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GUEST EDITORIAL

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The wisdom of winter is madness in May

Humans have been dealing with change for a long time; as illustrated by Heraclitus' (c. 500 BCE) truism, the only constant is change. However, while change has been constant, the rate of change is not fixed. Today, three broad trends—an increasing rate of technology-driven change, increasing interconnection and access to information, and convergence—present new challenges and opportunities for engineering education. Technology is transforming work, business, and organizational structures, bringing new pressures to bear on both engineering programs and the institutions of higher education in which they reside. To adapt to these changes, engineering education can benefit from better understanding its role in a large, complex ecosystem.

Change is a staple of conversations in engineering education research. In fact, it could probably be said that the desire to change something is a driving factor for many individuals' engagement with engineering education and we drive our own change as we redefine our identity. Whether to improve engineering education, address issues of equity and justice, or extend knowledge of how engineering is learned, change can be considered as a defining aspect of engineering education. Our history has been marked by roughly decennial reports suggesting how changes in society, the economy, and the engineering profession should be reflected in engineers' education. The 1918 Mann report (Mann & Press, 1918) was written at a time when industry was rapidly incorporating more scientific practices and framed engineering education as needing to serve industrial production. The Grinter Report (1994), which highlighted the importance of engineering science, was published 2 years before Sputnik in 1955 and coincided with rapid economic expansion and growing American hegemony. The ASEE *Goals of Engineering Education* report of 1968 (Walker, Pettit, & Hawkins, 1968), the year before the first manned moon landing, sought to address the tensions between the rapid growth of technical knowledge and the broad knowledge necessary to act as engineer, predating more recent conceptions of T-shaped engineers (Johnston, 1978). The National Academy of Engineering's 1985 *Engineering Education and Practice in the United States* (Committee on the Education and Utilization of the Engineer, 1985) and the 2004 *Engineer of 2020* (Clough et al., 2004) framed engineering as part of an increasingly complex socio-technical system, weaving engineering tightly into technical, social, economic, and environmental contexts that have great societal implications. Today, in-demand skills are expanding to include problem solving and critical thinking, the ability to work with others, technological literacy, and adaptability (Committee on Information Technology and the U.S. Workforce, 2017). While engineering education has always sought to balance acquiring technical knowledge with meeting societal and workforce needs, three trends are emerging that when taken together portend significant challenges for being able to maintain this tenuous balance.

One trend that impacts engineering education is that the rate of knowledge production is increasing, driven in large part by technologies created by engineers such as a ubiquitous high-speed mobile internet, artificial intelligence (AI), and the Internet of Things. The social sciences recognize a double hermeneutic which states that a theory can impact beliefs in the world, generating new evidence for the theory. The analog in engineering education is that our students will go on to create new technologies, capabilities, and knowledges, which in turn change engineering and thus how we educate engineers. Keeping up with knowledge growth has been recognized as a challenge in engineering education for some time. For example, the rapid growth of knowledge in some fields raises debates on what to include or leave out of their curricula. Interviews from "The Distributed System of Governance in Engineering Education" project (Akera, Riley, Cheville, Karlin, & DePree, 2018) show faculty and administrators in engineering education worry about how to manage the increasing body of knowledge. The challenge that rapid growth of knowledge creates for engineering education is how to be agile and forward-looking while maintaining the historical focus of the university on universal truths.

The second difference comes from increasing interconnection and access to information, which increases complexity. As information becomes more readily accessible, students have more opportunities to find alternative routes to a societally recognized learning credential that fits their budget. Our mental models of education—what Michel Foucault called an episteme (Foucault, 1994) and Thomas Kuhn a paradigm (Kuhn, 1996)—will need to shift as paths to credentials expand. The industrial-themed model of a pipeline is broadening to include multiple pathways (Malcolm & Feder, 2016), but engineering education exists within a broader, complex ecosystem involving schools, industry, governments and other entities (Lee, 2019; Lord, Ohland, Layton, & Camacho, 2019). While such complexity offers new opportunities, it also comes with costs, and raises questions around how learning should be measured and credentialed. A challenge for engineering education will be how to maintain and grow equity and access in increasingly fragmented education systems.

The third difference, which arises from increased connectivity and system complexity, is broadly termed convergence (National Research Council, 2014). Convergence denotes an increasing need to address challenges that require knowledge and skills from many disciplines; such problems are often framed as grand challenges or big ideas (Grand Challenges for Engineering Committee, 2008). Convergence requires not simply cooperation between disciplines but also the ability to transfer one's expertise to new domains, to mentally shift between disciplinary frameworks, and to communicate with and teach others with very different backgrounds. Engineering education serves as a good example of convergence since meaningful change in this field requires research on how to promote and support learning, create support structures that enable equity, craft policies that control the costs of education, effectively integrate new technologies, and credential learning in ways that protect privacy while sharing relevant educational accomplishments. Supporting convergence creates challenges for a higher education system, which is predominately structured by existing siloes of disciplinary knowledge.

