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Using Technology to Enhance Learning and Engagement in Engineering

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ABSTRACT

In this article, we explore how information, communications, and computational technology, or computer technology for short, influences the way that engineering is taught and learned. The goal of our analysis it to contribute towards a research, adoption, and policy agenda for propagating the effective use of computer technology in engineering education and for avoiding pitfalls associated with the connectivity that this technology enables. We seek to inform action and generate conversation amongst instructors, students, researchers, administrators, policy makers, and other key stakeholders in engineering education.

We organize our discussion through six main issues as the focus for systemic change for the effective integration of technology in engineering education. These issues were identified through a Delphi study with a group of engineering education experts. Our analysis of the issues then draws on major policy reports of the use of technology in education and the extant research literature from engineering education and science education as well as technology studies and science studies. Discussion of each of these issues leads to a summary set of recommendations.

Specifically, we address the role of technology in learning engineering, including both technologies developed specifically for learning engineering (learning innovations) and domain-specific computer technologies for engineering practice (computational tools). We next address technology-related issues around instructional design including learning outcomes, assessment, and instructional practice. We include discussion of professional development that better prepares faculty to effectively use technology in the classroom. Finally, we outline the broader ways technology interacts with the work of engineering students and faculty at the systems level - for better and for worse.

Key words: Computer technology, educational innovations, engineering practice, instructional design, assessment, faculty professional development.

People were being drawn out of their familiar worlds into one more free, less personal, in which associations that once attached to each person, place, and object came undone. It was a leap forward of extraordinary liberation and equal alienation.

Rebecca Solnit, 2003, *River of Shadows*, p. 11

INTRODUCTION

The above excerpt could be describing the impact of the Internet, personal computers, and mobile devices on human interactions in the early 21st century. However, it was written about a different network – the network of trains that fundamentally changed transportation, and western society, in the early 19th century.[1] Similarly, in *The Signal and the Noise*, Nate Silver (2012) comments about the invention of the printing press, created 400 years before the railroad infrastructure: "paradoxically, the result of having so much more shared knowledge was increasing isolation" (p. 3). Engineers are centrally involved in continued improvement of these technologies punctuated by the creation of revolutionary technology breakthroughs that change the core ways humans interact with the world and with one another. With an eye toward liberation, it is ethically incumbent for members of society to reflect on implications of how technology is used, and how it affects the central practices in which they engage (Mitcham, 1994).

The "information age" that has ushered in the 21st century has been built squarely on information, communications, and computational technology (ICCT), which we call "computer technology," for short. In this article, we explore how rapidly changing computer technology has and will substantially impact the way that engineering is taught and learned. We seek to be proactive and address the research and policy agenda for propagating the effective use of computer technology in engineering education and for avoiding pitfalls associated with connectivity that this technology enables. The goal of this analysis is to inform action and generate conversation amongst instructors, students, researchers, administrators, policy makers, and other key stakeholders in engineering education.

We consider two broad perspectives to approach this goal. First, engineering practice has always advanced its own boundaries through changing its technologies (National Research Council, 1985). As such, over the last several decades, computer technology has fundamentally shifted the ways engineering work is done by supporting discovery, collaboration, and innovation processes (Clough, 2004; Madhavan and Lindsay, 2014). In tandem, learning technologies promise to provide an unprecedented opportunity to improve instruction, provide adaptive learning, and foster increased engagement and

[1] Tom Standage (1998) used a similar analogy between the internet and the telegraph in *The Victorian Internet*.

broader access to education (Hilton, 2002; Pea et al., 2003; Woolf, 2010). Learning technologies consist of both tools and resources developed specifically for an educational setting and tools that have been repurposed and coupled with strategies that make them useful for learning (Johnson, Adams Becker, Estrada, and Freeman, 2014). However, the engineering education community is facing the challenge to adopt approaches to computer technology use that are grounded in theory, and educational researchers have called for evidence for the effectiveness of the uses of technology for teaching and learning (Woolf, 2010). Furthermore, it is unclear what aspects of learning can effectively be sourced to occur adaptively "in the technology," or to what degree it is fruitful to view technology primarily as a tool that augments the person-to-person social processes of learning. In general, like those who confronted with the opportunities presented by the printing press six centuries ago, educators (including engineering educators) have struggled to keep pace with quickly evolving computer technology.

In considering the impact of computer technology, we consider two distinct but related types of questions:

1. How can educators channel the ever-increasing number of learning technologies in ways that effectively promote meaningful learning and equitable engagement? How do they identify the ways that uses of technology circumvent their goals as educators?
2. How do educators best adapt engineering programs (curricula) to prepare students to contribute effectively in a rapidly changing, technology-rich professional environment?

In this white paper, we begin discussion with the first type of question while recognizing that the two types are interdependent and we cannot answer the first without elaboration of the second. Specifically, in the context of engineering learning environments, instructors must first identify what it is possible to accomplish with such technologies; that is their affordances. 'Affordance' refers the perceived and actual properties of an object, as related to its functional properties that define how such things could potentially be used (Gibson, 1979). Additionally, we consider computer technology as one element in the larger ecosystem where engineering learning occurs and the issues we present strongly interact with aspects of the other two articles in this special issue including learning in the classroom and pathways for an inclusive and diverse engineering community (Finelli & Froyd, 2019; Simmons & Lord, 2019).

Our premises and working scope for this paper include the following:

1. Computer technology is a tool that has potential to productively support teaching and enhance student learning especially with increasing class sizes and more diverse populations.
2. To be effective, uses of computer technology need to be approached in conjunction with content and with pedagogical considerations.
3. We choose to emphasize the use of technology for on-campus programs. While many of these systems can be used for learning at a distance, we are not directly addressing issues of solely distance education.

4. While the use of computer technology for on-campus and distance learning appear interchangeable at first blush, we believe that where and how technology is situated is foundationally related to how its uses are conceived and how it affects student learning.
5. We center the discussion on the undergraduate level engineering while acknowledging issues of technology in K-12 and graduate engineering education are also important.

CLASSIFICATION OF TECHNOLOGY

The uses of technology in education are broad, so it is practical to slice it up into more manageable categories. While there are many appropriate ways to approach this categorization, we choose one that is represented in Figure 1. It shows three ways to classify the use of computer technology in engineering education: (a) learning innovations specifically developed around instructional design to foster deep thinking and meaningful learning, (b) computational tools used in engineering

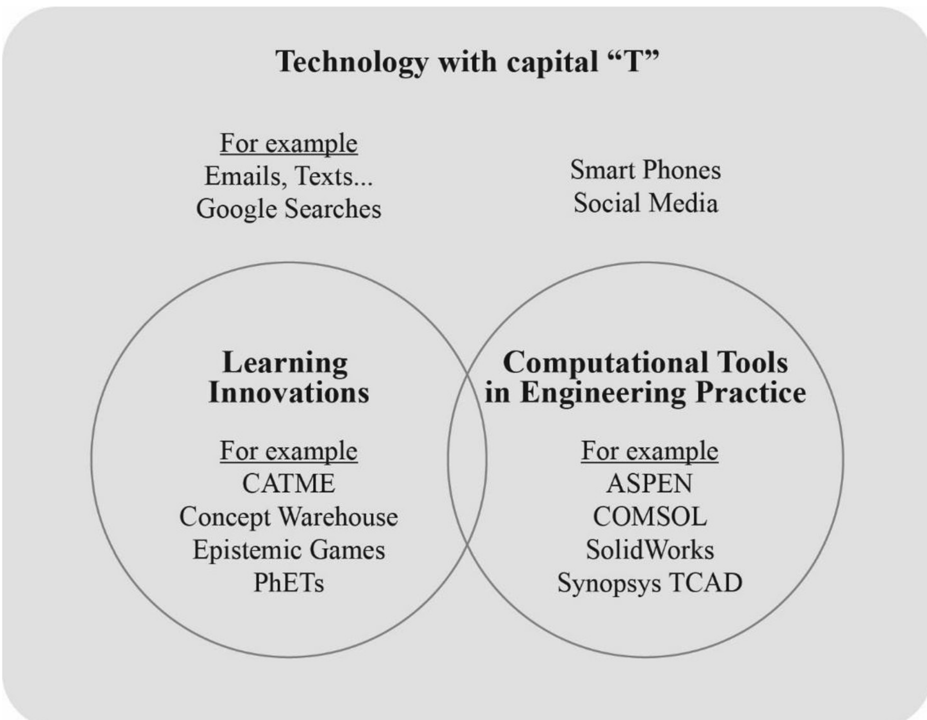

Figure 1. Three classes of computer technology (ICCT) in educational environments.

