INVITED PAPER

Five Major Shifts in 100 Years of Engineering Education

The authors discuss what has reshaped, or is currently reshaping, engineering education over the past 100 years up until the current emphasis on design, learning, and social–behavioral sciences research and the role of technology.

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ABSTRACT | In this paper, five major shifts in engineering education are identified. During the engineering science revolution, curricula moved from hands-on practice to mathematical modeling and scientific analyses. The first shift was initiated by engineering faculty members from Europe; accelerated during World War II, when physicists contributed multiple engineering breakthroughs; codified in the Grinter report; and kick-started by Sputnik. Did accreditation hinder curricular innovations? Were engineering graduates ready for practice? Spurred by these questions, the Accreditation Board for Engineering and Technology (ABET) required engineering programs to formulate outcomes, systematically assess achievement, and continuously improve student learning. The last three shifts are in progress. Since the engineering science revolution may have marginalized design, a distinctive feature of engineering, faculty members refocused attention on capstone and first-year engineering design courses. However, this third shift has not affected the two years in between. Fourth, research on learning and education continues to influence engineering education. Examples include learning outcomes and teaching approaches, such as cooperative learning and inquiry that increase student engagement. In shift five, technologies (e.g., the Internet, intelligent tutors, personal computers, and simulations) have been predicted to transform education for over 50 years; however, broad transformation has not yet been observed. Together, these five shifts characterize changes in engineering education over the past 100 years.

KEYWORDS | Accreditation; design; engineering education; engineering science; instructional technologies; learning

I. INTRODUCTION

In the 100 years since the founding of the Proceedings of the IEEE, continual interest in engineering education has led to five major shifts. Two of them have been completed. First, following World War II and the formation of the National Science Foundation (NSF), the engineering science revolution that changed the nature of engineering curricula and the jobs of engineering professors occurred. Second, in the late 1990s and early 2000s, based largely on the actions of the Accreditation Board for Engineering and Technology (ABET), engineering education and accreditation became outcomes based. The three shifts that are still in progress are: 1) a renewed emphasis on design; 2) the application of research in education, learning, and social-behavioral sciences to curricula design and teaching methods; and 3) the slowly increasing prevalence of information, communication, and computational technologies in engineering education.

In addition to marking the 100th anniversary of the Proceedings of the IEEE, 2012 is the centennial of the founding of the Institute of Radio Engineers (IRE), which merged with the American Institute for Electrical Engineering (AIEE) to form the IEEE about 50 years ago. The IRE Transactions on Education was founded in 1958 and became the IEEE Transactions on Education in 1963.

What were concerns of electrical engineers when the IRE Transactions on Education was founded in 1958? Some concerns sound amusingly archaic, such as worry about Russia's superior education system [1], [2], low pay of professors and their penury during retirement [2], [3], need for government research funds even though very few engineering professors will be interested [2], and assuming students are men. Some sound very familiar and easily fit

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into Cheville's snapshot of the current state of engineering education [4]. Familiar items include the importance of fundamentals [1], the need for funds to replace lab equipment [5], the inclusion of K-12 in educational interests [5], the need to relate educational concepts to what a student already knows [6], and the challenge of completing an electrical engineering degree in four years [6]. Some still appear visionary [7], which we will discuss later.

Since 1958, the IRE and then the IEEE Transactions on Education, the Proceedings of the IEEE and other engineering education journals, such as the *Journal of Engineering Education*, have focused on many other issues that are important in engineering education, including what content should be taught and how it should be taught, accreditation, design, engineering education research, and the use of technology in engineering education. Pedagogical threads will be woven into the remainder of this paper.

The five major shifts in engineering education that have occurred during the past 100 years are:

1) a shift from hands-on and practical emphasis to engineering science and analytical emphasis;
2) a shift to outcomes-based education and accreditation;
3) a shift to emphasizing engineering design;
4) a shift to applying education, learning, and social-behavioral sciences research;
5) a shift to integrating information, computational, and communications technology in education.

The first two shifts have already occurred, but they continue to have implications for engineering education. The latter three are still in process, and sustained influences on practice are difficult to forecast.

II. FIRST MAJOR SHIFT: ENGINEERING SCIENCE, ANALYTICAL EMPHASIS

The first major shift in engineering education in the United States occurred in the period 1935–1965 as "Stanford and other American engineering schools began replacing machine shop, surveying, and drawing classes with science and mathematics courses" [8]. Engineering curricula moved from hands-on, practice-based curricula to ones that emphasized mathematical modeling and theory-based approaches. Foundations for the shift were established by many European engineers and engineering faculty members, e.g., Timoshenko, von Karman, and Westergard, who immigrated to the United States and introduced European approaches to engineering education [8]–[10]. This change toward more math and science was accelerated by experiences in World War II, when engineers generally did not perform as well as physicists in solving unusual problems [8]. For example, Seely noted that "Frederick Terman, an electrical engineer who had specialized in radio and spent the war at the Radiation Laboratory at MIT, was not the only engineer irritated that physicists received most of the credit for wartime research accomplishments. But he also recognized that many engineers had been ignorant of the science underlying electronics and atomic weapons. As dean of engineering at Stanford immediately after the war, Terman was determined engineers would not play second fiddle in the future" [8]. Responding to continued turbulence over curriculum, in May 1952, S. C. Hollister, the President of the American Society for Engineering Education (ASEE), appointed a Committee on Evaluation of Engineering Education chaired by Prof. L. E. Grinter with the goal to evaluate engineering education and suggest new approaches to teaching engineering. The resulting 36-page report [11], [12] was the most significant in the history of ASEE. Engineering curricula that emphasized mathematics and science were codified in some, but not all, of the recommendations in the Grinter report [11]–[13] that brought engineering science courses into prominence. A further accelerator was the intercultural–political shock caused by Sputnik. Suddenly the United States was behind, and engineering education was partly to blame [13]. The shift to more science and engineering science is the most significant change in engineering education during the past 100 years and has been characterized in various ways:

