Resnick, 1996). At present, theoretical frameworks for research in engineering education do not distinguish themselves itself from frameworks for educational research in general, which tends to emphasize individuals learning. Research in the cognitive sciences, e.g., brain physiology, might contribute to a theoretical framework; however, constructing bridges from functions of individual or small groups of neurons to complex engineering concepts and processes would be a formidable task. Also, since engineering faculty members teach collections or organizations of individuals, a potential contributor to future theoretical frameworks may be organizational change (Weick & Quinn, 1999).

Similar statements can also be made about applicable research methodologies, i.e., engineering education research does not have a distinctive set of research methodologies. Engineering faculty members who apply engineering education research have backgrounds that condition them to understand quantitative research methodologies more easily than qualitative or mixed methodologies. As a result, efforts have been made to educate a large segment of the audience for engineering education research about the nature and value of the latter two sets of methodologies (Borrego, Douglas, & Amelink, 2009), but further progress is required.

3) Progression, Models, and Seminal Publications: Strobel, Evangelou, Streveler, and Smith (2008) think the first doctoral thesis on engineering education was published in 1929, and additional theses appeared occasionally up to about 1980. However, between 1980 and 1989, they found five to eleven theses published every year, and thereafter thesis production increased markedly, and several widely cited articles on research in engineering education were published (Atman, Chimka, Bursic, & Nachtmann, 1999; Besterfield-Sacre, Atman, & Shuman, 1997; Felder, Felder, & Dietz, 1998) in the 1990s. These papers laid foundations for (i) further understanding of how students learn the engineering design process and how verbal protocol analysis methodologies can support the research (Atman & Bursic, 1998; Atman et al., 1999); (ii) rigorous assessment and adoption of cooperative learning (and later, other innovations) in engineering (Felder et al., 1998; Haller, Gallagher, Weldon, & Felder, 2000); and (iii) the importance of and instruments for understanding engineering student attitudes and the roles they play in retention and learning. In the first decade of the new millennium, significant publications in engineering education research have become too numerous to mention in this short review.

Outcome Criteria (Implications for Practice)

A major initiative is underway in engineering education community to persuade members of the synergistic and complementary roles played by innovation and research, beginning with the ASEE Year of Dialogue in 2006. A high point in this initiative is publication of the ASEE report *Creating a Culture for Scholarly and Systematic Innovation in Engineering Education* (American Society for Engineering Education, 2009). However, the fact that such an initiative was required is indicative of a culture in which most engineering education practitioners are content to continue to focus on innovations and less concerned about theoretical foundations that might catalyze innovations or methodologies with which the efficacy of the innovations might be evaluated.

THE PATH FORWARD

Engineering education research has become an established field within the last decade, although its recognition and acceptance within the broader engineering community remains a challenge. It has established the critical physical infrastructure, e.g., centers, departments, journals, conferences, and funding, necessary for it to now devote increasing attention to its intellectual growth, e.g., conceptual and theoretical development, research methodologies, and progression. We foresee two major developments in the next decade: 1) major national or regional efforts to better integrate engineering education research into engineering programs, such as ASEE's effort *Creating a Culture for Scholarly and Systematic Innovation in Engineering Education* and the European effort, European and Global Engineering Education Network (EUGENE), and 2) increasing collaboration (and occasional tensions) among the growing global communities of engineering education researchers as the field continues to mature.

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Appendix I. Timeline of Events in Engineering Education and Engineering Education Research

Year	Events	Reports	ABET	Papers	NSF
1973				Stice paper: Hereford, S. M., & Stice, J. E. (1973). A course in college teaching in engineering and the physical sciences. Paper presented at the ASEE Annual Conference & Exposition.	
1976				Stice papers: (i) Stice, J. E. (1976). A first step toward improved teaching. Engineering Education, 66(5), 394-398; (ii) The What, Why, and How of Faculty Development, or Who, Me?"	
1981	Cooperative learning is introduced at the Frontiers in Education Conference, one of the two major conferences on engineering education in the United States			First in a series of papers on cooperative learning published in Engineering Education, Smith, K. A., Johnson, D. W., & Johnson, R. T. (1981). Structuring learning goals to meet the goals of engineering education. Engineering Education, 72(3), 221-226.	
1986					NSB releases the Neal Report calling for more scholarship in engineering, science, and mathematics education
1987				Stice publications: (i) Stice, J. E. (1987). Using Kolb's Learning Cycle to Improve Student Learning. Engineering Education, 77, 291-296; (ii) Stice, J. E. (Ed.). (1987). Developing critical thinking and problem-solving abilities (Vol. 30). San Francisco, CA: Jossey-Bass.	