practice, and (c) Technology with a capital "T." Here, the first two categories, learning innovations and computational tools, sit as overlapping sub-sets within the overencompassing span of Technology with a capital "T." We believe that there is risk for cross-talk in the conversation when different interlocutors implicitly argue from different lenses. Thus, we make categories explicit and address each with separate issues. However, we recognize that specific cases can also be considered as appropriately belonging to multiple categories.

The three categories are defined as follows:

1. *Learning innovations.* We consider what Fishman and colleagues (2004) call *cognitively oriented technology innovations (COTIs)*, which we call *learning innovations*, for short. Learning innovations form a subset of computer technology that are intentionally developed for educational uses in classroom settings. They are specifically designed to foster deep thinking and meaningful learning "rooted in cognitive and constructivist learning theories" (Fishman et al., p. 45). With these innovations, "technology is employed as a tool to support teaching and learning, as opposed to the object of learning. These innovations often use technology to scaffold teaching and learning practices that would be difficult to achieve otherwise, such as making complex causal modeling accessible to students" (p. 46). In some instances, instruction is delivered entirely though the computer, while in others, devices form a distributed resource to promote productive face-to-face interactions and learning, such as when audience response systems (e.g. clickers) are used to support *peer instruction* (Mazur, 1997).
2. *Technology uses in engineering practice.* We define professional practice as real-world activities, actions, or applied skills where individuals must think and act in the modes of a particular discipline. We consider development of students' skill in technology used in engineering practice. Important technologies include disciplinary specific design tools like ASPEN in chemical engineering and SolidWorks in mechanical engineering and more general tools like high-level scientific computing programming languages (e.g., MATLAB) and software platforms for analysis and simulation (e.g., COMSOL).
3. *Technology with a capital "T."* We consider the broad impact of Technology change on the instructional environment in engineering. In this aspect, there are both positive (e.g., increased resources) and negative (e.g., access to solution manuals) ways that Technology impacts the learning environment. We need to understand and manage the affordances between Technology as a large force in society and the uses in education. From this lens, it is useful to identify how Technology fits into the cultures of engineering programs and the culture of higher education, with the goal of promoting systemic change towards more effective instruction.

ISSUES

Correspondingly, we organize the discussion with six main issues that have been identified through a Delphi study of engineering education experts as the focus for systemic change for the effective integration of technology in engineering education (Besterfield-Sacre & Shuman, 2016). Our analysis of the issues then draws on major policy reports of the use of technology in education (Hilton, 2002; Honey & Hilton, 2011; Johnson et al., 2014; Pea et al., 2003; Sharples et al., 2015; Woolf, 2010), specific discussions of the uses of technology in engineering education (Madhavan & Lindsay, 2014; Froyd, Wankat, & Smith, 2012; Cheville, 2012), and the general research literature on technology and learning in engineering, the learning sciences, and other related disciplines (completed Jan. 2017).

We discuss the following six issues as shown in Figure 2:

1. Alignment of technology with learning: well-propagated learning innovations
2. Alignment of technology with learning: computational tools in engineering practice
3. Alignment of technology affordances with learning outcomes: a case study of virtual laboratories
4. Alignment of technology with assessment
5. Alignment of technology with instructional practice: faculty beliefs and pedagogical knowledge
6. Broader considerations: Technology with a "T"

As Figure 2 illustrates, for both learning innovations (Issue 1) and use of computational tools in engineering practice (Issue 2), we consider the interacting components of instructional design including

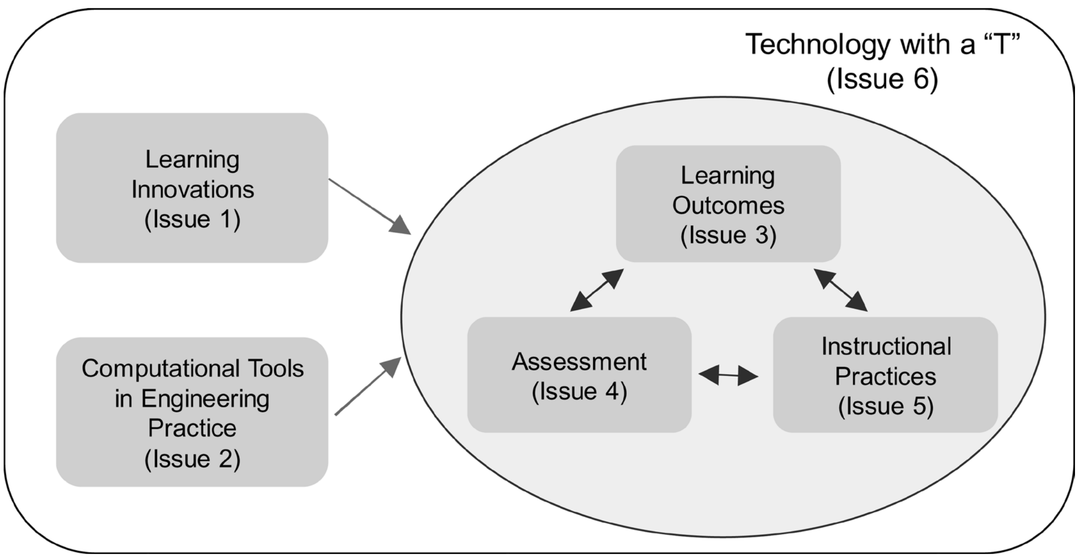

Figure 2. Six issues of computer technology in undergraduate engineering education.

learning outcomes (Issue 3), assessment (Issue 4), and instructional practice (Issue 5). These three components (Issues 3, 4 and 5) are the foundational elements considered when designing learning experiences and align with the elements of "backwards design" (Wiggins & McTighe, 2005). Finally, we address how all five issues are situated within the broader considerations of Technology (Issue 6).

For each of these issues, we first present a summary of our argument. We then present a synthesis of the literature of the current state of practice to support that argument, drawing from the research reports in the learning sciences, in engineering, and in related fields. We then provide a brief set of recommendations addressed at instructors, developers, researchers, administrators, policy makers, and other key stakeholders in engineering education.

Issue 1: Alignment of Technology with Learning: Well-Propagated Learning Innovations

In this section, we argue that educators need to intentionally align the development and use of learning innovations with learning processes (e.g., sense making, disciplinary practices) and with student engagement. At the same time, they must seek ways to use technology to scale effective instructional practices to mitigate ever increasing economic tensions in delivering high quality education (e.g., see Heller & Rogers, 2006).

We examined a set of exemplar learning innovations that have propagated well in engineering. These learning innovations were developed by collaborative teams and share the following broad characteristics:

- *Pedagogical Core*: They are all grounded in a core pedagogical approach that focuses on enhancing the experience of the learner, and the teams include pedagogy experts who centrally participate in technology development. This core pedagogical approach is usually theory-based but also has substantial empirical support.
- *Emergent Use*: They can be used in a diverse set of courses and can be flexibly implemented. This characteristic builds on a general set of *Core Components,* which lead to a broad *Span of Participation*.
- *Community Building*: They all contain strong community-building strategies and activities.
- *Research-Based*: They all have strong research on student learning integrated into the core project activity that is used to iteratively improve the technology-learning system and also keeps a core set of researchers engaged.