> "The first draft of the so-called Grinter Report stressed the need for more science in engineering curricula and then, more controversially, proposed two tiers of engineering instruction. The committee thought most students would be served by a professional-general program that provided solid training in fundamental science for jobs in industry. Only a few engineering schools needed to develop advanced undergraduate and graduate programs in fundamental engineering science (professional-scientific) to prepare students for government and industrial research programs. Readers of the report disagreed sharply, however, and the final version of the Grinter Report settled for a strong endorsement of the need for more science in engineering schools. Why the protest? The key, again, was military research funding. What engineering school would voluntarily cut itself off from military research dollars, the key to building academic engineering programs?" [8].

> "Grinter recommended that all engineering curricula include the following common set of courses in the 'engineering sciences': Mechanics of Solids, Fluid Mechanics, Thermodynamics, Heat and Mass Transfer, Electrical Theory, Nature and Properties of Material. The report also recommended that engineering curricula include coursework in the social humanities. This recommendation was clearly aimed at helping engineers to develop skills in interacting with people and to understand the social ramifications of technological development. This report had

> a foundational impact upon engineering curricula and firmly rooted the study of engineering in the sciences" [14].

At the end of this shift, United States engineering curricula more closely resembled their European counterparts. Further, some of the emphases and excesses during and after the shift generated rationale and momentum for some of the shifts described below.

III. SECOND MAJOR SHIFT: OUTCOMES-BASED ACCREDITATION

Through ABET and its predecessors "accreditation has provided quality control for engineering education in the United States, seeking to assure that graduates of accredited programs are prepared for professional practice" [15]. By the late 1980s, as the "number of accreditation visits multiplied. . .[and] the prospect of legal challenges to unfavorable accreditation decisions increased, ABET review criteria became more quantitatively focused and less dependent on professional judgment. Despite its best intentions, the pre-1990 ABET could well be characterized as a protector of the status quo" [15]. Further, "President James J. Duderstadt of the University of Michigan and President Charles M. Vest of the Massachusetts Institute of Technology, both engineers, stated publicly that engineering education must change significantly to support the new quality-oriented environment and that ABET's rigid, bean-counting implementation of the accreditation criteria created a significant barrier to needed innovations in engineering education. These concerns were echoed by members of the ABET Industry Advisory Council" [15] as well as "deans from major engineering schools" [15].

Based on educational research on student objectives and outcomes (discussed later), the Engineering Accreditation Commission (EAC) of ABET developed a wholesale change in accreditation of engineering programs, known initially as Engineering Criteria 2000 (EC 2000) [15]. EC 2000 required assessment of student learning based on 11 criteria (3 a-k) for student outcomes (what students should be able to do on graduation day), assessment of graduate achievement based on program developed objectives (what graduates should be able to do a few years after graduation), and continuous program improvement. Criteria for the current cycle are available at http://abet.org/.

Initially, most professors strongly resisted assessment, but many eventually acquiesced after realizing that direct instructor assessment for student outcomes, which satisfies ABET, can take little additional time for the technical criteria [16]. Rubrics are needed to assess the professional criteria, and sample rubrics are available [17]. Communication (criterion 3g), understanding ethical standards (criterion 3f), and teamwork (criterion 3d) are items that industry and most professors believe are important, can be taught, and can be assessed. Industry and faculty are interested in ethical behavior, but criterion 3f says nothing about behavior. Criterion 3i, "a recognition of the need for, and an ability to engage in lifelong learning," is widely believed to be important, but how to assess "a recognition" is not clear. Professional criteria 3h, "the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context," and 3j, "a knowledge of contemporary issues," are considered by practicing engineers one to ten years after graduation to be less important [18] and have significantly less faculty support than the other criteria [19]. Unfortunately, disconnects over globalization issues exist between new engineers and most professors and many experienced commentators who consider it to be critically important [20]–[23]. Some ABET program evaluators privately state that as long as a program does anything to teach and assess criteria 3i, 3h, and 3j, they accept it.

An extensive analysis showed that EC 2000 clearly had a positive effect on engineering education [19]. Writing and disseminating course objectives, which are required by EC 2000, improves courses [24]. Because outcomes-based assessment is more flexible than the former method, ABET EAC is more accepting of novel programs. Looking at individual outcome criteria and obtaining regular feedback from graduates and employers makes it much easier to spot shortcomings and strengths in programs. Another result of the EC 2000 criteria is that more professors have become involved in assessment and accreditation. Explicit requirements to teach and assess the professional criteria have improved graduates' skills in these areas [19]. More professors use active learning methods, although it is not possible to determine to what degree EC 2000 was responsible for this change [19]. Many engineering professors still oppose assessment, continuous improvement, and data-based decision making [19], although these methods improve engineering education. Lattuca *et al.*'s [19] major analysis of the effectiveness of EC 2000 relied on surveys and self-reports, which they carefully benchmarked as providing meaningful information. Ironically, surveys and self-reports would not be allowed as the only assessments of an engineering program [16], [25].

