SPECIAL SECTION ON INNOVATIONS IN ELECTRICAL AND COMPUTER ENGINEERING EDUCATION

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The Expansive (Dis)Integration of Electrical Engineering Education

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ABSTRACT This paper examines the history of electrical engineering education, leveraging the concept of ''expansive (dis)integration'' to frame a number of key trends and challenges in the field. Our account is organized historically, starting with the origins and early development of electrical engineering education beginning in the late 1800s, and then tracing out the rise of new subfields and specialties during the inter-war and post-WWII periods. The development of computer engineering as a field is given special attention as a case study in disciplinary (dis)integration, while setting the stage for a discussion of broader trends associated with the rising influence of digital techniques and technologies across electrical engineering. The final sections of this paper report on some contemporary challenges and opportunities that may further transform the field in upcoming years and decades, with particular emphasis on issues of demographic diversity and perceptions of broader relevance and impact. The approach of this paper is largely historical, drawing on a wide variety of primary and secondary source materials. It is expected that this paper will be of interest to anyone who would like to know more about the historical development of electrical engineering education, including in relation to more contemporary currents in the field.

INDEX TERMS Computer engineering, education, electrical engineering, engineering education, history.

I. INTRODUCTION

MIT historian Rosalind Williams has persuasively argued that engineering has been undergoing a process of ''expansive disintegration'' [1, Ch. 2]. As examples, she more specifically points to recent historical trends like a dramatic rise in the number of engineers and other technical professionals, and proliferation of engineering fields and specialties, ''mutations and hybridizations'' [1, p. 34]. She also notes the expansion of ''engineering-like'' activities, and ponders the relevance of engineers as agents of technical innovation when society, technology, and the natural world seem ever more intertwined. Per Williams, ''What is disappearing is engineering as a coherent and independent profession that is defined by well-understood relationships with industrial and social organizations, with the material world, and with guiding principles such as functionality'' [1, p. 31].

While Williams' notion of expansive disintegration has resonance across engineering fields, one might wonder how these forces and dynamics have played out historically, as well as in specific disciplines and contexts. In this essay we creatively borrow Williams' concept to examine electrical engineering education. As described in more detail below, the idea of expansion is relatively straightforward, reflected in the field's growth over the span of more than a century. Yet this growth has also been accompanied by competing forces of integration and disintegration. Integration refers to processes by which new areas or domains of activity are brought into the fold of a larger field or discipline, including through the naming of new research areas, curricula, degree programs, etc. Disintegration, by contrast, should not be understood as dissolution, but rather as a process of subdivision, fragmentation, or pulling apart. Two more specific types of (dis)integration dynamics are emphasized in this paper. The first, ''horizontal'' is concerned with the rise of new subfields and specialties. A second type, ''vertical'', involves new divisions of technical labor and expanding layers of abstraction in the midst of ever more complex technologies and systems.

The paper is organized historically, beginning with the origins and early development of electrical engineering education, and then tracing out the rise of new subfields and specialties during both the inter-war and post-war periods. The development of computer engineering as a field is given special attention as a case study in disciplinary (dis)integration, while also setting the stage for a discussion of some broader trends associated with the rising influence of digital techniques and technologies across electrical engineering. The final sections of the paper report on a variety of contemporary challenges and opportunities that may further transform the field in coming years and decades.

The approach for this paper is largely historical, drawing on a wide variety of primary and secondary source materials. The paper owes a particular debt to a number of previous historical accounts cited below that have sketched out many aspects of the story recounted here. It is further worth noting that the scope of this paper is limited to the U.S. context, as this keeps the account more manageable while enabling the authors to leverage their first- and second-hand experiences of the themes and trends described herein. It is expected that this paper will be of interest to anyone who would like to know more about the history of electrical engineering education. This paper may additionally help university faculty and administrators, as well as industry representatives and other stakeholders, reflect on how deeper historical forces and dynamics may inflect contemporary efforts to reimagine how electrical and computer engineers are educated.

II. DISCIPLINARY ORIGINS OF ELECTRICAL ENGINEERING

During the latter decades of the 19th century, formal university training in the fields of civil and mechanical engineering, and to a lesser extent military, mining and metallurgical engineering, were increasingly well-established in the United States. Spurred by both the Morrill Land Grant Act of 1862 and a broader shift in the profession from ''shop culture'' to ''school culture'' [2], the number of schools offering formal training in engineering jumped from just 17 in 1870 to 85 in 1880 [3, p. 6]. The formation of so many new pathways for training in engineering in turn created conditions amenable for the formal establishment of new engineering fields in response to broader developments and trends. As Lundgreen more specifically argues, the initial emergence of electrical engineering as a field stands as ''*the* case . . . of a linkage, both in time and in kind, between industrial and scientific developments'' [4, p. 58]. As compared to the older branches of engineering, electrical engineers often needed more advanced training in science and math to work with new technologies like alternating current [5, p. 115].

Hence, the question of the time was how the newly emerging areas of engineering, science, and technology fit within the existing landscape of academic disciplines. The initial development of degree programs in electrical engineering suggested at least three different ways of positioning the new field. The potential for a closer alliance with science was evident by at least 1882, when MIT became one of the first schools to offer formal instruction in electrical engineering under the aegis of the Physics Department and described in the catalog as an ''alternative course of physics'' [6, p. 1401]. While the program was renamed ''electrical engineering'' in 1884, it remained in Physics. Early moves to establish an electrical engineering program at the University of Wisconsin in the early 1890s raised similar questions about its preferred location in physics or engineering [6, p. 1401]. Terman more generally noted that many of the early electrical engineering department heads were actually physicists [7, p. 739], while Rosenberg and Nelson similarly describe how ''physicists dominated the intellectual leadership in the new field'' [8, p. 327].

A second possible location for the field involved affiliation with mechanical engineering. At Cornell, for instance, a course in electrical engineering was approved in 1883 as a division of mechanical engineering [9]. As one commentator later described it, the school taught electrical engineering as ''an application of mechanics, the only difference from other branches of mechanical engineering being in the source of the forces and the methods of transferring and transforming energy'' [9, p. 1072]. Taking this philosophy to heart, Cornell required the same coursework for students during their first three years of study regardless of whether they were in mechanical or electrical engineering, allowing them to specialize only in their fourth year [9, pp. 1071–1072].

Independent departments of electrical engineering were a third – and ultimately dominant – pattern of development, including at the University of Missouri in 1886, Purdue University in 1888, and Columbia University in 1889 [6], [10], [11]. A small department was also established at Stanford in 1892-3, reversing the previous year's recommendation that students with interests in electrical engineering should enroll in mechanical engineering [6]. MIT ultimately followed suit in 1902 with the formation of a separate Department of Electrical Engineering [6], while Cornell's School of Electrical Engineering finally gained its full independence in 1921 [12].

These early developments at specific schools also reflected broader patterns of growth. As Terman notes, by the 1890s electrical engineering enrollments at many schools were already equal to or exceeding enrollments in mechanical or civil engineering [6, p. 1401]. And according to a 1917 survey, a total of 74 American colleges had four-year degrees in electrical engineering [13]. In light of the preceding history, most of these were offered by independent departments *of engineering*, thereby cementing the field's position in the academy generally and in engineering more specifically.

This same 1917 survey also shed light on the type of education that was on offer at the time. Among the surveyed schools, an average of more than 50% of the curriculum was being dedicated to studies in electrical engineering (21.6%) and general engineering (31.1%) [13]. Terman later noted an early lack of courses and equipment specifically focused on electrical engineering, but over time the typical program came to focus on ''dc and ac circuits, on the characteristics of motors, generators, transformers, distribution systems, etc., and on the measurement of electrical quantities'' [6, p. 1401]. Period commentaries reveal particular emphasis on educating students in ''the design, manufacture and selection of [electrical] machinery'' [14, p. 478], and typically with a more "practical" than theoretical orientation so as to better meet the needs of firms hiring most of the graduates.

III. FROM POWER TO COMMUNICATIONS AND ELECTRONICS, SCIENCE AND GRADUATE STUDIES

As the preceding overview suggests, the origins and early growth of electrical engineering as an academic discipline were strongly aligned with the power industry and related technologies of the late 1800s. This orientation served the field well into the early 1900s, but the emerging area of radio communication raised a first challenge to the field's monolithic identity and focus. In fact, the 1912 founding of the Institute of Radio Engineers (IRE) was not only a rebuke to the older and more power–industry-oriented American Institute of Electrical Engineers (AIEE), but suggested a more general disintegration of the field into two partially distinct areas [15].