These four identified characteristics mutually support one another to allow high quality learning innovations to be developed and to scale. The Pedagogical Core ensures the innovation focuses on student activity and social interactions that are centered on evidence based practices (e.g., cooperative learning, concept-based active learning). Through Community Building, potential instructors and students learn about the innovation and are connected to others who use it. Emergent Use allows the innovation to be implemented in a variety of settings, both making it better fit the needs of individual instructors, and also providing the developers access to variations in learning environments to learn what works and where there might be opportunities for improvement. Research-Based means that the learning innovations are grounded in learning theory and that there are continued cycles of design-based implementation research that lead to iterative improvements and expansion of their scope.

We illustrate these four characteristics with four exemplar learning technologies as shown in Table 1: CATME, the Concept Warehouse, PhETs, and SCALE-UP. The first two systems were developed specifically for use in engineering while the second two were initiated in the physics education research community, but have shown significant propagation to engineering. The values for the extent of propagation reflect the status as of Jan. 2017.

The web-based Comprehensive Assessment of Team Member Effectiveness (CATME) system is built upon cooperative learning, a pedagogy developed by Johnson & Johnson (1999) based on social interdependence theory. Cooperative learning has shown strong positive effect sizes on student achievement, interpersonal relations, and psychological health (Johnson et al., 2000; Johnson & Johnson, 2009). CATME provides a web-based support for cooperative learning that includes several Core Components to enable instructors to more effectively manage teams. Training modules and meeting supports help students learn core socio-cognitive concepts of teamwork and teaming behaviors. One of its tools, the Team-Maker (Layton, et al., 2010), has an algorithm that lets instructors form teams based on their criteria and information submitted by students. CATME Peer Evaluation (Ohland, et al., 2012) and the associated rater training system allows self- and peer- evaluation processes that are research-based, building on the team effectiveness research literature to create a valid and reliable behaviorally anchored rating scale for team-member effectiveness. Through social media and in-person community building activities, CATME has reached 650,000 students of 12,000 faculty members at 1,900 institutions since 2005 that includes a Span of Participation across engineering, business, and other disciplines.

The pedagogical core for the Concept Warehouse is concept-based active learning (Koretsky et al., 2014). The Concept Warehouse houses a set of tools to lower the activation barrier for instructors to implement concept-based active learning in their classes. Its Core Components include ConcepTests, concept inventories, interactive virtual laboratories, and inquiry-based activities. These materials support what Chi (2009) calls *interactive activities* where students are both are cognitively active (e.g., students responding to conceptual questions) and participate in socially collaborative discourse where they make connections to the course topics while talking to one another [e.g., by using peer instruction (Lasry, Mazur, & Watkins, 2008; Mazur, 1997)]. The connectedness of concepts is promoted by having students reason through concept-based questions, link them to more extensive activities (interactive virtual laboratories, inquiry-based learning activities), reflect on the

Table 1. Examples of university-developed learning innovations that have evidence of propagation.

Learning Innovation	Public Release	Extent of Propagation	Pedagogical Core	Emergent Use: Core Components	Emergent Use: Span of Participation	Community Building	Research Activity (Examples)
CATME www.catme.org/	2005	12,000 faculty 650,000 students 1,900 institutions USA and International	Cooperative Learning – Team skills	Assignment of students into teams; peer evaluation; peer rater calibration; teaming scaffolds	Engineering, business,	Linked-in CATME User group; Workshops at professional society meetings	Team assignment (Layton et al., 2010); Peer evaluation (Ohland, et al., 2012; Loughry et al., 2007); Teamwork Skills (Loughry et al., 2014)
Concept Warehouse cw.edudiv.org/	2012	1,000 faculty 25,000 students 200 institutions USA and International	Concept-based active learning	ConcepTests; concept inventories; interactive virtual laboratories; inquiry based activities	Core chemical engineering courses; some related engineering disciplines (ME, MS)	Workshops at professional society meetings; Webinars; Community newsletter	Propagation (Friedrichson et al., 2016; Koretsky et al. 2014); Role of written justification (Koretsky et al., 2016a, 2016b; Brooks et al., 2016)
PhETs phet.colorado.edu/	2002	~130 simulations 40,000,000 "uses" USA and International	Self-guided scientific inquiry	Interactive simulations (feedback, implicit scaffolding, multiple representations, pedagogically useful actions, intuitive interface)	Science (physics, chemistry, biology, earth science) and mathematics	Website enabled support tools, e.g., teacher activity sharing; tips and resources to use PhETs and develop activities	Simulation design, scaffolding, and exploration (Adams et al., 2008; Podolefsky et al., 2010); In-class use (Chamberlain et al., 2014; Finkelstein et al., 2005).
SCALE-UP scaleup.ncsu.edu/	1997	300 departments 200 institutions USA and International	Cooperative Learning – Learning space	Classroom architecture and technology support (e.g., round tables with 9 students; whiteboards, …)	STEM courses (most in physics, 30%, engineering 7.5%)	Workshops; website with videos	Student learning (Beichner et al., 2007; Beichner et al., 2000) and retention (Dori et al., 2003); Propagation (Foote et al., 2014)

activities, and demonstrate understanding through assessment (concept inventories). The Concept Warehouse has three distinct but complementary functions: (i) a repository of resources with high quality topic-specific content, (ii) an audience response system and learning management system to deliver the content, and (iii) learning analytics that provide assessment data of student responses to instructors and researchers. Although relatively young, its Community Building activities have led to propagation within chemical engineering and related disciplines (Freidrichson et al., 2016). The Concept Warehouse has reached 1,000 faculty members at 200 institutions since 2012 that includes a Span of Participation across chemical engineering and other related engineering disciplines.

Similarly, the two physics initiated technology systems, PhETs and SCALE-UP, share the characteristics of Pedagogical Core, Emergent Use, Community Building, and Research-Based. PhETs are a set of over 100 simulations that have been developed primarily for the physical and life sciences and are based on a core pedagogy of scientific inquiry. The simulations use multiple representations and have built-in, implicit constraints to allow students to learn scientific principles. In engineering, they are used mostly in core, introductory engineering science courses like material and energy balances. Like CATME, SCALE-UP is also built on cooperative learning pedagogy. However, it deploys technology quite differently. It provides an architectural model to support cooperative learning in large classrooms. More detail about how PhETs and SCALE-UP align to the characteristics we have identified is provided in Table 1.

Recommendations

We recommend that, as much as possible, innovators work together to form collaborative teams and build technology *systems* with the four characteristics identified above: Pedagogical Core, Emergent Use, Community Building, and Research-Based. While we acknowledge the role of individual innovators is important, we recommend funding agencies include this type of broad, collaborative pedagogically-centered innovation as a key component to their portfolios. To this end, funding agencies could support small symposia or workshops that allow targeted networking of PIs with related but complementary expertise. These projects have potential to "cross the chasm" into mainstream use and achieve sustainable scalability.