IV. THIRD MAJOR SHIFT: RENEWED EMPHASIS ON DESIGN

The third major shift is increasing emphasis on design as a major and distinctive element of engineering [26]. One reason for the shift was the sense that the emphasis on engineering science, science, and mathematics has gone too far [8], [9], [27]. For example, Kerr and Pipes [28] wrote "[d]esign has fallen so low in the order of educational priorities that many engineers—especially young ones and students—do not understand its meaning." By the current millennium, influences of the shift were clearly evident. In 2005, over half the faculty and close to 3/4 of program chairs thought there was an increased emphasis on design in undergraduate curricula during the previous ten years [15]. Also, a study of how first-year and senior engineering students address a design challenge showed that engineering students do develop with respect to design knowledge and skills over the course of four-year engineering curricula [29].

A. Capstone Design Courses

Although not recent, the most widespread artifact of the shift is the capstone design course (or courses) present in many U.S. engineering curricula [30], [31]. Their existence has been encouraged by the EAC within ABET through its Engineering Criteria. In the 1970s, one-half year of engineering design became the standard requirement with the further stipulation that there had to be at least one course, preferably in the senior year, which was mainly design and which incorporated material from other courses [32]. The latter requirement is often interpreted as "capstone design," although the Engineering Criteria do not use this language. The one-half year of design requirement increased the amount of design, but it also caused endless arguments during accreditation visits over what was included as design. Current Engineering Criteria stipulate that students "must be prepared for engineering practice through a curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating appropriate engineering standards and multiple realistic constraints" [33]. Capstone design courses were also "developed recently in an effort to bring the practical side of engineering design back into the engineering curriculum" [34] and address concerns that graduates were unprepared for industrial practice upon graduation. Several studies and reports have articulated employer expectations for engineering graduates [20], [22], [33], [35]–[37]. Reviewing these expectations and comparing them with the learning goals for capstone design courses reveals considerable alignment.

Early models for the capstone design course included the senior project component of the Harvey Mudd Design Clinic [38], which was implemented in the mid-1960s, and the Major Qualifying Project in the WPI Plan [39], which was implemented in the late 1960s. Individuals who have played important roles in the Harvey Mudd Design Clinic, Clive L. Dym, M. Mack Gilkeson, and J. Richard Phillips, were recognized with the 2012 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education.

The state of capstone design courses has been documented in two surveys, one done in 1994 [31] and the second in 2005 [30], [40]. The second survey provided data on the age of the capstone design courses *in their current form*. From the 400 responses, 33% were five or less years old, 25% were 6–10 years old, 17% were 11–15 years old, 10% were 16–20 years old, and 14% were first offered 21 or more years ago [30]. Since over 50% of the capstone design courses were less than ten years old, the responses suggest that faculty continue to restructure and/or fine-tune courses and curricula.

Both surveys found that the vast majority of the capstone project courses organized students from one department in teams. As far as team size, 49% of 1994 respondents indicated that teams were composed of four to six students, while 60% of 2005 survey respondents indicate team sizes in this range [30]. The more recent survey found a noticeable increase in the prevalence of design teams populated by students from more than one department. In the 1990s, the SUCCEED Engineering Education Coalition, one of the six NSF-supported Engineering Education Coalitions [41]–[43] focused a significant percentage of its efforts on capstone design courses with student teams consisting of members from more than one department [44], [45]. In some cases, SUCCEED student teams were composed of only engineering students; in other cases, departments from outside engineering participated. Since 2000, the trend toward interdisciplinary capstone project courses appears to be continuing [46], [47], and courses often include students from majors other than engineering such as business and industrial design (http://eeic.osu.edu/capstone). Competitions such as the solar house or solar-powered car, which are inherently interdisciplinary and offer opportunities for participation from nonengineering fields as well, fit well into design courses and are strong motivators of many students [48], [49].

Assessment of student learning in capstone design projects [50] varies considerably. Respondents to the 2005 survey indicated that the following methods provided data for part or the entire final grade:

- individual deliverables throughout the term: 53%;
- group deliverables throughout the term: 67%;
- final group deliverable: 86%;
- evaluations by other team members: 57% [30].

Howe [30] reported some interesting findings: "Peer evaluations, as well as evaluations of individual and group deliverables throughout the term were each used by about half of programs. The reportedly common practice of evaluating intermediate and final group deliverables is consistent with findings by McKenzie *et al.* [12], but a notable finding is that 14% of respondent programs in 2005 did not use evaluations of final group deliverables at all. *A surprising theme shown in the pie charts is the number of programs that gave full weight to a single factor. Some based final grades on only group deliverables, while 2% based grades solely on group evaluations* [emphasis added]." Divergence among assessment methods suggests continued evolution as programs continue to mine approaches from other programs and develop new approaches.

B. First-Year or Cornerstone Engineering Design Courses

A second artifact of the shift toward increasing emphasis on design is the first-year engineering design course or cornerstone course [26], [27], [51]. In "the 1970s and early 1980s freshman design courses and course segments were common at ABET-accredited institutions," as evidenced by the activity in the annual Creative Engineering Design Display held at the ASEE Annual Conference & Expositions during these years [27]. However, during the 1980s, pressures to introduce computer programming into engineering curricula tended to squeeze out first-year design content so that by 1987 the Creative Engineering Design Display was canceled [27]. In the 1990s, there was a resurgence of first-year design activity, led in part by the NSF-supported Engineering Education Coalitions [41]–[43], particularly the ECSEL Coalition, with its emphasis on first-year engineering design [52], [53], the Synthesis Coalition [27], [54], the Gateway Coalition and implementations of the Enhanced Educational Experience for Engineers program [55], [56] on its various campuses, and the Foundation Coalition, with its emphasis on integrated first-year engineering curricula [57].