The historical record suggests that colleges and universities responded slowly to this bifurcation, with one commentator retrospectively referring to 1900-1930 as "stagnant years" [16]. Yet as Terman notes, courses and curricula featuring terms like "communications" and "radio" and strongly oriented toward electronics finally started to proliferate in the 1920s [7, p. 740]. As such offerings evolved and expanded during the inter-war period, some schools reacted by formalizing two curricular options for students, one in the "power" area and another focused on "communications" and later "electronics" [17], [18]. As Kline reports, more than 40 programs had multiple curricular options by the mid-1950s [19, p. 20]. This pattern helped buffer the discipline of electrical engineering from broader forces of fragmentation, preserving its disciplinary integrity. As still a further twist, many writings from the immediate post-WWII period noted the relative decline of power as an area of activity, leading one commentator to frame 1925-1950 as a period defined by the "ascendency of the circuit" [17, p. 582]. In fact, the historical record suggests that by the early 1950s about twice as many students were specializing in electronics as compared to those in the power area [19, p. 20].

The long-term vitality and integrity of the field also benefitted from three intertwined trends that took root during the inter-war period. The first of these was graduate education. As documented by Terman, considerable growth in the number of Master's degrees awarded in electrical engineering occurred during the inter-war years, spurred by the increasing complexity of devices such as the vacuum tube, and concomitant with a broader expansion of graduate education in general, and especially so in engineering and the sciences [6], [20]. Growth in Doctoral-level training was also evident around this time, particularly at schools like Cal Tech and MIT in the 1930s, but greatly expanded in the post-WWII period [6]. As a consequence, faculty in electrical engineering were increasingly expected to have graduate-level training, and graduate courses often served as incubators for new topics that were later introduced in undergraduate courses [19].

A second and closely related trend involved a turn toward science, particularly from the 1930s to 1960s [5]. While this change had broad impacts across engineering fields, the historical orientation of electrical engineering toward math and science placed the field on the front lines of this change. In fact, Kline documented gradual increases in science and math courses in electrical engineering curricula, as well as technical electives, from the 1910s to 1950s [19]. By the 1950s, renowned electrical engineer and Stanford administrator Frederick Terman was particularly outspoken about the need for greater emphasis on the "basic sciences" and "fundamental engineering principles" in the undergraduate electrical engineering curriculum [7], [21]. He went so far as to argue that without such a turn, electrical engineering might be forced to cede the field's most interesting and creative work to "Colleges of Applied Science" [7, p. 739]. His perspective was informed by a deep knowledge of period technologies, coupled with frustrations regarding the ascendency of physicists over engineers in the context of war-time research [5].

Terman's position was also potently validated by a 1955 report sponsored by the American Society for Engineering Education that called for more basic science and engineering science in the engineering curriculum [22]. And as documented by Seely, a 1965 follow-up report published by ASEE revealed that engineering science had moved solidly to the center of the curriculum [5]. Looking more specifically at electrical engineering education, this meant a revival of the field's historical relationship with physics, including in areas like electromagnetic theory, as well as nuclear, atomic, quantum, and solid-state physics [7], [23]. Later commentaries suggested that the post-war swing of the curricular reform pendulum had gone too far, with one University of Michigan professor arguing in 1968 that the typical electrical engineering curriculum had become "a virtual maze of mathematics and theory" [24, p. 79].

The rising qualifications of electrical engineering faculty coupled with a turn toward the sciences were synergistic with a third trend, namely growth in academic research. Describing his own study of the literature, Terman noted that few research publications emanated from electrical engineering departments in the 1920s, and those that did came from a handful of institutions [6]. Yet during the post-war period, electrical engineering educators dramatically increased their research activity, including by piggybacking on innovations from war-time R&D efforts and leveraging major increases in government support for university research [19].

By the 1950s it was also apparent that electrical engineering education was facing unprecedented growth in new specializations and subfields. Terman was largely positive about this trend, suggesting a "basic core" for the undergraduate curriculum paired with specialization in one or two more specific areas [21, p. 941]. He also acknowledged that a 5-year degree program could help relieve some of the curricular pressures being felt in many departments. Yet other commentators were not so optimistic. MIT electrical engineer Gordon. S. Brown, for example, went so far as to posit that educators were facing a problem of "unmanageable specialization", citing as evidence an NSF report that had identified 31 distinct categories of electrical engineering work [18, p. 111]. He went on to describe a solution that was being implemented at MIT which involved a curriculum organized around two partially distinct "stems", one in "energy conversion" and a second in "information processing." The contrasting curricular approaches described by Terman (core plus elective) and Brown (options, stems, or tracks) became widespread in electrical engineering, although by 1972 Van Valkenburg claimed that the former was more prevalent [25]. By the 1960s and 1970s it was also not clear whether these curricular models could accommodate the rapid and ongoing proliferation of technical specialties in the field.

IV. COMPUTER ENGINEERING: A CASE STUDY IN DISCIPLINARY (DIS)INTEGRATION

If one domain of electrical technology exemplifies how the field of electrical engineering has reckoned with powerful and conflicting forces of (dis)integration, computing is arguably a leading candidate. Buoyed by large war-time R&D investments made by the U.S. government, in the mid- and late-1940s about a half dozen universities were leading the design and development of the first electronic, high-speed, digital computers [26], [27]. Nonetheless, the role of electrical engineers varied considerably from site to site [28, Ch. 2]. They were more prominent at the University of Pennsylvania and MIT, for example, but less so at Harvard and Princeton. Additionally, Akera argues that a hierarchy of prestige was established during this period such that "the applied mathematicians who aided the physicists in their wartime work first garnered the highest authority with respect to computing research" [29, p. 336].

These kinds of hierarchies are precisely what had so vexed commentators like Terman, leading him to call for a turn toward science and intensified technical innovation by electrical engineering departments and faculties. One of Terman's 1956 commentaries on the state of electrical engineering education also acknowledged the expanding role of electrical engineers in the development of computing devices, as well as the increasing utility of computers in tackling computationally-intense engineering problems [21]. But like many other commentators from this period, Terman likely underestimated the full potential of computing as a disruptor of disciplinary boundaries.

The same cannot be said of Lotfi Zadeh, who later gained fame for his foundational work in the area of fuzzy logic and his leadership at UC-Berkeley. In 1950, shortly after completing his Ph.D. at Columbia University, Zadeh contributed a short paper to the *Columbia Engineering Journal* titled "Thinking Machines: A New Field in Electrical Engineering" [30]. Much of the paper was dedicated to introducing readers to the emerging field of "cybernetics" and describing how computing technologies were enabling the creation of so-called "thinking machines." Yet the paper ended on a cautionary note as Zadeh pointed out that "thinking machines . . . are the brain children of mathematicians and not of electrical engineers" [30, p. 31]. As he went on to argue, "[t]his situation will last until electrical engineers become more proficient in those fields of mathematics which form the theoretical basis for the design of thinking machines" [30, p. 31]. He added that electrical engineers were playing leading roles in the physical realization of such machines, and pointed to symbolic logic as a key area of theoretical expertise.

As Zadeh suggested, electrical engineering might bring computer development under its purview by linking knowledge of electronic devices and systems with more robust mathematical foundations. Indeed, pioneering groups at the University of Pennsylvania and MIT had earlier demonstrated how such a confluence could lead to breakthrough innovations in electronic digital computing. And while the historical record suggests that Zadeh's editorial was not very influential, it was one of the earliest commentaries to hint at the manifold challenges and opportunities that computing posed for electrical engineering. As discussed in more detail below, the paper was also the first of Zadeh's many attempts to envision and realize a strategic integration of computing and electrical engineering.

By the early 1950s, the term "computer engineering" was also coined and came into widespread use, with period commentaries explicitly linking the emerging field to "hardware" or the "physical components of which computers are made" [31]. A subgroup of the IRE was formed in 1951 to focus primarily on this growing field of activity, with significant gains in membership through the 1950s as the locus of computer design and development shifted from universities to the rapidly developing computing industry. As discussed in more detail elsewhere, the formation and development of the Association for Computing Machinery (ACM) from 1947 onward served as the main counterpart society for professionals concerned with "what computers do", including programming and applications [28, Ch. 3].

The historical record additionally reveals that electrical engineering departments responded slowly but incrementally to these larger trends. For instance, a 1955 survey identified courses on analog or digital computing offered by 22 electrical engineering, 10 mathematics, and 8 other departments [32]. While these courses covered the full gamut of computer design, operation, and use, the same survey identified about a dozen electrical engineering departments that were offering courses more specifically focused on digital computer design and related topics [33].