To work towards sustainable scalability, we recommend that education policy makers explore strategic and holistic approaches to technology development, such as considering technology "generations" to map out stages in potential university - industry partnerships. We could envision the earliest stages being single investigator for visionary high-risk proof-of-concepts, then collaborative university projects like the ones identified in Table 1 for broader implementation with pedagogical integrity, and finally university-industry partnerships or other vehicles (e.g. open source) to commercialize and bring to scale. Such strategies would lead to technologies that are not only research-based, but where research provides and integral part of the development and propagation. *Such an approach would lead to significant scale through continuous iterative improvement but, importantly, also be likely to keep the core pedagogical integrity of the innovation.*

Through these stages, the engineering education community needs to distinguish between general approaches that are inherently less effective and poor implementation of potentially fruitful approaches. While the strategy we recommend partially addresses this by having the innovations used in different ways and in different contexts, research is needed to identify characteristics that allow the community to distinguish between ineffective tools and poor implementation. The community also needs to address issues of technology failure and reliability, which make faculty reluctant. Current research practices discourage communication of this type of information; rather robustness and reliability studies could accompany a coordinated approach through technology generations.

We encourage programs like the Innovation Corps for Learning (I-Corps L; Chavela Guerra & Smith, 2016) where academic technology developers form teams and learn entrepreneurial tools and methods that underlie successful start-up companies. Importantly, like in I-Corps L, innovators should be challenged to step out of their local contexts and identify the value of the learning innovation to the broader community.

Issue 2: Alignment of Technology with Learning: Computational Tools in Engineering Practice

We argue that educators need to align expert uses of domain-specific computational tools with their affordances for connecting to engineering practice and to foundational disciplinary background knowledge. At the same time, they need to devise proper scaffolding methods or adaptations of the tools for novice learners to become fluent in the use of professional computational tools.

With Issue 2, we focus on computer technology in engineering practice as domain-specific computer software, tools, and packages that embed mathematics and/or engineering principles (herein called computational tools). Examples of these technologies include simulation and design tools like ASPEN in chemical engineering and SPICE in electrical engineering, and more general tools like numerical computing or analysis tools (e.g., MATLAB, COMSOL). The importance of developing this type of technical proficiency has been identified by many engineering education stakeholders. National reports such as the Transforming Undergraduate Education in Engineering report ([ASEE], 2013), recently identified that industry professionals value the ability to use computational tools to support problem solving and design thinking. For instance, an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice is a stated ABET (2013) student outcome and is reflected in the Washington (2011) and Dublin Accords (Patil , & Codner, 2007).

The use of these tools has consistently been identified as relevant to engineering practice over the last 100 years (e.g., Landau & Rosenberg, 1986; Mann, 1918), and consequentially has become an important part of undergraduate curricula, especially in the senior year. Typically engineering students use simulation and design tools as an extension of the analytical methods they learn in engineering science classes to more complicated systems and processes that they will face in engineering practice (Dahm et al., 2002). In this vein, simulations provide a critical computational tool for practice and just about every engineering program inevitably uses some type of commercial simulation, e.g., ASPEN, HYSIS, SolidWorks, or Synopsys TCAD, where students are asked to predict performance of an artifact or process unit (Lewin et al., 2004). For example, the 64 institutions responding to a survey of how design is taught in chemical engineering all reported the use of some kind of domain-specific process simulation software (e.g., ASPEN, ChemCAD) (Silverstein et al., 2013). Similarly, about 75% of the 73 respondents to a survey of mechanical engineering programs revealed that students were required to take a course to learn a general numerical computing tools (e.g., MATLAB, MAPLE) and then use that tool in the upper-division (Steele & Hodge, 2001).

In Figure 3, we present a conceptual organizer for the role of computational tools for learning engineering. Clearly, students need to learn first how to work with the tool and thereby become reasonably fluent with it (top circle). With fluency, accompanying mental models form about how a

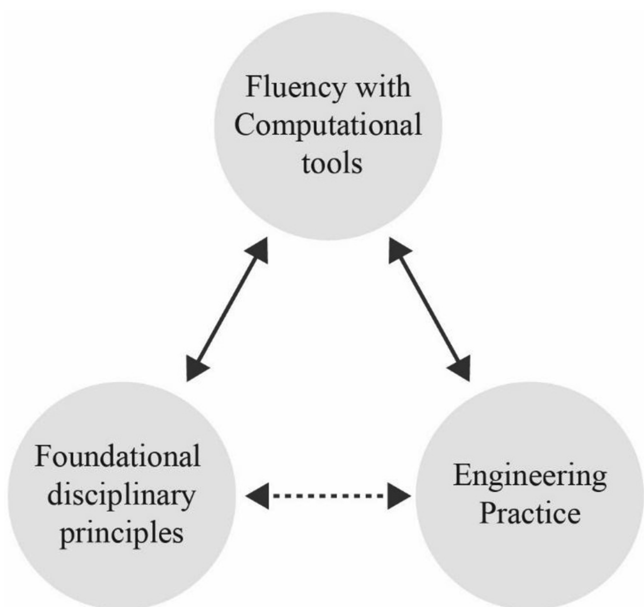

Figure 3. Computational tools as a bridge between foundational principles and engineering practice.

particular type of tool is structured and what the computational sequences entail. This conceptual understanding allows transfer within tools of the same type. For example, experience with one computational fluid dynamics (or statistics or process design) package can provide a type of knowledge that makes it easier to use another. We also believe the use of these tools can reinforce foundational disciplinary principles and concepts, and develop understanding in students of how this knowledge can be extended and applied to engineering practice (Magana, Falk, Vieira, & Reese, 2016). From this perspective, the use of computational tools can be seen as a bridge to help connect classroom learning to practice (dashed line). However, instructional strategies are needed to ensure students have sufficient fluency with the tool itself so that they are able to make these connections, and to develop activities and practices that support students in making such connections.

Pedagogical Supports to Develop Fluency

To make expert tools more accessible for novice learners to develop fluency, instructors can scaffold activity and thereby reduce the cognitive load on students. The cognitive load model posits that memory resources limit the amount of processing that can occur during problem solving (Sweller, 1988). When a task exceeds the learner's cognitive load, the learning benefit becomes limited (Paas, et al., 2004).

A very common pedagogical approach for developing fluency with computational tools has been through a guided activity by the instructor (e.g., Khan & Singh, 2015; Toto, Colledge, Frederick, & Pung, 2014), or by means of a self-paced or online tutorials (e.g., Beg, 2015; Castrellón, Botía, Gómez, Orozco, & Gil, 2011; El-ZEin, Langrish, & Balaam, 2009; Impelluso, 2009; Uribe, Magana, Bahk, & Shakouri, 2016). Another scaffolding strategy aimed to reduce cognitive load is the use of worked-examples. A worked-example is an expert solution to a problem (Atkinson, Derry, Renkl, & Wortham, 2000). By studying worked-examples students can start to solve problems by analogy, until they reach a stage of fluency in which they are able to solve other problems on their own (Sweller, Ayres, & Kalyuga, 2011). This scaffolding strategy is especially useful for novice learners who still may not have background knowledge (i.e. schemata) that would enable them to do problem solving from the beginning. The use of worked-examples has been identified as a useful strategy in supporting learning with engineering computational tools (Morrison, Margulieux, & Guzdial, 2015; Vieira, Yan, & Magana, 2015; Vieira et al., 2019). One way in which students can be prompted to actively explore the worked-examples is by engaging them in explaining the examples to others or themselves (Atkinson et al., 2000). Although the benefits of explanations in computer programming have been explored for more than twenty years (e.g., Pirolli & Recker, 1994), specific strategies on how to implement these as sense making strategies to help engineering students relate programming knowledge with disciplinary knowledge have just started to emerge (Vieira, Magana, Falk & Garcia, 2017; Vieira, Roy, Magana, Falk, & Reese, 2016; Vieira, Yan, & Magana, 2015). We next address research on how the use of computational tools ties back to foundational principles and concepts.