First-year engineering design courses have been shown to have positive influences on student development and retention. For example, first-year engineering design courses have been shown to positively influence intellectual development of students [58]. Students who chose to participate in the first-year engineering design course at the University of Colorado Boulder, with its Integrated Teaching & Learning Program and Laboratory (ITL), were retained at a statistically significantly higher rate than similar groups of engineering students who chose a different first-year engineering experience [59]. Incidentally, the prime movers in creating the ITL and courses it supports, Jacquelyn F. Sullivan and Lawrence E. Carlson, were recognized for their contributions to engineering education with the 2008 Bernard M. Gordon Prize for Innovation in Engineering and Technological Education. "Other studies of first-year engineering courses also reported improvements in retention [60]–[62]" [63].

Data on first-year engineering design courses are available through a survey of first-year programs conducted in 2005 [64]. The survey found that 13 respondents (from $N = 68$, 19.1%) of the first-year engineering courses were described as design courses, while 21 (from $N = 47$ respondents, 44.7%) indicated that their first-year engineering courses integrated design with other topics [64]. A survey to determine the extent to which engineering programs were aware and had adopted seven innovations in engineering education whose efficacy was well-established in the literature found that 92% (of 197 respondents) were aware of first-year engineering design courses, while 65% (of 197 responded) had implemented first-year design courses in their programs [63]. To support first-year engineering design courses, some institutions have found it very helpful to create physical spaces that support achievement of the educational goals and objectives that the institutions have established. At Purdue University, the Ideas to Innovation (i2i) Learning Laboratory is an experiential, collaborative, reconfigurable learning environment, which supports interactive technologies and team-based activities (see Fig. 1). Another helpful source of information is a review of first-year design education in Canada and the United States conducted by a member of the Canadian Design Engineering Network [65]. Bazylak and Wild noted that compared "with engineering science subjects, in which methods of instruction are remarkably uniform from university to university, the wide variation in [first year] engineering design instruction methods is striking. In part, this variation is due to the different resource constraints and priorities at each university" [65]. Faculty members teaching many engineering science subjects frequently choose from one of a small set of textbooks. For first-year engineering courses, a small set of dominant textbooks has yet to emerge. Whether this is a cause or an effect of the difference in variation between engineering science and first-year engineering courses is a debate left to the readers.

Fig. 1. ***The Ideas to Innovation (i2i) First-Year Engineering Learning Laboratory at Purdue University.***

C. Engineering Design in the Sophomore and Junior Years

Although the shift toward increasing emphasis on engineering design has resulted in changes to engineering curricula in the first and senior years, design content and experiences in the second and third years of the engineering curricula have not changed significantly. As a result, there is a gulf between student experiences with engineering design in the first year and the capstone culminating experience. The impact on student learning and presence of this gulf were documented in a study at the University of Colorado at Boulder that concluded, "there is deterioration in student confidence in both professional and technical skills between the end of the first year and the beginning of the senior year . . . and the decline is statistically significant for all the assessed categories" [66]. An exception to this nationwide pattern can be found in the engineering curricula introduced at Rowan University, in which students work on their learning with respect to engineering design in each of their eight semesters [67]. Recognizing this gulf, a multiyear study by the Carnegie Foundation for the Advancement of Teaching recommended a thick spine spanning the four years of the engineering curriculum to provide "experience with and reflect on the demands of professional practice, linking theory and practice. . .This emphasis on professional practice would give coherence and efficacy to the primary task facing schools of engineering: enabling students to move from being passive viewers of engineering action to taking their place as active participants or creators within the field of engineering" [68].

V. FOURTH MAJOR SHIFT: APPLYING EDUCATION, LEARNING, AND SOCIAL-BEHAVIORAL SCIENCES RESEARCH

Influences of research in education, learning, and social-behavioral sciences are continuing to evolve [69].

- Behavioral psychology research has resulted in learning objectives (or outcomes), formative and summative assessment, and mastery model research outcomes and objectives. Student learning outcomes are now an integral part of the ABET Engineering Criteria and many other accreditation models.
- Social psychology research has resulted in adoption by many faculty members of approaches to teaching that increase student engagement and have been characterized as active learning, interactive learning, and especially cooperative learning, together with approaches that emphasize building communities, such as learning communities and communities of practice.
- Inquiry-based learning methods including problem-based and project-based learning, approaches to promote conceptual understanding, and integrated course design approaches are products of research in cognitive psychology, education, and the learning sciences.

The extent to which research in education, learning, and social-behavioral sciences has and continues to influence engineering education is changing, and difficult to determine. Boyer [70] found that 7% of engineering professors are most interested in research and 43% lean toward research instead of teaching. In a 2009 survey studying extent to which seven innovations in engineering education had been recognized and/or adopted in engineering departments, Borrego *et al.* found the following awareness and adoption levels directly related to the focus of this section:

- student-active pedagogies (awareness: 82%, adoption: 71%, $N = 197$ respondents);
- learning communities (awareness: 85%, adoption: 44%, $N = 197$ respondents);
- curriculum-based engineering service learning projects (awareness: 79%, adoption: 28%, $N = 197$ respondents) [63].

Over the years, many workshops for engineering faculty members have emphasized teaching approaches derived from educational research, including the National Effective Teaching Institute (NETI) [71] and faculty development workshops offered by one or more of the Engineering Education Coalitions [72], [73]. Participants in the NETI workshop reported that their experiences have moderately or substantially increased their use of the following practices:

- learning objectives: 75%;
- Bloom's taxonomy: 55%;
- active learning: 74%;
- cooperative learning: 65%;
- problem-based learning: 55%;
- inquiry-based learning: 34% [71].