The proceedings of a 1955 conference on training personnel for the computing field suggested at least three reasons for why there was not greater demand for courses and curricula focused on computer design and development. The first of these was suggested by an IBM employee who noted a lack of openings for such experts, and particularly so as new hires [34]. A second reason centered on the notion that the more general kind of training found in most electrical engineering programs provided adequate preparation for entry into the computing field. As another commentator declared: "The engineering of design, servicing, and testing an electronic machine is too specialized to be a typical topic for the candidate for a degree of Bachelor of Science in Engineering" [35, p. 41]. Third and finally, there was growing sentiment around this time that innovations in computer design and performance were outpacing progress in programming and applications, thereby limiting the need for computer design talent [28, pp. 146-147].

By the late 1950s and into the 1960s the number of computer systems installed nationwide (and worldwide) was increasing rapidly, accompanied by rising demand for computer-oriented workers of all types. As historian Paul Ceruzzi writes, during this period "it was also recognized that many topics that had much in common with each other (and all in common with the computer) were being taught in various departments around most universities" [36, p. 266]. Recognizing and responding to these trends, a number of forward-looking individuals proposed the establishment of a new discipline or even "supradiscipline" of computing with names like the "communication sciences" [37], "computer science(s)" [38], and "computer and information sciences" [39]. As such titles suggest, these writers were strategic in proposing a "scientific" mantle for the new field, and one can also find in their accounts efforts to portray the new field as primarily oriented toward theory, mathematics, and computer programming.

Gorn's remarks in particular reflected growing passion among advocates for the new discipline. Framing the field's initial "gestation" in mathematics and engineering as a historical "accident", he suggested that maintaining such disciplinary affiliations would limit the field's development [39, p. 155]. As a mathematician in the University of Pennsylvania's Moore School of Electrical Engineering, Gorn faced an uphill battle realizing this discipline-building project in his own institution. Yet like-minded colleagues at other institutions fared somewhat better. In fact, one report identified 143 undergraduate and graduate degree programs in computer science and related areas by 1964-5, with 58 (or more than 40%) specifically dedicated to computer science or communication science, and often located in departments of the same name [40]. By contrast, departments of mathematics and electrical engineering oversaw roughly one-third of the surveyed programs, respectively claiming 17% (24 of 143) and 13% (19 of 143) of the total.

From its 1962 formation onward, the ACM's Curriculum Committee on Computer Science (C3S) provided computer science degree programs and departments with additional credibility and support, including through publication of both the group's preliminary recommendations in 1965 and its influential *Curriculum 68* report. The latter was organized around three main subject areas: information structures and processes, information processing and systems, and methodologies [41], [42]. Such activities suggested adequate justification for a claim made at a 1967 conference, namely that there was growing consensus around the idea of computer science as a "separate academic discipline" [43].

In parallel with the initial development of computer science, discussions around the place of computing in engineering continued to simmer. For example, a 1957 conference paper by University of Wisconsin faculty member Vincent Rideout represented one of the earliest discussions of "computer engineering curriculums" [44]. The author more specifically argued that electrical engineering departments were especially well-suited to train the "'triple-threat' men [sic] so eagerly desired in industry today – men who are soundly versed in mechanics, in electronics, and in computing" [44, p. 156]. A 1960 special issue of the *Journal of Engineering Education* on the topic of "Computers in Engineering Education" followed in much the same vein. Papers contributed by engineering faculty from MIT, the University of Pennsylvania, and the University of Michigan framed engineering as an obvious locus of activity for all phases of computing, with Michigan's Norman Scott going so far as to present a number of topics and subjects appropriate for graduate-level study in "computer design and engineering" [45]. And in 1963, a lengthy overview paper on the topic of "Computer Education" identified two flavors of curricula then under development, one focused on the "engineering design of computers" and the other on the "utilization of computers" [46, p. 142]. As evidence of activity in the former area, this same paper referenced 14 textbooks related to computer engineering, logic, and system design.

As the 1960s wore on, the continued growth of computer science and increasing recognition of its disciplinary status started to attract more notice from leading figures in electrical engineering education. In fact, it was none other than Lotfi Zadeh who helped spearhead a first wave of mobilization. Zadeh's commentaries from the period stressed two key points [47], [48]. First, he saw a strong affinity between electrical engineering and computer science. And while acknowledging that others felt the same about mathematics and computer science, Zadeh underscored his own position by citing an unpublished Bell Labs memo that framed engineering and computing as a "holy alliance" and argued for a "philosophy" of computing that was rooted in engineering rather than science [48]. Second, Zadeh built on this claim to advocate for the establishment of computer science options in electrical engineering departments, as well as the renaming of such departments to underscore the union of "electronics and information processing" [47].

Zadeh's efforts during this period also went well beyond his writings. Having taken over as chair of Berkeley's Department of Electrical Engineering in 1963, Zadeh was instrumental in two key reforms. First, 1964 saw the establishment of Computer Science as one of four undergraduate degree options in the department, along with: Electronics, Fields, and Plasmas; Systems, Information, and Control; and General Electrical Engineering [49]. And second, Zadeh's own unit was renamed the Department of Electrical Engineering and Computer Science in 1965 [50].

But perhaps even more significantly, Zadeh teamed up with University of Illinois electrical engineer Mac Van Valkenburg to organize a 1965 meeting of electrical engineering heads at Berkeley, in turn seeding formation of the Computer Sciences in Electrical Engineering (or COSINE) committee [51]. Active from 1965-1972, the group held numerous meetings and workshops, conducted site visits, and published 11 reports [28, Ch. 5]. As suggested by both the group's name and an inaugural report with a similar title [52], [53], the committee's early agenda was well-aligned with Zadeh's views on bringing the computer sciences ''within the fold'' of electrical engineering. In fact, much of their first report was dedicated to proposing specific coursework and sample curricula for computer science programs in electrical engineering, albeit with a stronger orientation toward hardware and systems as compared to ACM recommendations for computer science curricula. It is also worth noting the group's calls to more generally emphasize ''discrete systems'' throughout electrical engineering curricula [53].

Yet evidence of an important shift in the group's orientation soon surfaced. One notable harbinger of change can be found in the proceedings of a 1968 COSINE meeting that included a talk by Clarence Coates, at the time a University of Texas-Austin faculty member who later went on to lead Purdue's School of Electrical Engineering. Central to Coates' remarks was a passionate plea for ''University Education in Computer Engineering'' [54]. As Coates opined: ''Where we have failed is to recognize that computer science education and computer engineering education are *not* the same and that there is a need for both'' [54, p. 10]. In addition to noting a lack of attention to hardware and the hardware-software interface in computer science education, he advocated for computer engineering options in electrical engineering with an emphasis on control systems, information and communication theory, logic design and switching theory, machine organization, and programming. Coates argued that to make room for such topics, computer engineering students likely did not need exposure to the ''power area'' and he also advocated for less coverage of traditional staples like electromagnetic theory, network theory, electron materials and devices, and electronic circuits. ''I am not now suggesting that the electronics epoch is ending'' Coates concluded, ''although this may be true'' [54, pp. 7, 10]. Such ideas received further attention in a workshop at the same conference titled ''Computer Engineering Rather than Computer Science'' [55, p. 19].

This turn in the direction of the committee culminated in the efforts of a task force under Coates' leadership that ultimately produced a report titled *An Undergraduate Computer Engineering Option for Electrical Engineering* [56], [57]. Noting a more general turn toward discrete signals in the field of electrical engineering, the group offered a succinct definition of computer engineering, framing it as that part of electrical engineering responsible for ''the organization, design, and utilization of digital processing systems as general purpose computers or as components of systems concerned with communication, control, measurement, or signal processing'' [57, p. 855]. These reports also carefully distinguished computer engineering from computer science, and offered detailed course descriptions and extensive curricular recommendations in the computer engineering area.

Yet even as the task force started to publish their work, their proposal looked something like a *fait accompli*. In fact, a 1971 paper reporting on the task force's recommendations included results from a survey showing that 87 of 203 electrical engineering departments were already offering an undergraduate option or program in computer engineering, with yet another 35 planning such offerings within the next year [57, p. 854]. New survey results published in 1973 indicated that more than half (or 54%) of 151 responding universities had computer science departments while almost half (or 49%) had computer engineering options, with the authors observing that real growth in the latter only started occurring after 1965 and pointing to 1968 as the average year of establishment [58, pp. 32–33]. Two additional trends reflect both the increasingly stable identity of computer engineering in the 1970s and its close alliance with electrical engineering. First, at least three departments had taken the name Electrical and Computer Engineering by the mid-1970s [59]. And second, accreditation of the first degree program formally named ''computer engineering'' occurred at Case Western Reserve University in 1971, and in 1978 the Engineers' Council for Professional Development (progenitor of ABET) approved specific guidelines for accrediting such programs [60], [61]. These developments helped firm up the two educational pathways that remain dominant in the field, namely computer engineering options attached to electrical engineering degrees and dedicated computer engineering degrees offered by, or affiliated with, electrical engineering departments.