Foundational Principles and Conceptual Understanding

Unfortunately, learning gains resulting from the uses of computational tools in the classroom have not been thoroughly reported in the literature and the few instances identified are not conclusive. Studies have primarily reported students' level of satisfaction and found that students commonly believed that computational tools are useful for their learning (e.g., Ayasun & Nwankpa, 2006; Brinson, Belytschko, Moran, & Black, 1997; Castrellón et al., 2011; Hoole, Sivasuthan, Karthik, & Hoole, 2015; Impelluso, 2009; Khan & Singh, 2015). Other studies have reported learning gains when students' solutions to projects, exams or homework assignments are compared to other courses or with previous offerings of the same course before changes were implemented. For example, a study with 151 students who performed computational analysis and model validation against experimental response using Java, Maple or MATLAB reported mixed results. Examination of pre and post-activity testing revealed that the upper 27% of students showed a significant improvement on most of the questions following the completion of the module while the lower 27% showed mixed results (Khan & Singh, 2015). Another study that implemented Computational Fluid Dynamics models and analysis of results in electronics revealed a significant increase in student understanding of fundamental thermal management principles (Okamoto, Hsu, & Bash, 2009).

A study reporting pretest and posttest evaluations in an undergraduate environmental engineering course identified that introducing the concept of scaling and its application (using computer models) into undergraduate engineering courses enhanced students' learning and decision making skills (Najm, Mohtar, Cherkauer, & French, 2010). Likewise, Alabi and colleagues (2015) identified similar results when using the Gibbs tool (Cool, García, & Bartol, 2015) to support students' understanding of thermodynamics concepts. They concluded that the use of the Gibbs tool might have helped students develop representational competence. More work is needed to share instructional design strategies and practices of how students can explicitly connect foundational disciplinary principles to the use of computational tools, especially the domain specific design tools. Importantly, research is needed that provides evidence of how these practices lead to students' developing conceptual understanding.

Engineering Practice

We next address the ways computational tools can be used in educational settings to extend student knowledge as it is applied to engineering practice. Several affordances of computational tools in supporting development of the skills needed in engineering practice have been identified, including: problem solving (e.g., Delale, Liaw, Jiji, Voiculescu, & Yu, 2011), analysis, calculation and optimization (e.g., Brinson et al., 1997; Castrellón et al., 2011; Hoole et al., 2015; Khan & Singh, 2015), modeling and simulation (e.g., García–Herreros & Gómez, 2013; Najm et al., 2010; Okamoto, Hsu, & Bash, 2009); 3D modeling (e.g., Toto et al., 2014), integration of programming skills (e.g., El-ZEin et al., 2009; Impelluso, 2009; Magana, Falk, & Reese, 2013), connecting or enabling operation of hardware, equipment, sensors and other cyber-physical systems (Magana & Coutinho, 2017), and characterization and experimentation skills (e.g., Ayasun & Nwankpa, 2006; Beg, 2015). However, information of how engineering practices were enacted by students and the effects on their learning these skills (i.e., design skills, modeling and simulation skills, problem solving skills, and computation skills, among others) are often incomplete or lacking. Additionally, one might consider doing engineering work effectively within these computational tools as a skill within itself.

To develop instructional strategies, educators should draw on ethnographic studies that have identified the ways computational tools are used in engineering practice (Vinck, 2003). For example, Auregemma and colleagues (2013) investigated the design process of a microfluidic lab-on-a-chip device. The developers used CAD software, COMSOL, and MATLAB in an iterative process that involved mental models, computational models, and building and testing prototypes. In another study of an authentic and industrially situated process development design task, Sherrett and colleagues (2013) found that experts used computational tools in a design process which included information gathering, problem formulation, and iterative modeling and experimentation. Results from the ethnographic analysis characterized the experts' solution into fourteen competencies.

These findings suggest a critical step in the process of designing instruction for the use of computational tools consists of first identifying the ways professionals use them, followed by a clear definition and proper guidance to enact the practices or competencies the tool affords. Along this line, Magana and Coutinho (2017) proposed a range of possible affordances of computational tools for supporting a wide variety of modeling, simulation and experimentation practices. The practices they proposed were aligned with different curricular levels as informed from experts in industry and academia. Building on this idea, Magana and colleagues (Magana, Falk, Vieira, & Reese, 2016; Vieira, Magana, Roy, Falk, & Reese, 2016), explicitly aligned desired professional practices afforded by the computational tools with disciplinary learning objectives for core undergraduate courses in a materials science and engineering program.

While experts fluently apply computational tools to their design work, integrating these practices into the undergraduate curriculum is challenging. Diefes-Dux and colleagues (2004) investigated the effectiveness of a multi-level, steady-state food process design tool. They evaluated students uses of Foods Operations Oriented Design System Block Library (FOODS-LIB) running in the MATLAB-supported SIMULINK simulation toolbox. The activity was delivered via seven online learning modules where students used the existing unit operations library to study a single effect evaporator model and construct a new generalized unit operation: compositional split. The implementation took place over an eleven-week period. While students successfully completed the learning modules, they were unable to transfer their knowledge and skills to the design of processes. They identified weak MATLAB coding skills and students' inability to conceptualize or write out algorithms for their designs as barriers to productive use of this tool in practice. A similar conclusion was found by García–Herreros and Gómez (2013) in a study that evaluated students use of process simulators through the modeling and optimization of a crude distillation unit using PRO/II 8.0. They also found a barrier in using computational tools in practice and concluded that the main problem was the lack of convergence of the model as a result of poor initial estimates. They attributed it to student shortcuts amidst deadline pressures and lack of understanding of the tool's optimization algorithms. These two studies suggest that algorithmic (computational) thinking may be challenging for students and this way of thinking needs to be progressively developed and supported when using computational tools in engineering practice.

Integration of Conceptual Tools

We argue that the use of computational tools for teaching engineering is most effective when there is alignment between learning outcomes, pedagogical methods and supports, and technology uses (Chen et al., 2000; Kadiyala & Crynes, 2000). We believe that the alignment of learning objectives and affordances of computational tools is not enough. We recommend that instructional design methods, pedagogical strategies, and scaffolding methods be identified and properly embedded into the instructional environment, so students can fully benefit from the integration of computational tools for learning.

Instructional design principles, such as the How People Learn (HPL) framework (Bransford, Brown, & Coocking, 2000) can help educators address issues of the types of integration depicted in Figure 3. The HPL framework focuses on instructional design that is (a) leaner-centered by first considering students' required background knowledge and possible challenges they may encounter when learning with computational tools; (b) knowledge-centered by explicitly connecting disciplinary knowledge with engineering practices via the computational tool; (c) assessment-centered by providing students with frequent feedback and opportunities to improve their work; and (d) community-centered by allowing students to learn from each other. For instance, two studies have reported on scaffolded instructional design using the HPL framework to plan and integrate engineering computational tools into engineering courses (Greenberg, Smith & Newman, 2003). These studies show that with scaffolding students demonstrated significantly better understanding, but they found the demands extremely challenging compared with other courses. Alternatively, designers have developed scaffolds based on Cognitive Load Theory (Guzdial, 1994; Sweller, 1994; Vieira, Magana, Roy, Falk, & Reese, 2016). While this approach has elicited positive feedback from instructors and students (Impelluso, 2009), more research is needed that identifies how and when students are overloaded and what effective supports can be provided to overcome such difficulties.

Finally, students' attitudes and beliefs about computational tools can shape how they engage in learning. One study has found that male students tend to have more positive attitudes than female students (Hornaes and Royrvik, 2000). In another study (Hutchison, Follman, Sumpter, & Bodner, 2006), researchers found students who listed computing as an important influence on their self-efficacy beliefs frequently cited their ability to use one or all of the computing tools taught in a course, their programming abilities, and their ability to use a computer in general. Gender trends emerged in student responses to factors that affect confidence in success. Specifically, relatively few men saw computing as negatively affecting their self-efficacy beliefs; while in contrast, nearly one-third of women reported computing as negatively affecting their self-efficacy beliefs. However, results reported from Magana and colleagues (2016; Vieira et al., 2018) suggest that frequent exposure to computational tools and methods may increase students' self-efficacy beliefs and their value of these tools for their academic and professional careers.