These results are congruent with the University of California Los Angeles (UCLA) Higher Education Research Institute Faculty Survey results, which indicate that 59% of faculty surveyed report using cooperative learning in all or most classes [74]. Workshops, courses, and programs on teaching for engineering and science graduate and postdoctoral students will likely influence teaching approaches by these potential faculty members [75].

Section V-A and B describe learning outcomes and student engagement, where there seems to be agreement among engineering educators in terms of the practice of engineering education. Then, Section V-C–F highlight areas where there is some emerging support among engineering educators.

A. Educational Objectives, Mastery, and Student Learning Outcomes

Educational objectives, especially student learning outcomes because of ABET EAC requirements, are now part of the fabric of the engineering education community, other professional communities, and university accreditation. Before ABET adopted outcomes, the work and publications of Jim Stice, University of Texas at Austin, and Richard Felder, North Carolina State University, were very influential in introducing engineering faculty to objectives and the educational literature on objectives [76]. Through a series of articles, workshops and follow-up conversations [77]–[82], Stice, and later Felder, provided convincing arguments for the importance of carefully identifying and specifying objectives. Heywood [83] provides an excellent summary of the development of educational objectives in his extraordinary synthesis of work in engineering education.

Often faculty members find taxonomies of learning objectives useful in that they reveal richness and diversity in how learning objectives may be written [84]. This review of taxonomies of learning objectives shows that Bloom's taxonomy [85] has many effective characteristics.

Although the 1956 version of Bloom's Taxonomy of Educational Objectives [85] is widely used by engineering educators, we recommend considering the adoption of the updated and revised taxonomy [86].

Use of educational objectives, and, more broadly, student learning outcomes and Bloom's Taxonomy (original or revised) is an indication that research in psychology, education, and learning science is having a noticeable influence on the engineering education community. However, in the case of Bloom's taxonomy, there are, of course, as noted by Shulman [87], drawbacks to using taxonomies, which highlight differences, and like all tools we need to use them with care.

B. Student Engagement

Student engagement or involvement in learning is the second area for which there is evidence of the influence of research in psychology, education, and learning science on the practice of engineering education. The idea of the importance of student involvement was advanced by many, including John Dewey, and in the 1980s and 1990s was supported by research by Astin [88], Light [89], and many others. A 1984 U.S. Department of Education report made a very strong case for the importance of student involvement [90].

One of the most common ways that engineering faculty members have embraced student involvement is through the use of cooperative learning. Cooperative learning and its underlying theoretical framework, social interdependence theory, have been systematically studied in engineering education for over 50 years; the first study with engineering students was conducted at the Massachusetts Institute of Technology (MIT) in 1948 [91]. Engineering faculty began embracing cooperative learning shortly after it was introduced by Karl Smith in engineering education conferences and journals in 1981 [92], [93], and its use continues to grow, both in engineering [94]–[97] and physics [98]–[100] and in higher education in general [101]–[110]. For example, the University of Minnesota Active Learning Classrooms (ALCs) are designed to foster interactive, flexible, student-centered learning experiences, and operate using central teaching stations and student-provided laptops. ALC is a modification of the Student Centered Activities for Large Enrollment Undergraduate Program (SCALE-UP) concept that originated at North Carolina State University [98] and the Technology Enhanced Active Learning (TEAL) concept at MIT [100], and uses an adaptation of the projection capable classrooms (PCC) technology system (see Fig. 2). The empirical and theoretical evidence supporting the efficacy of cooperative learning and, to a lesser extent, active learning in engineering is vast [95], [111], [112]. Cooperation among students typically results in 1) higher achievement and greater productivity; 2) more caring, supportive, and committed relationships; and 3) greater psychological health, social competence, and self-esteem [96], [102], [104].

Fig. 2. *Active Learning Classroom (ALC) at the University of Minnesota.*

The National Survey of Student Engagement (NSSE) [113] has deepened understanding of how students perceive classroom-based learning, in all its forms, as an element in the bigger issue of student engagement in their college education. The annual survey of first-year students and seniors asks them how often they have participated in learning activities in which they have been actively engaged, for example, projects that required integrating ideas or information from various sources. Approaches that emphasize building communities, such as learning communities [114], [115] and communities of practice [116], also foster more student engagement. As shown by these and other studies, engaged students learn, are retained, and graduate. However, most students do not start in engineering as highly motivated, engaged students [4]—it is up to the faculty to engage them.

C. Inquiry

The idea of inquiry was articulated by John Dewey, who saw it as part of an ideal school [117]:

- a "thinking" curriculum aimed at deep understanding;
- cooperative learning within communities of learners;
- interdisciplinary and multidisciplinary curricula;
- projects, portfolios, and other "alternative assessments" that challenged students to integrate ideas and demonstrate their capabilities.

Inquiry and inquiry-based or guided approaches focus first on the question, problem, challenge, or goal to be addressed. Then, students learn content, concepts, and processes while addressing the question, problem, challenge, or goal. Inquiry approaches and evidence that they are effective are evident in problem-based learning [96], [118], [119]; project-based learning [96], [118]–[120]; model-eliciting activities [121]–[123]; challenge-based learning, including an entire NSF-supported Engineering Research Center [VaNTH] that focused on using ideas from *How People Learn* [124] to redesign biomedical engineering curricula [125]–[127]; and problem-based service learning [128], [129], including the Engineering Projects in Community Service (EPICS) model [130], for which Ed Coyle, Leah Jamieson, and Bill Oakes were recognized by the 2005 Bernard M. Gordon Prize for Innovation in Engineering & Technology Education. Prince and Felder [131], [132] provide a comprehensive framework for analyzing these inductive instructional methods, and a National Research Council report [133] provides guidance for teaching and learning using an inquiry approach.