These three trends—an increasing rate of change driven by technologies, a shift in paradigm towards complexity, and convergence (Akbar et al., 2017)—have powerful synergies that will have wide-ranging effects. For example, new technological affordances in capturing and analyzing data have spread beyond engineering and are being widely utilized in all sectors of the economy. These tools—broadly captured by terms such as AI, machine learning, or big data—are rapidly transforming the way work is done, business is conducted, and how organizations are structured and individuals behave (Madhavan & Richey, 2016). Such transformations are accelerated by increasing support for convergence research designed to mobilize numerous and diverse stakeholders around important problems and inform the policy, organizational, and funding decisions needed to craft and implement solutions (National Research Council, 2014). Learning credentials serve as an example of how these trends are impacting education. Information technologies supported the development of on-line degree programs, which first arose at for-profit institutions seeking to control costs rather than at traditional universities (McCluskey & Winter, 2012). As the costs of higher education continued to rise, alternative credentials such as certificates became the fastest growing form of credential (Carnevale, Rose, & Hanson, 2012; Cronen, McQuiggan, Isenberg, & Grady, 2017). To fill perceived needs for more focused credentials, new organizations such as boot camps are seeking roles as credential grantors, which increase complexity within the educational ecosystem.

These trends are also impacting the engineering workforce that students will enter. The insights provided by complexity and network theories along with the ability to capture and look for trends hidden in large amounts of data are helping organizations better understand interactions within a workplace. While such understanding could help mitigate injustices and improve organizational effectiveness, it can also change expectations for how individuals act within the organizational culture—that is, the norms, values, and ways people interact within an organization. A culture in which technological affordances influence expected behavior may sound dystopian, but it is likely that engineering education will increasingly have to prepare students to be both technically and socially adaptable (Heywood, 1989). If real time data increasingly drive organizational decisions, students will enter work cultures in which one's expertise needs to change rapidly to keep up with technological advances while also keeping up with a culture where data shift expectations. These changes have been likened to a Fourth Industrial Revolution—the first being mechanization, the second electrification, and the third digitization—that revolves around systemic connection supported by autonomous decision-making. If the prospect of working within the space described above is uncomfortable, and it is for some of the authors, it may be a sign that our technology may be overtaking our ability to adapt to change.

Engineering education is neither immune to, nor isolated from, these larger trends. While in the short-term change will manifest in employer expectations, course content, and the tools students use, over the longer term these trends will impact educational structures and affect educators' roles. For example, the last decade saw massively open on-line courses, or MOOCs, suddenly appear in the public spotlight. Although MOOCs have faded from the news cycle, they are still actively evolving to establish themselves for a wide range of educational audiences. One of these evolutions is the SPOC, or Small Private Online Course. In one such SPOC, Boeing has collaborated with academics to create an online course on architecture and systems engineering (MIT xPro, 2018) that includes many aspects found in face-to-face courses such as technical content, mentored projects that focus on tacit knowledge, and social networking. The course is heavily instrumented and backed by analytics that tailor course materials and progression to learner needs. Surprisingly, preliminary analysis shows learning behaviors fit a small number of profiles, which could allow learning needs to be predicted to enable customized learning trajectories (Richey et al., 2017). Microsoft has developed similar learner pathways on the EdX platform through its Microsoft Professional Program and related offerings (Microsoft Professional Program, 2019). These offerings are a form of micro-credentials that integrate in-demand topics into the structure of a university course and leverage AI and other technologies to generate immediate benefits for employers with relatively small investment. Meet the new credential grantors.

As these trends drive increasingly rapid change in industries that employ engineers, the ability to support ongoing learning has become critical to the bottom line and building corporate resilience; industry invests in courses and credentials because learning has a direct effect on the business. Early studies on aircraft production found a decreasing power law relationship between the costs to assemble an aircraft and the number of aircraft produced. These power law distributions, or learning curves, were later observed in other domains (Argote & Ophir, 2002; Madni et al., 2015). In an economy that is increasingly focused on intangibles (Haskel & Westlake, 2017), the ability to learn rapidly becomes more critical. Interest in supporting learning now extends beyond employees since growing a community of learners and users around a product or platform has beneficial subsidiary effects for companies; examples are maker, gamer, and application development communities who create content around a platform. Conversely, when organizational knowledge is disrupted—by losing a contract, employees leaving, mergers, or rapid changes in technology—costs rise and customer loyalty may decrease. Thus, the learning that industry seeks to foster is not just focused on creating more effective employees but encompasses changing and tightly interconnecting organizational cultures. With the recognition that learning is embodied in networks that span scales—from reorganizing neural networks in the brain, to connecting information and concepts in developing schemas, to distributed knowledge embodied social networks of people—learning can be broadly characterized as network formation. These networks are described by nascent complexity theories and social network analysis and can be broadly characterized as complex adaptive ecosystems in which individuals occupy different niches, keystone species connect niches, and maintaining information flow and diversity is critical to maintaining organizational resilience. Since organizations that can create and sustain learning networks gain competitive advantages, corporations increasingly seek to understand how individuals access information, how to improve the fidelity of information acquisition, and how such networked learning supports individuals' abilities to act in ways that improve processes.