In a 1971 paper Zadeh advocated for more flexibility in electrical engineering degree programs, arguing that a ''free curriculum . . . comes to grips with a basic fact of life, namely, that electrical engineering is no longer a unified field of study with a clearly definable single core; rather, it is an aggregation of subject areas'' [62, p. 154]. While the rise of computer engineering during this period served to affirm Zadeh's claim, the preceding historical account suggests that forces of disintegration had been impacting the field since at least the original schism between power and the new area of radio and electronics. What is notable about this story is the partial success achieved by electrical engineering in successfully claiming and integrating a large slice of the computing field. Embracing the ''computer engineering'' moniker proved advantageous given that it explicitly linked the field to engineering and distinguished it from computer science. In contrast with Zadeh's uphill battle to define ''computer science as a discipline'' and claim it as a part of electrical engineering [48], later COSINE reports simply framed computer engineering as a ''new dimension'' of electrical engineering [56]. This shift in terminology also brought the identity of university departments and degree programs into alignment with terms and titles (e.g., computer engineers/ing) that were already long dominant in the context of industry and professional societies [31].

The historical compromise worked out from the mid-1960s through mid-1970s cast long shadows over the academic landscape, extending all the way to the present. In fact, subsequent efforts to better integrate the field – including the "computer science and engineering" movement from the mid-1970s to mid-1980s and "computing as a discipline" in the late 1980s and early 1990s [28, Ch. 7] – ultimately led to relatively little change in the macro-level organization of academic disciplines and programs. More recent evidence for this historical momentum can be found in the splintering of the Computing Curricula 2001 initiative into separate efforts focused on four distinct fields of computing, including a report dedicated to computer engineering that features an entire chapter dedicated to distinguishing "computer engineering as a discipline" [63]. We return to these themes below.

V. DIGITAL (DIS)INTEGRATION IN EE EDUCATION

While the rise of computer engineering was itself a significant historical development, it was part and parcel of a much broader "digital revolution" that cut across electrical engineering. Although a host of factors and trends helped set the stage for this transformation, it is worth noting two in particular. First, war-time R&D on technologies such as radar led to exploration of many new techniques for generating and manipulating nonsinusoidal waveforms, including pulse and digital signals. This was a major departure from the sinusoidal waveforms long dominant in the field of radio electronics. A second key factor involved the invention, development, and commercialization of the transistor, especially from 1947 through the 1950s. The convergence and diffusion of these two trends, including in the context of university classrooms and labs, can in turn be traced to the 1956 publication of Millman and Taub's *Pulse and Digital Circuits* [64]. While the first draft of the book was primarily focused on techniques for designing the book's namesake circuits using conventional devices such as vacuum tubes, the publisher asked the authors to add a chapter focused on transistors, as well as a larger number of applied problems. Retrospective accounts have described the widespread influence of this text and its 1965 successor volume [65], both within and well beyond electrical engineering classrooms [66].

Even more generally, Kline has documented the post-war rise of courses and textbooks on radar, microwave, and related topics [19]. Yet these developments proved foundational for two broader (dis)integration trends in electrical engineering education and practice. The first such trend centers on the integration of digital technologies and techniques into a much wider range of courses and curricula. While this gradual revolution was initially most evident in graduate-level courses in areas such as circuits and computer design, undergraduate education was increasingly impacted in the 1960s. For example, period papers described development and implementation of courses and laboratories focused on digital circuits and logic [67], digital controls [68], and digital systems [67], [69], to name a few. The 1969 publication and rapid subsequent uptake of Gold and Rader's highly influential textbook *Digital Processing of Signals* [70] stands as another example of how the turn toward the digital was ushering in wide-ranging changes across the fields and subfields of electrical engineering.

As suggested by the preceding section, the COSINE committee was additionally a product of, and champion for, these broader transformations in the field. This was evident in the introduction to their first report, for example, which pointed to "the emergence of computer sciences as a highly important field of study, coupled with the growing shift in emphasis in information processing technology from the analog and the continuous to the digital and discrete" [52, p. 6]. A later commentary from the group declared that every electrical engineering student should be introduced to "logical design" and "digital information processing techniques" [55, p. 17], while another COSINE task force reporting on the "view from industry" went even further by arguing that graduates should have "equal familiarity" with digital and analog circuits [71, p. 1].

To further scaffold associated efforts to develop and reform curricula, other COSINE reports offered detailed recommendations for an undergraduate course and laboratory in the digital subsystems area [72], [73]. Surveys conducted in the committee's latter years provide still more evidence for the changes underway in the field. A 1971 report, for instance, indicated that the number of "digital faculty" in the "typical school" had increased from one in 1965-66 to three or four in 1972-73, with the total number of such faculty across all institutions doubling during this same period [58]. This same report also noted large gains in the number of electrical engineering students taking at least one digital course beyond introductory programming. While such trends were surely being felt unevenly across various subfields and local sites (e.g., departments), these findings suggested considerable momentum toward a more thoroughgoing integration of digital technologies and techniques in electrical engineering.

A second kind of (dis)integration trend evident during this period involved post-war changes in the organization of technology and technical expertise, especially in the electronics industry and related sectors. As the preceding account suggests, one notable example of these transformations can be found in the computer field's budding sociotechnical divisions of labor, with increasingly distinct educational and career pathways developing for hardware-oriented electrical (or computer) engineers and software-oriented computer scientists. Within the domain of electrical engineering one can find further evidence of how divisions of labor were proliferating in tandem with the creation of increasingly complex and multi-layered technological systems.

In the 1950s, multiple writers more specifically described how the design and development of computer systems and related equipment typically involved three groups of experts, one focused on circuit and component design, another on logical design, and still another on system design [74], [75].

A later report by Linvill et al. more generally discussed how integrated electronics were impacting electrical engineering education, similarly emphasizing four key domains of activity: 1) technology, with a focus on fundamental scientific, physical principles and techniques for device design, 2) device design, or packaging up discrete devices for economical sale, 3) circuit design, focused on combining circuit components to carry out specific functions, and 4) system design, or combining subsystems to create a larger, system for some specific purpose [76]. Summarizing results from a survey of industry representatives, this same report noted a number of key trends, including growing need for experts who could work and communicate across these four areas, excel in system design more specifically, and have greater awareness for the "social and economic" dimensions of their work. In terms of specific recommendations, the authors went on to suggest a revision of curricula to provide students with a broader base of technical knowledge, depth in a specific area of technical interest, awareness for system-level considerations, and exposure to state-of-the-art technologies, tools, and techniques. If "integrated electronics" was the main problem, the authors' solution seemed to call for nurturing a more "integrated" kind of technical expert.

The issues and recommendations outlined by Linvill et al. echo persistent tensions in electrical and other engineering fields about how to strike an appropriate balance in breadth versus depth of training, including in terms of both technical expertise and broader kinds of capabilities (e.g., developing professional skills). Yet the increasing complexity and pace of technical innovation during this period hinted at broader challenges. As the "hierarchies of design" continued to expand in computing and other high-technology industries, each specific level of technology and technical expertise (e.g., device, circuit, system) became increasingly opaque from the perspective of the other levels, conceptualized as abstractly as possible to allow coordination and interfacing across levels. While this type of abstraction and modularization enables the development of highly complex technological systems, it also has a number of potential implications. As Linvill et al. note, one such issue was a lack of engineers who could assume a system-level perspective regardless of their position in the hierarchy. A second issue centered on a growing gap between much engineering work and its ultimate application – including the "social and economic" dimensions noted above. Third and finally, these divisions of labor reflected and reinforced a rising trend that Williams has called "dematerialization", or a shift in the focus of engineering work from "matter" (actual physical devices and machines) to the manipulation of symbols, models, and code [1, p. 47]. Williams concludes that this turn toward the abstract and ephemeral creates a professional field with a "ghostly lightness of being" [1, p 47].