Recommendations

Our recommendations from this issue are addressed to engineering educators and engineering education researchers. In summary, we posit that students must first develop fluency in using a domain-specific computational tool, and that associated mental models will develop allowing for more routinized use and for transfer to other tools of the same type (e.g., between computational fluid dynamics packages). Fluency can be developed more quickly through pedagogical supports, embedded scaffolding, or adaptations of the computational tools in order to lower the barrier of entry and diminish cognitive overload. For example, engineering educators should consider the use of worked-out examples. However, research is needed to better characterize the mental models that form in learners while developing fluency, what instructional strategies best develop the models, and how the models connect to the transfer to other similar tools.

We advocate for two elements to be included in instructional design progressions when integrating computational tools: (i) have students connect the use of these computational tools to foundational disciplinary knowledge, and (ii) engage students in uses of the tools that reflects professional practice. We also posit that increased fluency gives students cognitive bandwidth to make connections to foundational disciplinary knowledge and to engineering practice. But again, research is needed to better understand these relationships. Indeed, we might imagine that fluent use of computational tools increases disciplinary knowledge and that such increases feedback to increased capability with the tool itself.

Developing fluency and making connections is a complex process. Therefore, we recommend vertical integration of the use of the appropriate set of domain-specific computational tools throughout the undergraduate curriculum (e.g., Hinds & Somerton, 2007; Hinds, Urban-Lurain, Sticklen, Amey, & Eskil, 2005; Sticklen, Amey, Eskil, Hinds, & Urban-Lurain, 2004; Urban-Lurain, Amey, Sticklen, Hinds, & Eskil, 2004), so students not only develop technical fluency but also confidence and self-efficacy and see the value in using these tools. Strategies need to be developed in the viable ways for faculty to interact in this type of curricular coordination.

We recommend that instructional activities deliberately follow instructional design frameworks, such as the HPL framework, to guide the learning process. For example, educators could consider a four-step instructional design process consisting of:

a. deliberately connecting the use of the domain-specific computational tool with both foundational disciplinary principles and with realistic engineering practices,
b. taking those connections and then identify a pedagogical approach and a set of scaffolds that can properly support student learning,
c. providing frequent feedback along with opportunities to iteratively improve their work, and
d. properly identify assessment mechanisms that truly evaluate students' gains of foundational disciplinary principles, but more importantly how students improve their performance in enacting engineering practices when engaging with computational tools (see Issue 4 for more details about assessment).

We advocate for research that provides concrete evidence of the learning when using these tools (e.g., Magana, Fennell, Vieira & Falk, 2019), along with transferrable understandings of how computational tools of engineering practice can be effectively be incorporated into learning activities, particularly in ways that respond to the rapid changes in the function and capability of these tools. To this end, we also advocate development of interaction models between industry and academia that allow identification of the changing ways that practitioners use computational tools in practice and allow translation to educational activities and learning systems.

Issue 3: Alignment of Technology Affordances with Learning Outcomes: A Case Analysis of Virtual Laboratories

With Issue 3, we consider transformative potentials of computer technology for learning. We argue that the most effective learning innovations are not pallid, clones of traditional learning environments. Rather, they identify and leverage the affordances of technology to support engaged learning environments that reconstitute the ways students interact with the content, with each other, and with knowing others (e.g., instructors or peer mentors)[2]. To provide an analogy, we believe too many learning technologies are developed in a way similar to seeking to provide a credit-card reader for the taxi driver

[2]In analogy, in the *Victorian Internet*, Tom Standage (1998) describes the initial conceptualizations of the telephone as a "'speaking telegraph' – an improvement of an existing technology rather than something altogether different"

to more readily accept fares rather than reconstituting the environment the way companies like Uber and Lyft have.[3] From this perspective, learning innovations are most effective when they do more than provide an alternative mode for existing instruction but extend to embody paradigmatic shifts in the ways learners interact with content, peers and instructors to generate learning. These interactions can lead to shared creation, collaboration, and mastery of knowledge.

When assessing and evaluating technology, there is an inclination to focus on the "category" of technology rather than thinking about the opportunities for learning the technology affords, the ways it can fit into instructional design to take advantage of those affordances, and the potential obstacles that may need to be addressed in different learning contexts. Without articulating the thinking processes and social interactions they want students to experience, educators may tend to revert and use technology to support traditional types of instruction. Alternatively, a more fruitful approach is to recognize ways that technology enables interactions between the student and other learners, the instructor, and content that are not otherwise possible. Such an approach more fully utilizes the affordances of technology to engage learners and produce learning.

We choose the virtual laboratory (de Jong et al., 2013; Koretsky et al., 2008; Ma & Nickerson, 2006) as an exemplar to illustrate different ways that a single technology category can be integrated into learning systems towards different instructional purposes and learning goals. In a virtual laboratory (also called a simulation laboratory), computer simulations based on mathematical models provide values of output variables in response to user-selected input variables. Students work with representations of laboratory apparatuses on the computer to observe and make measurements of targeted phenomena based on the simulated output. We use the term virtual laboratory to contrast the students' orientation in the learning activity with the more common use of simulation in the post-secondary engineering classroom, as was discussed with Issue 2. In summary, we refer to engineering simulations as tools students and practicing engineers use to apply theory to engineering analysis and design whereas we use virtual laboratory to emphasize facilitated "laboratory-like" student exploration of the phenomena associated with a specific system, device, or process.

We choose the virtual laboratory as an example of the different ways engineering educators and technology developers have leveraged the affordances of technology in their instructional designs. We begin with designs that essentially use the technology in the same way as traditional instruction and progress to other ways that technology is leveraged in unique and deliberate ways. While the

(p. 197). We argue that in a similar way, educators should conceive how computer technologies can transform the fundamental social and cognitive interactions that produce learning rather than merely reproducing earlier practices.

[3] If we pursue this analogy further, educators might consider how these technologies disrupt existing social systems, and the positive and negative ramifications of the disruption.

case is made in the context of the virtual laboratory, we argue that these fundamental considerations apply to many emerging learning technologies such as electronic textbooks and audience response systems. In fact, this example was chosen, in part, since it is straight-forward to envision the design choices we describe in the development of emergent technologies like immersive virtual reality where students can have the perception of being physically present in the non-physical world (Freina & Ott, 2015).

Analog to Current Instructional Laboratory Use (replacement and preparation)

In its most common rendition, the virtual laboratory simulates the same phenomena as a corresponding physical laboratory at the university. Virtual laboratories with this instructional design can be used to replace the analogous physical laboratory where students are asked to do the same activity, only on a computer screen (Sehati, 2000; Shin et al., 2000; Wiesner and Lan, 2004, Pyatt and Sims, 2007). In some cases, care is taken to word the tasks identically in the virtual and physical modes (Finklestein et al., 2005). This use of virtual laboratory technology has benefits: it requires fewer resources, provides greater flexibility in scheduling, and experiments can be run quickly providing immediate feedback for students. Learning outcomes between the physical and virtual modes have been compared via pre-post testing, written and oral exam analysis, and surveys. Findings often show equivalent, and occasionally greater, learning gains in the virtual mode, especially towards connecting the laboratory activity to foundational disciplinary concepts (Wiesner and Lan, 2004; Campbell, Bourne, and Mosterman, 2002; Powell et al, 2002; Finklestein et al., 2005; Lindsay, and Good, 2005; Zacharia, 2007; Pryatt and Sims, 2012; Zacharia and Olympiou, 2011). Differences in learning outcomes between physical and virtual laboratories have been attributed to: shifts in focus from working with the equipment to collect data to understanding the causal relations between variables and outputs (Kolloffel and de Jong, 2013); variations in the patterns of collaboration among students (Corter et al., 2007); and the greater control that each student has over his or her own learning (Hazel and Baillie, 1998). *However, when it is used solely to replace a corresponding physical laboratory, the enactment of technology sits within a traditional curricular structure. We argue next that there is greater opportunity for technology to impact student learning when technology is leveraged to reconceive instructional designs and even more so when it is used to reconceive the learning system, itself. It is these uses that take greatest advantage of the affordances of technology.*