D. Integrated Approach to Course and Program Design

Understanding by Design (UbD) is an increasingly popular tool for educational planning focused on teaching for understanding. The emphasis of UbD is on "backward design," the practice of first looking at the outcomes in order to design curriculum units, performance assessments, and classroom instruction. UbD is defined by Wiggins and McTighe as a "framework for designing curriculum units, performance assessments, and instruction that lead your students to deep understanding of the content you teach" [134]. An engineering version of the UbD approach was presented by Felder and Brent [135], who describe how the UbD approach can help engineering departments address the ABET EAC Engineering Criteria. An integrated engineering approach has been enthusiastically embraced in the Purdue Engineering Education Ph.D. program and by faculty in numerous national and international workshops facilitated by Ruth Streveler and Karl Smith [136]. This approach is gaining acceptance in engineering education for course and program design [137]–[139]. Duderstadt [140] claims, "It could well be that faculty members of the twenty-first century college or university will find it necessary to set aside their roles as teachers and instead become designers of learning experiences, processes, and environments."

E. Importance of a Broader Range of Knowledge, Skills, and Attributes

Evidence of increased emphasis on a broader range of knowledge, skills, and attributes (or habits of mind and modes of thinking) for engineering graduates abounds. Several studies—Boeing and RPI's The Global Engineer [141], NAE's Engineer of 2020 [23], Purdue Future Engineer [142], The 21st-Century Engineer [143], Engineering for a Changing World [140]—have begun to articulate the knowledge, skills, and habits of mind that are needed for students to perform satisfactorily in an interdependent world [144].

F. Scholarly Approach to Engineering Education through the Scholarship of Teaching and Learning (SoTL) and Engineering Education Research

Boyer's [70] report *Scholarship Reconsidered* dramatically expanded the language for conversations about scholarship in higher education. Boyer argued for expanding scholarship beyond discovery to include integration, application, and teaching. Hutching and Shulman [145] contrasted "teach as taught" with three levels on inquiry within education, and Streveler *et al.* [146] expanded on the list by adding a fourth level, engineering education research:

- teach as taught ("distal pedagogy");
- level 1: effective teacher;
- level 2: scholarly teacher;
- level 3: scholarship of teaching and learning (SoTL);
- level 4: engineering education research.

Borrego *et al.* [147] described these levels of inquiry in more detail.

Emergence of increased emphasis on a scholarly approach to engineering education is indicated by numerous developments, including the ASEE Year of Dialogue, the National Academy of Engineering's Center for the Advancement of Engineering Education and especially the Annals of Research on Engineering Education [148], the rigorous research in engineering education project [146], [147], [149], the repositioning of the *Journal of Engineering Education* "to serve as an archival record of scholarly research in engineering education" [150], the global emphasis on engineering education research [151], and the heavy emphasis in the NAE (2005) report on the use of research to convince faculty to change their teaching methods. Building on these initiatives, two ASEE reports have attempted to address a core question: "How can we create an environment in which many exciting, engaging, and empowering engineering educational innovations can flourish and make a significant difference in educating future engineers?" [152], [153].

G. Summary

Although there is agreement on many educational research-based aspects of engineering education, we need to be mindful that panaceas do not exist. Mastery, inquiry, and student engagement are good ideas, but educators have a tendency to take good ideas and try to universalize them [154], [155]. The push to extremes of mastery and inquiry almost destroyed these good ideas, and many have similar worries currently about student engagement. Bruner argued for making inquiry an integral part, but not the sole part, of a student's education [156].

In a new challenge, Boyer [157] encouraged all of us to make connections across all forms of scholarship by embracing the scholarship of engagement, writing, "The scholarship of engagement means connecting the rich resources of the university to our most pressing social, civic and ethical problems, to our children, to our schools, to our teachers and to our cities."

Finally, Ramaley argues that we also need to bring a scholarly approach to change:

"Achieving transformational change is a scholarly challenge best dealt with by practicing public scholarship, which is modeled by the leader and encouraged in other members of the campus community. Like all good scholarly work, good decision making by campus leadership begins with a base of scholarly knowledge generated and validated by higher education researchers" [158, p. 75].

VI. FIFTH MAJOR SHIFT: INFLUENCE OF INFORMATION, COMMUNICATION, AND COMPUTATIONAL TECHNOLOGIES (ICCT) ON ENGINEERING EDUCATION

Starting with the second issue of the *IRE Transactions on Education*, electrical and computer engineers have emphasized application of information, communication, and computational technologies (ICCT) in engineering education. In a surprisingly accurate futuristic 1958 article, Ramo [7] described a future educational enterprise that heavily used unspecified machines for routine teaching. His statement, "The whole objective . . . is to raise the teacher to a higher level . . ., and remove from his [sic] duties that kind of effort which does not use the teacher's skill to the fullest," is echoed by many current papers. Ramo also essentially predicted the rise of engineering education as a separate discipline, "There is probably a new profession known as 'teaching engineer,' that kind of engineering which is concerned with the educational process and with the design of the machines, as well as the design of the material." Perhaps because he was not an academic, Ramo underestimated the time required for these changes. In addition to their positive aspects, potentially disruptive aspects of ICCT are delineated by Cheville [4].