The efforts of the COSINE committee again offer a glimpse of how the field responded to these larger forces and dynamics. To begin, their 1971 recommendations for computer engineering degree programs highlighted the need for coursework covering a full hierarchy of design associated with "information processing systems", including exposure to devices and circuits, logical design and machine organization, and programming, with elective opportunities to gain depth in specific areas [57]. They also recommended coursework covering system programming and digital subsystem design, but fell short of calling for dedicated courses on system engineering, much less coursework covering broader societal issues or concerns. However, it is notable that the group's 1969 "view from industry" report called on educators to create "socio-technical courses …that stress the relationship between technology and the problems facing society" [71, p. 5]. Foreshadowing concerns that would only intensify in later years and decades, the group went on to argue that such courses could help address growing concerns among students about the "relevance" of their studies and the "moral and social consequences of their training" [71, p. 5]. Yet as suggested below, efforts to update the technical content of the curricula during the intervening decades have largely overshadowed moves to both create a sense of connectedness and engender awareness of broader social impacts among the field's students and professionals.

VI. CONTEMPORARY CRISES IN ELECTRICAL AND COMPUTER ENGINEERING EDUCATION

Questions about the lasting vitality and disciplinary integrity of electrical engineering education have periodically surfaced in recent decades. In 1984, for instance, a commentary appearing in *IEEE Spectrum* aptly summarized many of the key transformations that had swept through the field [77]. Describing how the job of the electrical engineer had become ever more "analytical and abstract", the paper pointed to trends such as the partitioning of circuit and semiconductor design work into ever-smaller pieces, and the rise of computer science and engineering as domains increasingly disconnected from the physical machinery of computing. And while the author said little about education reform beyond a need to balance fundamentals with the rapidly changing realities of professional practice, he ended the paper by pointing to a possible "restructuring of electrical engineering in ways that recognize the constant changes in the field" [77, p. 37]. Yet as the remainder of this section suggests, few steps have been taken toward a reorganization of this type, especially in terms of academic curricula or departmental structures.

Concerns were also raised in the early 1980s about stagnant growth in the number of electrical engineering graduates, particularly at the graduate level, as well as inadequate and outdated facilities, a shortage of faculty, and a lack of qualified personnel to fill job openings [78]–[80]. The field was also impacted by a downward trend in overall engineering enrollments during the latter half of 1980s [81]. And while the 1990s seemed to be a period of relative stability, a 2004 *IEEE Spectrum* article raised a new batch of concerns about "Electrical Engineering's Identity Crisis" [82]. Responding to the question of "When does a vast and vital profession becoming unrecognizable diffuse?'', Wallich pointed to a continued proliferation of new technical areas and hybridizations (e.g., quantum computing, bioengineering), longstanding tensions between generalist versus specialist approaches to training electrical engineers, and a growing sense of disconnect between the physical devices of electronics and computing, on one hand, and higher-order abstractions, simulation, and models, on the other. He also noted a 45% decline in the number of bachelor's degrees in electrical engineering between 1987 and 2001. Even more recently, the ECEDHA has undertaken a ''Vision, Branding and Advocacy'' initiative in response to growing concerns that even as electronic and computer technologies become more pervasive, the field of electrical and computer engineering seems less and less visible among students and the public [83].

With these commentaries and initiatives as a backdrop, it is worth reviewing some additional evidence regarding the field's contemporary state of (dis)integration. To begin, the unification of electrical and computer engineering looks like an enduring success. Today, more than 60% of nearly 240 U.S. departments belonging to the Electrical and Computer Engineering Department Heads Association (ECEDHA) have assumed the hybrid name ''Electrical and Computer Engineering'' [84]. Regarding undergraduate education specifically, current ABET accreditation requirements specify common criteria for ''Electrical, Computer, Communications, Telecommunication(s) and Similarly Named Engineering Programs'', and with only discrete mathematics listed as an additional requirement for computer programs [85]. Yet there is also considerable fragmentation in department organization. Examining the 17 departments responsible for the top 15 programs in the electrical/electronic/communications and computer engineering categories (as ranked by U.S. News and World Report) reveals anywhere from 3 to 31 distinct research areas listed on their respective web sites, with a median count of 10.

In terms of undergraduate student enrollments, Wallich's aforementioned comments about declining enrollments might initially appear overblown. In fact, 2015 saw the awarding of 19,695 degrees in electrical and/or computer engineering, or 18.5% of the 106,659 engineering degrees awarded that year [86]. This total was second only to mechanical engineering, which claimed 25,436 (or 23.8%) of graduates that year. One further finds that the number of electrical engineering graduates more specifically has remained fairly constant between 1999 and 2015 [87], [88]. Yet further interrogation of these numbers reflects a marked reversal of fortunes during a decade-long period of impressive overall gains in the number of engineering degrees awarded. Indeed, the field's high water mark occurred in 2004 with 21,038 undergraduate degrees awarded in electrical and/or computer engineering, representing 29% of that year's 72,893 engineering graduates [86]. By comparison, mechanical engineering only had 14,182 graduates that year, or 19.5% of the overall total [87].

These data point to yet another concern, namely a continued lack of demographic integration in the field. In terms of gender, the percent of women earning B.S. degrees in electrical engineering rose steadily from about 1% in the mid-1970s to 13% in 1987-88 [88], [89]. Since that time, however, the trend has been relatively flat, with a peak of 15.1% in 2003-04 and falling back down to 12.8% in 2014-15. To be sure, some of these trends can be linked to a migration of women toward other fields, including computing. Indeed, one finds that the number of women graduating with computer engineering and computer science degrees showed an even more promising early trend, rising from 8.1% in 1973 to a peak of 23.0% in 1983-84. Yet these numbers also leveled off until they stabilized around 16% in the 1990s, then fell again to around 10% in 2008-9 before rising back up to 13.8% in 2014-15. In 2015, the percentage of women graduating with bachelor's degrees in electrical, electrical/computer, and computer engineering programs was respectively 12.5%, 13.7%, and 10.9%, while computer science programs had 14.8% (within engineering) and 14.3% (outside of engineering) women graduates [89]. At present these are among the lowest rates of gender representation across all engineering fields. In fact, only mechanical engineering has numbers in the same range, with 13.2% female B.S. graduates in 2014-15. By contrast, biomedical claimed 40.9% female graduates while environmental engineering achieved near gender-parity with 49.7%. The continuing and woeful lack of women in electrical, computer, and allied specialties is a cause for alarm with manifold implications for the field's future vitality and relevance, including by artificially limiting the potential for women to pursue, thrive in, and ultimately enrich and transform ECE degree programs and career paths.

The outlook for underrepresented ethnic racial/minority groups is somewhat more mixed. To begin, the percentage of B.S. degrees in electrical, electrical/computer, and computer engineering awarded to Black or African American students has hovered in the 6-7% range from the late 1990s to the present, falling slightly in recent years to 5.9% in 2014-15 [89]. This represents about half of the 11.7% U.S. residential population identifying as Black in 2013 [90, Ch. 3]. Hispanic/Latino students similarly represented less than 6% of B.S. degree graduates in the same fields as of 1997-98. Yet their numbers have gradually marched upward in recent years, to an all-time high of 11.9% in 2014-15. This brings their representation in the field much closer to parity with the overall residential population in the U.S., which was 14.6% Hispanic/Latino as of 2013 [90, Ch. 3]. The relative success in recruiting and retaining Hispanic/Latino students in ECE degree programs suggests a need for further investigation to better understand these trends and inspire follow-up initiatives.

Recent research by Lord et al. examining student trajectories in EE and CmpE programs paints an even more nuanced picture of these trends [91], [92]. With regard to historically underrepresented groups more specifically, this research suggests that Black men and women enter both electrical engineering and computer engineering degree programs at higher rates relative to other demographic groups, while Hispanic men choose computer engineering at higher rates. However, both white and Hispanic women are much less likely to start in electrical and computer engineering, and Hispanic women in particular graduate at lower rates in both types of programs. This research also finds particularly low graduation rates in computer engineering for women and Black students. Such findings further underscore the need for more research focused on underlying explanations for why certain groups are not enrolling and/or persisting in such programs. Nonetheless, these same studies point to a number of factors that may contribute to these historical patterns of underrepresentation. On the student side of the equation, for instance, they cite studies on early socialization patterns, socioeconomic differences, variations in self-confidence, and the influence of family, role models, and mentors [91], [92].

Still other factors in these two papers by Lord et al. speak to deeper historical currents in the field itself. For example, they point to research documenting the prevalence of negative stereotypes and masculine cultural dynamics in these fields, including in both school and workplace settings [92]. They additionally note that core technical coursework in the field often prioritizes theory and abstract concepts over broader impacts, even as other engineering disciplines are doing more to appeal to student demands for a greater sense of relevance or "connectedness" in their studies [92]. Finally, they point to research by Godfrey [93] characterizing a more "traditional" culture in older fields like electrical engineering, where prevailing norms related to curricula, pedagogy, and professional issues are often deeply entrenched, as well as increasingly outdated and resistant to change.