The simplest way to modify an instructional design is to have students use the virtual laboratory in preparation for the physical laboratory. Here, the virtual laboratory technology allows the experiment to be practiced, stopped and repeated (Abdulwahed and Nagy, 2009; Hodge et al., 2001; Mosterman, et al., 1994; Rutten at al., 2012; Zacharia, 2007). A number of studies confirm that using virtual laboratories for preparation enhances the effectiveness of physical laboratories (Akpan &

Strayer, 2010; de Jong, Linn, & Zacharia, 2013; Jaakkola et al., 2011; Kolloffel and de Jong, 2013; Pyatt & Sims, 2012; Toth, et al., 2009; Zacharia, Olympiou, & Papaevripidou, 2008).

Added Representations

Rather than adhering to the sensory limits of a physical laboratory, virtual laboratory technology affords added representations that are not possible in the physical world. Indeed, Lindgren and Schwartz (2009) suggest that making the virtual laboratory as faithful as possible to the real laboratory might deter from its pedagogical effectiveness. Virtual laboratories have been extended beyond their physical analogs, usually with the intent of more effectively helping students develop conceptual understanding. One common enhancement is the inclusion of visual cues or alternative representations not possible to observe in physical laboratories such as emergent molecular interactions, the flow of electric current, and vector electric or magnetic fields (Bowen, Reid, and Koretsky, 2015; Brophy, Magana, & Strachan, 2013; Corter et al., 2007; Dorneich & Jones, 2001; Finkelstein et al., 2005; Schank & Kozma, 2002; Sengupta and Wilensky, 2009; van Joolingen & de Jong, 2003; Wieman et al., 2008). Additionally, the instructional design strategies of *in preparation* and *representation* can be combined. In a set of electrical circuits experiments, Zacharia and de Jong (2014) showed similar learning gains between the physical laboratory alone and the virtual laboratory as preparation for the physical laboratory in simpler experimental configurations, but higher gains when the virtual mode is included for more complex configurations. They attribute the latter result to the technological affordance of visualization of the current flow. These molecular and field representations allow technology to uncover the invisible and provide a dynamic venue for students to construct conceptual understanding.

Thinking in Disciplinary Contexts

In another approach, instructional developers have used virtual laboratory technology to situate learning in disciplinary practice (Koretsky et al., 2015, 2019; Shaffer, 2006). Here technology can be used to simulate processes that would not otherwise be available at the university due to their complexity or incompatible length and time scales (e.g., Uribe, Magana, Bahk, & Shakouri, 2016). This pedagogical strategy supports learning by placing learners in real-world contexts and prompting them to shift from the role of student to the role of scientist or engineer. Learning activities are then organized to foster productive participation in the practices of disciplinary communities by providing the learner an opportunity to apply disciplinary tools and concepts to make meaning of observed phenomena and design processes and products. This context allows students to engage in interlocking material, conceptual, epistemic, and social aspects of disciplinary practice in ways that catalyze student learning (Ford & Forman, 2006; Koretsky et al., 2019; Pickering, 1995, Shaffer, 2006;

Windschitl and Calabrese Barton, 2016). In this way, virtual laboratory technology can complement and extend student experiences in disciplinary practice beyond capstone projects and internships. As examples presented below illustrate, when technology is deployed in this manner, it does not directly replicate typical learning systems at the university, but rather allows students to experience aspects of the professional context that they would not otherwise have access to.

The use of virtual laboratory technology that is situated in contexts of practice is much more common in the sciences than in engineering. Thus, we first discuss learning systems that place learners in the role of scientists and center on the practice of inquiry, then we extend the discussion to learning systems in engineering around aspects of design.

Scientific Inquiry. A host of virtual laboratories have been developed in response to educators and policy calls to engage students in scientific inquiry (de Jong & van Joolingen, 1998; Edelson, Gordin, & Pea, 1999; Nelson and Ketelhut, 2007). In inquiry-based learning, students engage in experiments in a manner designed to align, as much as possible, with practicing scientists. Such practices include: formulating questions, developing hypothesis, planning investigations, critiquing experiments, revising models, arguing from evidence, and negotiating explanations with peers (National Research Council, 1996; de Jong & van Joolingen, 1998, Linn et al., 2003; Windschitl and Calabrese Barton, 2016).

One approach to using technology in this way is to create immersive worlds for students to engage in similar types of inquiry processes as experienced in practice. For example, multiuser virtual environments (MUVEs), such as *River City* (Dede et al., 2004), *Quest Atlantis* (Barab et al., 2005), and *Habitable Worlds* (Horodyskyj et al., 2018) allow students to take on the role of scientist and observe and measure phenomena. In contrast to most physical laboratories at the university, students can gather data continuously over days or weeks, an affordance that allows students to iteratively modify their hypotheses in light of new information and understanding, and also, gives them time to develop that understanding (Nelson and Ketelhut, 2007). MUVEs afford an iterative element to science inquiry by providing opportunities to test hypotheses by manipulating independent variables and observing any changes in the environment.

Alternatively, the virtual laboratory can provide a resource for dynamic data collection while the conceptual processing is supported by a pedagogical design that relies on face-to-face student-student and teacher-student interactions in the classroom. For example, Bell and Trundle (2008) described the virtual laboratory *Starry Night Backyard* that allow students to observe moon phases from any location on earth over long time periods without being hindered by experimental obstacles like weather, physical obstructions, or time of day. This virtual laboratory is used in conjunction with McDermott's (1996) instructional design that promotes the cognitive dissonance that can lead to conceptual change. In a variation of the hybrid approach, Raineri (2001) described an instructional design where students first perform experiments in the physical laboratory and then use a virtual laboratory to iteratively generate and analyze new data sets and to perform experiments that are too expensive and time consuming to perform in the physical laboratory. Raineri's design allows students to engage in analysis practices and to gain experience with state-of-the-art techniques in molecular biology that would not be possible in the physical laboratory alone.

The description of scientific practice as "inquiry" has been criticized as broad and vague (Windschitl and Calabrese Barton, 2016). An alternative conception is that modeling is a core scientific practice. Based on this pedagogical commitment, virtual laboratories have been developed to guide students to construct scientific models to relate the data from the phenomena to scientific principles and theories (de Jong and van Joolingen, 2008; Giere, 1999) such as modeling photosynthesis in *Co-Lab* (van Joolingen et al., 2005) or the response of airbags in automobile collisions in *WISE* (McElhaney and Linn, 2011).

Engineering Design. While the practices of science focus on inquiry, engineering work focuses on the design of products and processes to meet social needs (Dym, Agogino, Eris, Frey, & Leifer, 2005; Simon, 1996); therefore, virtual laboratories focusing on engineering practice inevitably center on design. The design process is built around iteration, where a design idea is improved based on the identified shortcomings of previous attempts (Crismond, 2001; Cross, 2006; Dym et al., 2005). Identified shortcomings allow a feedback cycle where the designers can identify gaps in their knowledge and understanding, providing impetus for further learning. For engineering professionals, this practice of knowledge building through iterative design cycles is critical (Vincenti, 1990). The ability of virtual laboratories to simulate phenomena of a wider range of length scales, time scales, and complexity than available in the physical laboratory affords iteration in realistic design tasks (Koretsky et al., 2008). However, virtual laboratories based on design tasks are far less common than those based on scientific inquiry (de Jong et al., 2013).