Some of the principal instructional technologies and their applications have been:

- content delivery: television, videotape, and the Internet;
- programmed instruction: individualized student feedback;
- personal response systems ("clickers");
- computational technologies;
- intelligent tutors: second phase of individualized student feedback;
- simulations;
- games and competitions;
- remote laboratories;
- grading.

MIT has offered one of their visions for classrooms that support combinations of a subset of these technologies through their Technology Enhanced Active Learning (TEAL) [100], which incorporates collaborative learning, networked laptops to desktop experiments that students perform and analyze, and media-rich software for visualization (see Fig. 3). In teaching electromagnetics, MIT faculty members have provided visualization materials in five categories: vector fields, electrostatics, magnetostatics, Faraday's law, and light.

Fig. 3. ***TEAL classroom for teaching electromagnetics at MIT.***

A. Content Delivery: Television, Videotape, and the Internet

In the 1950s, 1960s, and 1970s, many educators thought that television and videotape were the instructional method of the future [7], [159]–[161]. Television and videotape did prove very useful in distance education as a method for distributing content. Controlled experiments at Stanford University showed no significant difference in student learning between students in a live classroom and students taught by a tutored videotape method [161]. After the Internet became ubiquitous, distance learning was redefined to be online learning, most often through content delivery, and studies showed "no significant differences in learning outcomes for online and on-campus students as measured by test scores" [162]. Internet delivery can also include intelligent tutoring systems and remote laboratories—both of which are discussed later.

B. Programmed Instruction: Individual Student Feedback

Initially, technological methods were used solely for content delivery. Probably the first paper in an engineering education journal with data on providing individual student feedback with a teaching machine was a reprint [163] of a paper from *Science* by famed psychologist B. F. Skinner [164]. Skinner noted "[t]he machine itself, of course, does not teach. It simply brings the student into contact with the person who composed the material it presents. It is a laborsaving device because it can bring one programmer into contact with an indefinite number of students. This may suggest mass production, but the effect upon each student is surprisingly like that of a private tutor." Two years later engineering applications included programmed learning of Kirchhoff's laws [165] and development of the PLATO teaching machine [166]. It was quickly understood that immediate, individual feedback to students was the main reason for the effectiveness of the method [165]. However, as Dunn notes, "Used alone [programmed instruction], students could and did learn the Fortran language, but the course was somewhat stale and motivation was lacking for some students" [167]. As long as the student got everything right, these tutors worked quite smoothly [168]. The approach was objectivist, and there was no individualization of the responses.

C. Personal Response Systems ("Clickers")

Personal response systems (colloquially known as "clickers") have rapidly become quite popular on campuses [169]–[172], including in engineering [173]–[175]. Clickers provide immediate feedback in lecture, help keep students from being overly passive, and are easy to incorporate in a lecture. Properly used with appropriate questions and required student peer instruction, clickers help students understand what they do not know [175] and result in increased student learning [176]. Unfortunately, clickers, like any other tool, can be misused—for example, by exclusively using questions at the knowledge level of Bloom's taxonomy. Beatty *et al.* offer guidelines for creating effective questions [177]. Another advantage of clickers is that they lower the resistance of traditional teachers in transforming to a more student-oriented pedagogy [169].

D. Computational Technologies

It is easy to forget that the electronic calculator, introduced in 1972, had a major effect on engineering education since it allowed students to solve realistic problems within time-constrained classroom settings that were almost impossible with a slide rule [178]. Today, the computational power that can be provided in a device about the size of a calculator is impressive: graphing, equation solving, and symbolic manipulation are some of the capabilities available in a handheld device. However, debates continue over which and how much computational power (and memory) students should be allowed to use, especially in testing situations. The Fundamentals of Engineering (FE) examination places strict limits on the computational devices students can use. Mathematics courses in many institutions do not permit students to use calculators during examinations. Questions about what students will be asked to do and what can be off-loaded onto computational technologies continue to be debated.

Personal computers (PCs), on the other hand, had a slower rate of penetration and less early impact than expected [179], perhaps because they were an order of magnitude more expensive than calculators. Shifting PC ownership to students made them an ordinary cost of education that could be paid for by student loans or scholarships. This innovation plus the reduced cost of PCs eventually increased the impact of PCs in engineering education. Spreadsheets [180]–[182] and equation solving programs such as MATLAB [183]–[185] are probably the most common uses of the computer in engineering education. Currently, tablet PCs with interactive software [186] and tablets are being tried as waves of the future.

E. Intelligent tutors: Second Phase of Individualized Student Feedback

Through the 1960s and 1970s, programmed instruction and teaching machines slowly became more sophisticated and reflected a constructivist approach to student learning. "The questioning program must be capable of adjusting itself to the particular needs and problems of each user," wrote Bestougeff *et al.* [187]. These programs are known as intelligent tutor systems (ITS) or computer-aided instruction (CAI) or computer-aided learning (CAL). Antao *et al.* [188] developed a program to teach simulation (e.g., with SPICE) that monitors student learning and reconfigured the order of presentation based on the student's answers. An extension of this idea was to have students take the Index of Learning Styles [189] and use this information to make the ITS adaptive [190]. To prevent students from passively turning the electronic pages and not trying the exercises, tutors may require a correct answer before allowing the student to move forward [191].