Historically, learning in universities has been dictated by class schedules, department-determined curricula, and access to professors. Technology and access to information are, however, giving students more control of their learning and letting universities track individuals' pathways through courses while analyzing learning patterns for large numbers of students. New technological capabilities in learning analytics inch us closer to personalizing learning in online and hybrid environments in which students, who enter with different prior knowledge and skills, do not follow preset pathways. These new capabilities may eventually catalyze deep structural and credentialing changes in universities given the cost savings and scalability technology offers. While these technologies will not change the university overnight, economic concerns increasingly drive educational decision making, so it will be difficult for administrations to resist the potential cost savings. For example, the percentage of full-time instructional faculty has steadily fallen over time as that of lower-cost, part-time instructors has risen (College Board, 2015); this situation is widely recognized as less than ideal by all parties but was seen as economically necessary. Furthermore, without adapting to new technological affordances, universities risk losing their historical position as credential grantors, creating increased pressures on an already strained higher education system.

Whether or not universities can adapt to the increase in credential pathways by undertaking the needed structural changes in ways that promote broad equity and access will depend on the types of mental models or paradigms educators and administrators bring to their work. In the pipeline model of STEM education, for example, costs are addressed by seeking efficiencies, for example fixing leaks, which makes the task of engineering education relatively clear—improve retention. However, in an ecosystem or convergence paradigm, how education is offered cannot be disentangled from how it is funded, changing technologies, and a dynamic work place that is integrating AI into more and more workflows (Committee on Information Technology and the U.S. Workforce, 2017). In other words, accomplishing meaningful change in engineering education increasingly requires addressing economic and technological considerations, that is, convergence, which requires engineering educators and others to expand our mental models to include those from other disciplines so we can better address issues such as the cost of higher education.

One example of such a mental model is the current "mortgage model" for funding college education. In the United States, education is paid for upfront and supplemented by loans and forms of financial aid in the same way an individual might finance a house. However, as college costs and student loan balances—now approaching $1.5 trillion or just under 10% of the U.S. gross domestic product (Center for Microeconomic Data, 2018)—increase, the long-term viability of this model becomes increasingly tenuous. From the ecosystem perspective, costs arise not just from the price tag of college but also from the risk inherent in student loans, which in turn are driven by information asymmetries (different information being available to students and lenders) inherent to the way universities are structured, privacy is valued, and credentials are defined. Should the type of information about learning that is generated through online courses be integrated into funding models, it could help reduce these asymmetries, lowering costs. Similarly, alternative funding structures that spread costs among stakeholders may make education more affordable. To explore such models, the authors held a small workshop in Dublin, Ireland, in 2017 that convened engineers, educators, policy makers, and macro- and micro-economists to develop an insurance-based model that aligns better with the types of workforce development opportunities that industry is pursuing (Cheville, Heywood, Larkin, & Corbet, 2018). In this model, the individual, government, and industry establish an educational insurance policy the individual can draw benefits from when they need additional education, for example, after a layoff or when their job description changes, effectively funding life-long learning. If ideas for such convergence experiments are to gain traction, it will be critical to bring industry, government, and universities together (Stephens & Richey, 2013). In the United States, industry is currently partnering with federal funding agencies to co-fund efforts that will help prepare the future workforce (Marrongelle, Kurose, Tilbury, & Lupia, 2018).

As we continue in our quest to change engineering education, we need to remember to keep looking outward to see what changes are happening in other parts of the larger educational ecosystem. Unfortunately, our ability to see change depends on our position within the ecosystem, our connection to the other niches within it, as well as the mental models we hold. Taking a wide view is vital, however, because while the Fourth Industrial Revolution has the potential to increase equity and improve education, the tempting affordances of technology may also cause education to become decoupled from its fundamentally human nature, which could reduce access to quality education for the more vulnerable in our society. Furthermore, it is likely the changes engineering education faces will be both systemic and structural, catalyzing new relationships among universities, industry, governments, and students. For example, new forms of industry–university partnerships may lead to a life-long relationship between students and the university as insurance-based models allow for regular updates to their education. While it is not yet clear how technologically driven change will affect engineering faculty or students, understanding the broader connections between these domains and developing theories and models that embrace the inherent complexity of educational systems can help us to cope with an uncertain future. Engineering education is positioned at a critical intersection between important domains in society. Given the emphasis the engineering codes of ethics place on human welfare, we have a professional obligation to respond to change. While change of this magnitude can be frightening, it is worth remembering that engineering education is ideally positioned to thrive in the future since engineers created the technologies, which are driving change, and educators are experts at preparing others for the world that is to emerge. Hang on, it is going to be a wild ride!

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