Indeed, it is no stretch to suggest that electrical engineering departments have been more reactive than proactive when it comes to curriculum reform. While pockets of innovation continue to appear at the level of individual schools and smaller consortia, there remains a surprising lack of larger-scale initiatives or projects focused on scrutinizing the current state of – and future directions for – ECE education. Development and implementation of ABET's EC2000 accreditation curriculum from the late 1990s onward impacted all engineering fields, but the publication record suggests a muted and perhaps even resigned reaction among electrical and computer engineering degree programs. New interest around curriculum reform surfaced in the late 2000s and early 2010s, including through the 2011 formation of an IEEE Ad Hoc Committee on Reform in Engineering, Technology and Computing (ETC) Education [94]. Yet these efforts produced little in the way of outcomes. And it seems that the ECEDHA's recent discussions about the vitality and future of the field have also stopped short of critically interrogating the form and content of ECE education [83].

This lack of activity stands in marked contrast to fields such as civil engineering, as evidenced by publication of two successive editions of the ASCE's ambitious *Civil Engineering Body of Knowledge for the 21st Century* report [95]. Nonetheless, curriculum development efforts specifically focused on computer engineering have received considerable attention through joint sponsorship of the ACM and IEEE under the auspices of the larger "Computing Curriculum" initiative. As mentioned above, the group published recommendations for undergraduate computer engineering programs in 2004 and more recently released an updated draft [96]. Especially noteworthy is the group's approach, similar to that of the ASCE, in specifying detailed sets of learning outcomes for all of the areas and topics that comprise the proposed computer engineering "body of knowledge." Yet evidence for how these reports have actually impacted computer engineering degree programs remains scarce.

VII. CONCLUSION

Questions about the status and identity of electrical engineering as a distinct field or discipline continue to circulate. In one recent column, for instance, Robert Lucky observes that circuit design is about the only discipline-specific knowledge that all electrical engineering students encounter, and he points to the 39 constituent societies of the IEEE as yet another sign of the field's diversity [97]. Noting a continued migration of interest and activity to "layers above the physical level" and "to ever higher and more functional design" he concludes his column by rhetorically asking what commonalities might hold together the field of electrical engineering, as well as how it might be differentiated from other engineering fields.

Both the preceding history and the authors' own experiences suggest that the ECE education complex is not yet taking serious steps to explore – much less answer – such questions. We further predict that many stakeholders will continue a longstanding historical preoccupation with how to handle the many specialties and subspecialties emerging from both within the field and on its edges. Cyber-physical systems, the Internet of things, cloud computing, smart grid technologies, quantum computing, and bioengineering and bioelectronics are just a few among many ascendant topics, in part reflected in the naming of departmental research areas and new coursework. Lucky additionally points to "machine learning, big data, security, autonomous vehicles, robots, and the blockchain" as currently ascendant areas of interest and activity for electrical and computer engineers, but adds that such topics are cross-disciplinary by their very nature [97]. Other fields have also been proactive and strategic in bringing electrical technologies into their respective orbits, as evidenced by the activity of mechanical engineering in the power and energy area, or industrial engineering's embrace of sensing technologies and the Internet of things. Debates will surely intensify about whether and how to cover such topics in existing ECE departments and curricula.

Yet the preceding account also suggests the need for more fundamental reforms in ECE education that could help vault it into a leadership position among engineering fields. Two specific themes are worth emphasizing. First is a need to break down the horizontal barriers or "silos" between disparate technical topics and specialties, both within ECE and more broadly across engineering disciplines. All too often our students do not have a clear understanding of how specialized knowledge in a given technical area relates to other areas. Second, ECE students often lack opportunities to work vertically across multiple levels of abstraction, including to better grasp how devices and components are combined into larger and more complex systems. Further, increasing exposure ''vertically'' from the device to application level could help students more intentionally explore the technology-society nexus. Such explorations would in turn benefit from expanded engagement with the social sciences and humanities, which have a long history of asking questions about technology such as ''to what end?'' and ''who benefits?'' And this brings us back full circle to the crossing of disciplinary boundaries, not only in the technical realm but also in helping students see their work in more situated and ''sociotechnical'' terms.

To be sure, these are not entirely new ideas. Prior scholarship by the likes of Bordogna et al., for instance, built a strong case for a more ''integrated'' and ''holistic'' approach to engineering education [98]. One finds similar ideas presented in Sheppard et al.'s ''spiral'' or ''networked'' model for reimagining engineering courses and curricula, along with their recommendation to expand the use of ''project-centered learning'' [99]. Even more recently, the NAE's Grand Challenges Scholars Program has proposed engaging and inspiring engineering students (and faculty) through five types of learning, namely: 1) hands-on project or research experiences, 2) interdisciplinary curricula within and beyond engineering, 3) entrepreneurship, 4) global perspectives, and 5) service learning [100]. While more than 120 engineering schools have signed on to this program, further work is needed to see what this initiative could mean for ECE specifically. Indeed, proactively exploring how a more diverse and inclusive ECE education and research enterprise could address a wide variety of global grand challenges and ''wicked problems'', thereby helping to counterbalance historical forces of disintegration by infusing the field with a new spirit of connectedness, relevance, and impact.

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REFERENCES

[1] R. Williams, *Retooling: A Historian Confronts Technological Change*. Cambridge, MA, USA: MIT Press, 2003.
[2] P. Meiksins, ''Engineers in the United States: A house divided,'' in *Engineering Labour: Technical Workers in Comparative Perspective*, P. Meiksins and C. Smith, Eds. New York, NY, USA: Verso, 1996, pp. 61–97.
[3] C. R. Mann, *A Study of Engineering Education*. New York, NY, USA: Carnegie Foundation for the Advancement of Teaching, 1918.
[4] P. Lundgreen, ''Engineering education in Europe and the U.S.A., 1750–1930: The rise to dominance of school culture and the engineering professions,'' *Ann. Sci.*, vol. 47, no. 1, pp. 33–75, 1990.
[5] B. E. Seely, ''Patterns in the history of engineering education reform: A brief essay,'' in *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*. Washington, DC, USA: The National Academies, 2005, pp. 114–130.
[6] F. E. Terman, ''A brief history of electrical engineering education,'' *Proc. IEEE*, vol. 64, no. 9, pp. 1399–1407, Sep. 1976.
[7] F. E. Terman, ''Electrical engineers are going back to science!'' *Proc. IRE*, vol. 44, no. 6, pp. 738–740, Jun. 1956.
[8] N. Rosenberg and R. R. Nelson, ''American universities and technical advance in industry,'' *Res. Policy*, vol. 23, no. 3, pp. 323–348, 1994.
[9] H. H. Norris, ''The attitude of the technical school toward the profession of electrical engineering,'' *Proc. AIEE*, vol. 26, no. 7, pp. 1065–1075, Jul. 1907.
[10] R. McCaughey, *A Lever Long Enough: A History of Columbia's School of Engineering and Applied Science Since 1864*. New York, NY, USA: Columbia Univ. Press, 2014.
[11] L. A. Geddes, *A Century of Progress: The History of Electrical Engineering at Purdue*. West Lafayette, IN, USA: Purdue Univ., 1988.
[12] Cornell University, Ithaca, NY, USA. (2009). *Cornell Engineering: A Tradition of Leadership and Innovation*. [Online]. Available: https://www.engineering.cornell.edu/about/upload/Cornell-Engineering-history.pdf
[13] E. Berg, ''Annual report of educational committee,'' *Trans. AIEE*, vol. 35, no. 1, pp. 743–752, 1918.
[14] D. C. Jackson, ''The technical education of the electrical engineer,'' *Trans. AIEE*, vol. 9, no. 1, pp. 476–499, Jan. 1892.
[15] A. M. McMahon, *The Making of a Profession: A Century of Electrical Engineering in America*. New York, NY, USA: IEEE Press, 1984.
[16] J. D. Ryder, ''The way it was: A renowned educator gives a firsthand account of the decades that shaped EE education,'' *IEEE Spectr.*, vol. 21, no. 11, pp. 39–43, Nov. 1984.
[17] J. D. Ryder, ''The renaissance in electrical education,'' *Elect. Eng.*, vol. 70, no. 7, pp. 581–584, Jul. 1951.
[18] G. S. Brown, ''Educating electrical engineers to exploit science,'' *Elect. Eng.*, vol. 74, no. 2, pp. 110–115, Feb. 1955.
[19] W. Kline, ''World War II: A watershed in electrical engineering education,'' *IEEE Technol. Soc. Mag.*, vol. 13, no. 2, pp. 17–23, May 1994.
[20] P. J. Gumport, ''Graduate education and research imperatives: Views from American campuses,'' in *The Research Foundations of Graduate Education: Germany, Britain, France, United States, Japan*, B. R. Clark, Ed. Los Angeles, CA, USA: Univ. California Press, 1993, pp. 225–260.
[21] F. E. Terman, ''Electrical engineering curricula in a changing world,'' *Elect. Eng.*, vol. 75, no. 10, pp. 940–942, Oct. 1956.
[22] L. E. Grinter, *Report of the Committee on Evaluation of Engineering Education*. Washington, DC, USA: ASEE, 1955.
[23] D. E. Garr, ''The changing electrical engineering environment,'' *Elect. Eng.*, vol. 80, no. 4, pp. 271–273, Apr. 1961.
[24] A. D. Moore, ''The modern engineering bandwagon,'' *IEEE Spectr.*, vol. 5, no. 7, pp. 79–82, Jul. 1968.
[25] M. E. Van Valkenburg, ''Electrical engineering education in the U.S.,'' *IEEE Trans. Edu.*, vol. E-15, no. 4, pp. 240–244, Nov. 1972.
[26] W. Aspray, ''Introduction,'' in *Proc. Symp. Large-Scale Digital Calculating Machinery*. Los Angeles, CA, USA: MIT Press, 2000, pp. 9–23.
[27] W. Aspray, ''Was early entry a competitive advantage? U.S. Universities that entered computing in the 1940s,'' *IEEE Ann. Hist. Comput.*, vol. 22, no. 3, pp. 42–87, Jul./Sep. 2000.
[28] B. K. Jesiek, ''Between discipline and profession: A history of persistent instability in the field of computer engineering, circa 1951–2006,'' Ph.D. dissertation, Dept. Sci. Technol. Soc., Virginia Tech., Blacksburg, VA, USA, 2006.
[29] A. Akera, ''Calculating a natural world: Scientists, engineers, and computers in the United States, 1937–1968,'' Ph.D. dissertation, Dept. History Sociol. Sci., Univ. Pennsylvania, Philadelphia, PA, USA, 1998.
[30] L. A. Zadeh, ''Thinking machines: A new field in electrical engineering,'' *Columbia Eng. Quart.*, vol. 3, pp. 12–13 and 30–31, Jan. 1950.
[31] B. K. Jesiek, ''The origins and early history of computer engineering in the United States,'' *IEEE Ann. Hist. Comput.*, vol. 35, no. 3, pp. 6–18, Jul. 2013.