1988					NSF launches first program for curriculum development; NSF funds grant that leads to development of the E4 program at Drexel University (E4 program was the foundation for the Gateway Engineering Education Coalition funded in 1992); NSF funds grant that leads to development of the Engineering Core Curriculum at Texas A&M University the Engineering Core Curriculum was a pillar in the formation of the Foundation Coalition, a NSF Engineering Education Coalition funded in 1993)
1989					NSF funds grant that leads to development of the Integrated, First-Year Curriculum in Science, Engineering and Mathematics (IFYCSEM) (IFYCSEM was a pillar in the formation of the Foundation Coalition, a NSF Engineering Education Coalition funded in 1993)

1990	ECSEL and Synthesis Engineering Education Coalitions started. EXCEL and Synthesis were engineering education Coalitions. NSF invested about $30 million in each Coalition to catalyze systemic improvement in engineering education; Leonhard Center for Enhancement of Engineering Education was established at Pennsylvania State University; Presidential Young Investigator (PYI) Colloquium held and report published	America's Academic Future: A Report of the Presidential Young Investigator Colloquium on U.S. Engineering, Mathematics, and Science Education for the Year 2010 and Beyond			
1991	Cooperative Learning Publications	Johnson, Johnson & Smith, Cooperative Learning ASHE-ERIC Research Report		First edition published: Johnson, D. W., Johnson, R. T., & Smith, K. A. (1998). Active learning: Cooperation in the college classroom (2nd ed.). Edina, MN: Interaction Book Company.	

1992	SUCCEED and Gateway Engineering Education Coalitions started		ABET President John Prados challenged the Board of Directors to consider radical revisions in accreditation philosophy, criteria, and procedures [26].		
1993	Foundation Coalition (Engineering Education Coalition) started			Part I of longitudinal study of cooperative learning in chemical engineering: Felder, R. M., Forrest, K. D., Baker-Ward, L., Dietz, E. J., & Moh, P. H. (1993). A longitudinal study of engineering student performance and retention. I. Success and failure in the introductory course. Journal of Engineering Education, 82(1), 15-21.	NSF funds the first Presidential Young Investigator (PYI) awards in engineering education (PYI was the precursor to CAREER program)

1994	Greenfield Coalition (Engineering Education Coalition) started	Report: Engineering Education for a Changing World. Report by the Engineering Deans Council and the Business Roundtable of the American Society for Engineering Education	ABET holds three consensus-building workshops for the Accreditation Process Review Committee. Workshops involve more than 125 participants from academia, industry, and government.	Part II of longitudinal study of cooperative learning in chemical engineering: Felder, R. M., Mohr, P. H., Dietz, E. J., & Baker-Ward, L. (1994). A longitudinal study of engineering student performance and retention. II. Rural/Urban Student Differences. Journal of Engineering Education, 83(3), 209-217.	