Immediate feedback and explanations for incorrect answers can help students learn. Tutoring is effective—an untrained human tutor can produce about 0.4 sigma increase in learning [192] while a trained human tutor can produce about 2 sigma increase. A typical ITS can produce about 1 sigma increase and in some cases with natural language dialog built into the tutor up to 1.5 sigma [192]. If time is available, students will repeat the tutor to obtain mastery [193]. ITSs that provide hints are more effective than systems that do not, and a comparison of a hinting ITS with professors providing hints found no significant difference [194]. Initial development of ITS was slow partially because the estimated construction time without dialog was about 100 hours per hour of instruction [168]. Currently, development time has been reduced since developers can use authoring tools such as Authorware [195] or platforms such as AutoTutor [192]. The experimental evidence is clear that CAI increases student learning. However, this is true only if students use the computer, and many students will not unless strongly encouraged to do so [196]. Despite their advantages, ITS systems do not appear to be widely used in engineering education [197].

F. Simulations

Simulations have proved to be very useful in both engineering practice and in engineering education. Simulators can be public domain programs such as SPICE [198], [199], homegrown programs [200], or commercial products such as Aspen Plus, which is widely used as a process simulator in chemical engineering [201]. Simulation, which can be considered a third way to obtain knowledge along with theory and experimentation, has become ubiquitous in engineering education. Simulation has the advantage of being an active learning method that is easily coupled with intelligent tutoring programs. Real effects such as measurement errors and stiction can be programmed into simulations [202], but simulations do not replace the need for experiments. Combining simulation (aka virtual laboratories) with real laboratories provides benefits to both. "Analyses of metacognitive statements of students show enhanced awareness of experimental design, greater references to critical thinking and higher order cognition in the virtual laboratory and an enhanced awareness of laboratory protocol in the physical laboratories" [203]. A rigorous study of the effect of 3-D simulations showed that the simulations benefited male students more than female students, and international students struggled perhaps due to language or IT difficulties [204]. Because practicing engineers use simulations and because simulations are considerably less expensive than adding laboratories, they are widely used in engineering education.

G. Games and Competitions

Educational games are similar to simulations except that games have goals [205]. A review of the few available studies shows that video games can satisfy many of the requirements necessary for learning, such as increased time on task, and result in more learning than occurs in lectures [205]. Honey and Hilton [206] noted that while simulations and games have great potential for learning science particularly through inquiry, the research literature on the effectiveness of simulations and games is very limited. They recommended an extended research program on learning from simulations and games.

Although cooperative learning is an extremely effective learning strategy, competitions are also effective motivators, particularly when cooperative teams compete. An early software game was the "software hut game," which asked student groups to develop software and improve another team's software [207]. If the contest ties into the students' competitiveness and they believe they have the chance to win, students will work extremely hard [49]. Other programming competitions have also been developed [208]–[210]. Various robotic contests have proven to be excellent vehicles for involving high school and college students [211]–[215].

H. Remote Laboratories

Remote laboratories, a method that can at least partially replace live experimentation, was first developed by Aktan *et al.* [216]. In a remote laboratory students use a computer to control an actual experiment that is in a different physical space. Students can use a remote-controlled camera to observe the experiment and direct modifications [183]. Remote labs can easily be used with other tools such as SPICE and MATLAB [184]. Remote laboratories allow institutions to share expensive equipment, and equipment downtime is reduced. Since many industrial facilities are controlled remotely, use of remote laboratories provides students with experiences that can transfer to work settings. Remote experiments are used in addition to hands-on experimentation and demonstrations in Slovenia in high schools and universities [217]. A very recent modification of remote labs is augmented reality, which combines real content with computer integrated virtual content [218]. Since remote and in-person labs are not fully fungible [219], it is doubtful remote labs will fully replace in-person labs, even though remote labs can be more cost effective. Although remote labs are not yet common in engineering education, their economic advantages will probably lead to increased use.

I. Grading

A number of other ICCT applications may be useful for specialized educational functions. Because grading is one of the most tedious activities of faculty, automation of grading was first studied with punch cards [220]. Also, in some ways grading is a natural extension of intelligent tutors that provide feedback. Tutors provide formative assessment, while programs that score or grade student work provide summative assessment. Later computer software for automatic generation and grading of different multiple choice tests to avoid cheating in large classes was developed [221]. Similar methods are used in intelligent tutoring systems to generate assessment questions. Spreadsheets are commonly used for keeping grade records [180]. Cheating in the form of plagiarism can be detected automatically in papers [222] (now available in commercial systems such as Turnitin and iThenticate) and in code [223]. The thought process students go through when committing plagiarism is discussed in a thoughtful paper [224].

VII. CONCLUSION

As illustrated in both the first and third major shifts, there are continuing healthy debates about goals for undergraduate engineering education, e.g., how important are design skills, how important are analytical and modeling skills, how important are professional skills, especially in comparison to content of a particular engineering discipline. In addition to debates about content for engineering programs, there are continuing healthy debates about how to achieve these goals. For example, engineering education journals, conferences, and reports have explored approaches to teaching engineering. Research on learning and teaching has developed new approaches (fourth major shift) for achieving goals established for engineering education. Research has shown that students learn more with methods such as cooperative learning, problem-based learning, and inquiry-based learning when compared to approaches that emphasize information delivery through presentation. Finally, the use of technologies to achieve educational goals is growing, but in most cases growth has been slower than expected. Growth is faster when the technology is inexpensive and easy to use (e.g., clickers) or is used extensively in industry (e.g., spreadsheets and simulators). ■

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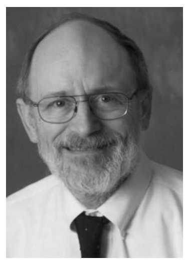

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