[32] H. D. Huskey, “Status of university educational programs relative to high speed computation,” in *Proc. First Conf. Training Personnel for the Computing Machine Field*, A. W. Jacobson, Ed. Detroit, MI, USA: Wayne Univ. Press, 1955, pp. 22–25.

[33] H. H. Goode, “PGEC student activities and education in computers,” *IRE Trans. Comput.*, vol. EC-4, no. 2, pp. 49–51, Jun. 1955.

[34] G. T. Hunter, “Manpower requirements by computer manufacturers,” in *Proc. First Conf. Training Personnel for the Computing Machine Field*, A. W. Jacobson, Ed. Detroit, MI, USA: Wayne Univ. Press, 1955, pp. 14–18.

[35] A. A. Bennett, “The impact of automatic computing machines upon the undergraduate curriculum,” in *Proc. First Conf. Training Personnel for the Computing Machine Field*, A. W. Jacobson, Ed. Detroit, MI, USA: Wayne Univ. Press, 1955, pp. 40–46.

[36] P. Ceruzzi, “Electronics technology and computer science, 1940–1975: A coevolution,” *Ann. Hist. Comput.*, vol. 10, no. 4, pp. 257–275, Oct./Dec. 1989.

[37] J. B. Wiesner, “Communication sciences in a university environment,” *IBM J. Res. Develop.*, vol. 2, no. 4, pp. 268–275, Oct. 1958.

[38] L. Fein, “The role of the university in computers, data processing, and related fields,” *Commun. ACM*, vol. 2, no. 9, pp. 7–14, 1959.

[39] S. Gorn, “The computer and information sciences: A new basic discipline,” *SIAM Rev.*, vol. 5, no. 2, pp. 150–155, Apr. 1963.

[40] J. W. Hamblen, *Computers in Higher Education: Expenditures, Sources of Funds, and Utilization for Research and Instruction 1964–1965, With Projections for 1968–1969*. Atlanta, GA, USA: Southern Regional Education Board, Aug. 1967.

[41] C. D. Conte *et al.*, “An undergraduate program in computer science—Preliminary recommendations,” *Commun. ACM*, vol. 8, no. 9, pp. 543–552, Sep. 1965.

[42] W. F. Atchison *et al.*, “Curriculum 68: Recommendations for academic programs in computer science,” *Commun. ACM*, vol. 11, no. 3, pp. 151–197, Mar. 1968.

[43] W. F. Atchison, “The position of computing science in the university structure: A report of the workshop,” in *Proc. Conf. Graduate Academic and Related Research Programs in Computing Science, Held at the State University of New York at Stony Brook, June 1967*, A. Finerman, Ed. New York, NY, USA: Academic, 1968, pp. 169–175.

[44] V. C. Rideout, “Curriculum needs in the computing field,” in *The Computing Laboratory in the University*, P. C. Hammer, Ed. Madison, WI, USA: The Univ. Wisconsin Press, 1957, pp. 153–159.

[45] N. R. Scott, “Computer design courses in the engineering curriculum,” *J. Eng. Edu.*, vol. 50, no. 10, pp. 852–855, Jun. 1960.

[46] H. E. Tompkins, “Computer education,” in *Advances in Computers*, vol. 4, F. L. Alt and M. Rubinoff, Eds. New York, NY, USA: Academic, 1963, pp. 135–168.

[47] L. A. Zadeh, “Electrical engineering at the crossroads,” *IEEE Trans. Educ.*, vol. E-8, no. 2, pp. 30–33, Jun./Sep. 1965.

[48] L. A. Zadeh, “Computer science as a discipline,” *J. Eng. Edu.*, vol. 58, no. 8, pp. 913–916, Apr. 1968.

[49] L. A. Zadeh, “Curricula for computer science,” in *Summary of Talks and Discussion Group Recommendations, Conference on Computer Sciences in Electrical Engineering Education*. Washington, DC, USA: COSINE Committee of the Commission on Engineering Education, 1967, pp. 9–10.

[50] R. Karp, “A personal view of computer science at Berkeley,” Department of Electrical Engineering and Computer Sciences, Univ. California, Berkeley, Berkeley, CA, USA, 2004. [Online]. Available: https://www2.eecs.berkeley.edu/bears/CS_Anniversary/karp-talk.html

[51] M. E. Sloan, “The impact of the COSINE committee on the undergraduate electrical engineering curriculum,” *IEEE Trans. Edu.*, vol. E-17, no. 4, pp. 179–189, Nov. 1974.

[52] COSINE Committee of the Commission on Engineering Education, *Computer Sciences in Electrical Engineering*. Washington, DC, USA: National Academy of Engineering, 1967.

[53] COSINE Committee of the Commission on Engineering Education, “Computer science in electrical engineering,” *IEEE Spectr.*, vol. 5, no. 3, pp. 96–103, Mar. 1968.

[54] C. L. Coates, “University education in computer engineering,” in *Proc. Meeting on Computer Science in Electrical Engineering of the Commission on Engineering Education*. Washington, DC, USA: National Academy of Engineering, 1968, pp. 5–11.

[55] COSINE Committee of the Commission on Engineering Education, *Proc. Meeting on Computer Science in Electrical Engineering of the Commission on Engineering Education*, Washington, DC, USA: National Academy of Engineering, 1968.

[56] COSINE Committee of the Commission on Education, *An Undergraduate Computer Engineering Option for Electrical Engineering*. Washington, DC: National Academy of Engineering.

[57] C. L. Coates *et al.*, “An undergraduate computer engineering option for electrical engineering,” *Proc. IEEE*, vol. 59, no. 6, pp. 854–860, Jun. 1971.

[58] M. E. Sloan, C. L. Coates, and E. J. McCluskey, “COSINE survey of electrical engineering departments,” *Computer*, vol. 6, no. 6, pp. 30–39, Jun. 1973.