1995	Frontiers in Education Conference (FIE): The FIE Conference held in Atlanta was the first of a new format for the conference that attracted a relatively large crowd and made a substantial profit, enabling Education Research and Methods (ERM) Division of ASEE to begin to take on a number of creative activities.		ABET Board of Directors approved the publication of new criteria for evaluating engineering programs—Engineering Criteria 2000 (EC2000) for public comment.	Part III and IV of longitudinal study of cooperative learning in chemical engineering: (i) Felder, R. M., Felder, G. N., Mauney, M., Charles Hamrin, J., & Dietz, E. J. (1995). A longitudinal study of engineering student performance and retention. III. Gender differences in student performance and attitudes. Journal of Engineering Education, 84(2), 151-163; (ii) Felder, R. M. (1995). A longitudinal study of engineering student performance and retention. IV. Instructional methods. Journal of Engineering Education, 84(4), 361-367	
1996			Pilot evaluations conducted using Engineering Criteria 2000 at five diverse institutions.		
1997	Frontiers in Education (FIE) Conference: The FIE Conference held in Pittsburgh introduced the New Faculty Fellows program and published the outstanding papers from the Conference in the Journal of Engineering Education				USEME (precursor to DUE) formed

1998	Center for Engineering Learning and Teaching (CELT) at University of Washington established			Part V of longitudinal study of cooperative learning in chemical engineering: Felder, R. M., Felder, G. N., & Dietz, E. J. (1998). A longitudinal study of engineering student performance and retention. V. Comparisons with traditionally-taught students. Journal of Engineering Education, 87(4), 469-480.	
1999	National Research Council (NRC) Board on Engineering Education moved to National Academy of Engineering (NAE) and renamed to Committee on Engineering Education (CEE)			Atman et al publish first study comparing performance with respect to engineering design. Paper compared engineering design performance of first-year and senior engineering students: Atman, C. J., Chimka, J. R., Bursic, K. M., & Nachtmann, H. L. (1999). A comparison of freshman and senior engineering design processes Design Studies, 20(2), 131-152.	NSF funds the first Engineering Research Center (VaNTH) with a focus on engineering education; NSF initiates its Action Agenda program to facilitate adaptation of innovations in engineering and science education
2000	Center for Engineering Education was established at the Colorado School of Mines				

2001	The Engineer of 2020 Project was started by the Committee on Engineering Education of the NAE		Outcomes-based criteria (formerly referred to as Engineering Criteria 2000) become the only criteria used for accrediting engineering degree programs.		
2002	Center for the Advancement of Scholarship in Engineering was established at the NAE as one of the initiatives of the Committee on Engineering Education				
2003	National Academy of Engineering (NAE) established the Bernard M. Gordon Prize for Innovation in Engineering and Technology Education ($500,000 award); Journal of Engineering Education focuses exclusively on research in engineering education				NSF funds the first Center on Teaching and Learning (CLT) on engineering education, Center for Advancement of Engineering Education (CAEE)

2004	Purdue University and Virginia Tech each create a Department of Engineering Education	Report: Engineer of 2020			
2005	Engineering Education Research Colloquies (EERC). A series of four colloquies designed to spur discussion on the future of engineering education. The first of these colloquies occurred in September 2005. Invited scholars known for their experience and expertise in the field begin preparing a roadmap for engineering education and an engineering education research agenda; JEE publishes first special issue, the Art and Science of Engineering Education Research, whose articles are the most cited since the launch of JEE as a research journal			Special Issue of Journal of Engineering Education; John Heywood book "Engineering Education: Research and Development in Curriculum and Instruction"	
2006	Advances in Engineering Education (AEE) launched				Not sure the exact year but about this time the EEC/ENG division started creating EER programs

2007	The first conference on engineering education research, International Conference on Research in Engineering Education (ICREE) launched with meeting in Honolulu; Global Colloquium in Engineering Education (GCEE) hosts its first track on engineering education; JEE initiates a new monthly column in Prism, "JEE Selects: Research in Practice"				
2008	ASEE launches Advances in Engineering Education (AEE) as a repository for successful applications to complement JEE's focus on research; JEE begins forming international partnerships, 10 created by 2010; Research in Engineering Education Symposium (REES), successor to ICREE holds its first meeting in Davos, Switzerland				

2009	REES holds its second meeting in Palm Cove, Queensland, Australia	Creating a Culture for Scholarly and Systematic Innovation in Engineering Education (CCSSIEE), Phase 1 Report			
2010		Creating a Culture for Scholarly and Systematic Innovation in Engineering Education (CCSSIEE), Phase 2 Report			
2011	JEE celebrates centennial issue				