[59] M. E. Sloan, “Survey of electrical engineering and computer science departments in the U.S.,” *Computer*, vol. 8, no. 12, pp. 35–42, Dec. 1975.

[60] E. C. Jones, Jr. and M. C. Mulder, “Accreditation in the computer profession,” *Computer*, vol. 17, no. 4, pp. 24–27, Apr. 1984.

[61] IEEE Educational Activities Board, “ECPD accreditation guidelines: Preliminary computer science and engineering programs,” *Computer*, vol. 11, no. 2, pp. 67–69, Feb. 1978.

[62] L. A. Zadeh, “Impact of computers on the orientation of electrical engineering curricula,” *IEEE Trans. Edu.*, vol. E-14, no. 4, pp. 153–157, Nov. 1971.

[63] The Joint Task Force on Computing Curricula, “Computer engineering 2004: Curriculum guidelines for undergraduate degree programs in computer engineering,” *IEEE Comput. Soc.*, 2004. [Online]. Available: https://www.acm.org/education/education/curric_vols/CE-Final-Report.pdf

[64] J. Millman and H. Taub, *Pulse and Digital Circuits*. New York, NY, USA: McGraw-Hill, 1956.

[65] J. Millman and H. Taub, *Pulse, Digital and Switching Waveforms*. New York, NY, USA: McGraw-Hill, 1965.

[66] S. Derman, “Miliman and Taub’s pulse and digital circuits—A pioneer text in its field,” *IEEE Trans. Edu.*, vol. E-27, no. 4, pp. 232–236, Nov. 1984.

[67] S. A. Steele and G. G. Balazs, “A course sequence for the teaching of digital systems,” *IEEE Trans. Edu.*, vol. E-9, no. 4, pp. 198–201, Dec. 1966.

[68] H. R. Martens, “A digital control laboratory,” *IEEE Trans. Edu.*, vol. E-11, no. 3, pp. 177–182, Sep. 1968.

[69] D. E. Troxel, “A digital systems project laboratory,” *IEEE Trans. Edu.*, vol. E-11, no. 1, pp. 41–43, Mar. 1968.

[70] B. Gold and C. M. Rader, *Digital Processing of Signals*. New York, NY, USA: McGraw-Hill, 1969.

[71] COSINE Committee of the Commission on Education, *Impact of Computers on Electrical Engineering Education—A View From Industry*. Washington, DC, USA: The National Academy of Engineering, Sep. 1969.

[72] COSINE Committee of the Commission on Education, *Some Specifications for an Undergraduate Course in Digital Subsystems*. Washington, DC, USA: National Academy of Engineering, Nov. 1968.

[73] COSINE Committee of the Commission on Education, *Digital Systems Laboratory Courses and Laboratory Developments*. Washington, DC: National Academy of Engineering, Mar. 1971.

[74] C. W. Adams, “The contribution of the computing laboratory to the university curriculum,” in *The Computing Laboratory in the University*, P. C. Hammer, Ed. Madison, WI, USA: Univ. Wisconsin Press, 1957, pp. 139–143.

[75] M. Phister, *Logical Design of Digital Computers*. New York, NY, USA: Wiley, 1958.

[76] J. G. Linvill, J. B. Angell, and R. L. Pritchard, “Integrated electronics vs electrical engineering education,” *Proc. IEEE*, vol. 52, no. 12, pp. 1425–1429, Dec. 1964.

[77] P. Wallich, “The engineer’s job: It moves toward abstraction,” *IEEE Spectr.*, vol. 21, no. 6, pp. 32–37, Jun. 1984.

[78] S. Kahne, “Education: A crisis in electrical engineering manpower,” *IEEE Spectr.*, vol. 18, no. 6, pp. 50–52, Jun. 1981.

[79] A. W. Bennett, “A position paper on guidelines for electrical and computer engineering education,” *IEEE Trans. Edu.*, vol. E-29, no. 3, pp. 175–177, Aug. 1986.

[80] National Science Foundation and Department of Education, *Science and Engineering Education for the 1980s and Beyond*. Washington, DC, USA: National Science Foundation and Department of Education, 1980.

[81] R. W. Heckel, "Current and emerging statistical trends in engineering education," *J. Eng. Edu.*, vol. 83, no. 4, pp. 363–369, Oct. 1994.

[82] P. Wallich, "Electrical engineering's identity crisis—When does a vast and vital profession become unrecognizably diffuse?" *IEEE Spectr.*, vol. 41, no. 11, pp. 66–73, Nov. 2004.

[83] ECEDHA, Chicago, IL, USA. *Electrical and Computer Engineering Department Heads Association (ECEDHA), Workshop on the Strategic Shaping of ECE: Vision, Branding, and Advocacy*. [Online]. Available: http://www.ecedha.org/docs/default-source/meetings/detailed-description-here-.pdf?sfvrsn=0

[84] ECEDHA, Chicago, IL, USA. *Electrical and Computer Engineering Department Heads Association (ECEDHA), Membership Directory*. [Online]. Available: http://www.ecedha.org/membership/directory

[85] ABET, Inc., Baltimore, MD, USA. (2015). *ABET Engineering Accreditation Commission, Criteria for Accrediting Engineering Programs*. [Online]. Available: http://www.abet.org/wp-content/uploads/2015/10/E001-16-17-EAC-Criteria-10-20-15.pdf

[86] B. L. Yoder, *Engineering by the Numbers*. Washington, DC, USA: ASEE, 2015.

[87] M. T. Gibbons, *Engineering by the Numbers*. Washington, DC, USA: ASEE, 2007.

[88] R. W. Heckel, "BS DiscipDegcharts 1945 to present.xlsx," Houghton, MI, USA: Engineering Trends.

[89] ASEE, Washington, DC, USA. *ASEE Engineering Data Management System*. [Online]. Available: https://edms.asee.org/

[90] National Science Board, Arlington, VA, USA. (2016). *Science & Engineering Indicators 2016*. [Online]. Available: https://www.nsf.gov/statistics/2016/nsb20161/#/

[91] S. M. Lord, R. A. Layton, and M. W. Ohland, "Trajectories of electrical engineering and computer engineering students by race and gender," *IEEE Trans. Edu.*, vol. 54, no. 4, pp. 610–618, Nov. 2011.

[92] S. M. Lord, R. A. Layton, and M. W. Ohland, "Multi-institution study of student demographics and outcomes in electrical and computer engineering in the USA," *IEEE Trans. Edu.*, vol. 58, no. 3, pp. 141–150, Aug. 2015.

[93] E. Godfrey, "Cultures within cultures: Welcoming or unwelcoming for women?" in *Proc. ASEE Annu. Conf. Expo.*, Honolulu, HI, USA, 2007, pp. 1–19. [Online]. Available: https://peer.asee.org/cultures-within-cultures-welcoming-or-unwelcoming-for-women

[94] IEEE, New York, NY, USA. *Ad Hoc Committee on Reform in Engineering, Technology and Computing (ETC) Education*. [Online]. Available: http://www.ieee.org/about/corporate/ad_hoc/42070871

[95] Body of Knowledge Committee, Committee on Academic Prerequisites for Professional Practice, *Civil Engineering Body of Knowledge for the 21st Century: Preparing the Civil Engineering for the Future*, 2nd ed. Reston, VA, USA: ASCE, 2008. [Online]. Available: http://www.asce.org/uploadedFiles/Education_and_Careers/Body_of_Knowledge/Content_Pieces/body-of-knowledge.pdf

[96] Joint Task Group on Computer Engineering Curricula, *Computer Engineering Curricula 2016: Curriculum Guidelines for Undergraduate Degree Programs in Computer Engineering*. New York, NY, USA: ACM and Los Alamitos, CA, USA: IEEE Computer Society, 2016. [Online]. Available: https://www.acm.org/binaries/content/assets/education/ce2016-final-report.pdf

[97] R. W. Lucky, "The ever-evolving field of electrical engineering," *IEEE Spectr.*, vol. 53, no. 11, p. 27, Nov. 2016.

[98] J. Bordogna, E. Fromm, and E. W. Ernst, "Engineering education: Innovation through integration," *J. Eng. Edu.*, vol. 82, no. 1, pp. 3–8, Jan. 1993.

[99] S. D. Sheppard, K. Macatangay, A. Colby, and W. M. Sullivan, *Educating Engineers: Designing for the Future of the Field*. San Francisco, CA, USA: Jossey-Bass, 2009.

[100] National Academy of Engineering, "NAE grand challenges scholar program," Washington, DC, USA: National Academy of Engineering, 2016. [Online]. Available: http://engineeringchallenges.org/14365/GrandChallengeScholarsProgram.aspx

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