Xie and colleagues have developed a set of virtual laboratories in which high-school students either design a house or an entire city block to maximize energy efficiency (Xie et al., 2014; Purzer et al., 2015; Xie, 2016). Students learn and apply concepts of radiative heat transfer as they need to account for how solar radiation varies over a day and over the year. This knowledge is used to address the open-ended design problem and account for competing constraints. The technology automatically logs fine-grained student use data and the researchers have developed visual process analytics as a data mining tool to investigate student activity and learning in these complex and non-linear design tasks (Xie, 2016).

Shaffer and colleagues have developed the virtual laboratory *Nephrotex* in which first-year, undergraduate engineering students take on the role of interns at a high-tech bioengineering firm tasked with designing a kidney dialyzer based on iterative experimentation (Chesler et al., 2013). The student teams treat the process as a "black box" and are directed towards statistical experimental design, completing two iterative cycles. In the first cycle they look at one of the input parameters, and in the second cycle they look at all four input parameters. The computer provides both the platform for experimentation and interactive correspondence with simulated co-workers and supervisors. Shaffer and colleagues described the instructional goal of these *Epistemic Games* as ranging far beyond the "conceptual understanding" pursued in many learning environments. Rather, they are used to develop students' skills, knowledge, identity, values, and epistemology common to the community of practice of the engineering workplace (Rupp et al., 2010).

Koretsky and colleagues have developed a set of "industrially-situated" virtual laboratories in which students take on the role of process development engineers tasked with determining the process input parameters (the "recipe") for a chemical or biological engineering process (Koretsky et al., 2011). The hybrid design uses virtual laboratory technology to simulate complex industrial processes but relies on in-person social interactions with others on the engineering development team (played by other students) and their supervisor (played by the instructor). These projects are designed for senior-level engineering students and allow for professionally productive social interactions (Gilbuena et al., 2015). For example, instructor feedback on professional skills helps students recognize how to represent themselves as legitimate members of an industrial community of practice. Material and conceptual aspects were found to interlock in this learning system where students developed and used models to make sense of experimental data and move their design forward (Koretsky et al., 2019).

Recommendations

In this section, we have argued that technology can enable creation of instructional designs and learning contexts that can fundamentally shift the type of activity where learning occurs. We have illustrated this point in detail through the affordances of one "category" of technology, the virtual laboratory, but such shifts in instructional design apply to other uses of computer technology as well. These designs support engaged learning in ways that fundamentally reconstitute the interactions of students with the content, with each other, and with instructors. We believe that if educators and developers approach technology genres from this perspective, they can better utilize the affordances to positively disrupt static and passive learning environments and provide access to more diverse populations of engineering students. They can also achieve the benefits at a larger scale.

In summary, we recommend that technology developers and engineering educators take a systems approach guided by findings in the learning and cognitive sciences to conceive what is possible rather than replicate traditional classroom structures, norms, and interactions. Specifically, they should explicitly connect the technology affordances to how their proposed designs support learning through articulation of foundational learning theory. We encourage a broad conceptualization of what learning engineering entails, including: conceptual understanding; disciplinary practices, discourse, and process and social skills; understanding the nature of engineering; and motivation and equitable engagement.

However, engineering educators are only beginning to see enactments of computer technology used in this way, and the instantiations are often local to the direct sphere of the innovator and have not propagated broadly. There are several reasons for this limited realization. First, not all attempts to shift the activities in which learning occurs are going to be effective. Engineering educators need to understand what works, but just as importantly, what has not worked and why. Second, there is a need for a productive hybrid content-pedagogical-technological development "space"; innovators and developers need to be grounded with fundamental content knowledge and have deep understanding of learning, but also stay connected to the possibilities afforded by the wave of next generation computer technologies. Better understanding is needed of how to create spaces where content, pedagogy, and technology expertise overlaps. Successful collaborative processes and environments need to be better characterized and understood. Third, learning and classroom instruction occur within the culture of higher education. Normative conceptions of learning and institutional rewards and recognition for teaching can limit the degree to which classes and systems are ready to take up these innovative uses of technologies. This aspect is addressed in more detail with Issue 6 below.

We recommend funding agencies prioritize technology innovations that identify paradigmatic shifts in the learning environment and that empirically and theoretically study the resulting interactions with student learning, engagement, and equitable access. We also recommend that agencies support research to better understand characteristics of successful collaborations and ways to shift or overcome cultural barriers in institutions of higher education.

Issue 4: Alignment of Technology with Assessment

We argue that educators need to identify and implement systematic uses of technology that provide or leverage existing data to inform formative and summative assessment, adaptive instruction, and research on learning engineering (National Research Council, 2014). Technology-based assessments have attracted interest in educational contexts because they can enable the design of learning environments that provide real time feedback, and scalable and personalized support

([DOEd], 2010, 2016). At the same time, advancements in cyberinfrastructure, cyberlearning innovations and online learning environments have resulted in data that can be used for improving learning and for educational research purposes (Borgman et al., 2008). Challenges however still remain, in order to fully realize the potential of uses of data from technology. In addition, concerns of confidentiality, security and privacy must be addressed (Madhavan & Richey, 2016).

Technology and Datasets for Feedback, Assessment, and Personalized Instruction

We advocate for the identification of practices, tools, and methods that can provide formative feedback to faculty (in addition to summative feedback), so they can appropriately adapt instruction (e.g., just-in-time teaching). This activity includes identifying what types of feedback are most effective for learning, relating that to information available through technology, and developing interfaces that provide that information to students and faculty in ways that they can use. Currently, a number of commercial personalized or adaptive instruction systems tout the ability to provide students computer-based formative feedback throughout the learning process. Such tools can help students with spaced repetition, and rapid and adaptive feedback. These platforms can also be useful for instructors as the feedback is instantaneous and it reduces grading load. Furthermore, advances combining artificial intelligence, machine learning and learning analytics offer the possibility of realizing personalized learning. For example, learning analytics could be combined with student uses of learning materials, behaviors, and performance already captured with a classroom management system (e.g., Arnold & Pistilli, 2012). While the prospect of learning that is solely mediated through a computer is compelling, it is important to establish its limits. Simultaneously, other ways should be identified for instructors to use computer-based assessment to support student learning (e.g., changing pedagogy, in-person feedback, and so forth), and at the same time explore the effectiveness of non-traditional models of delivery such as inverted classrooms (e.g., Magana, Falk & Reese, 2013), or hybrid models combining online and face-to-face approaches.

Computer-based assessment methods have had a long tradition in helping educators measure student learning (e.g., Brown, Race, & Bull, 1999; Mayrath, Clarke-Midura, Robinson, & Schraw, 2012). According to Recker and colleagues (2016), when compared to paper and pencil assessment methods, technology-based assessments can offer advantages such as (a) predicting students' future learning by creating models that incorporate information such as students' knowledge, behavior, motivation, and attitudes; (b) discovering models that characterize the subject matter to be learned (e.g. math, science, etc.), identify fruitful pedagogical sequences, and suggest how these sequences might be adapted to students' needs; (c) studying the effects of varied pedagogical decisions on student learning; (d) advancing scientific knowledge about learning and learners through building models of learning processes that incorporate data about students, teachers, understanding of subject matter, pedagogies, and principles from learning sciences; and (e) supporting learning for all students by adapting learning resources to fit the particular needs identified, including adaptations for individual students when warranted.

In higher education settings, computer-based assessment (Miller, 2009) and intelligent tutors (Goel, 2016) have been used as a mechanism to provide just-in-time formative feedback and to help improve students' performance (Tair & El-Halees, 2012). For instance, by identifying technology-learner interactions that are more conducive to learning, educators and educational technologists can support personalization by generating content semi-customized to the learner (Cheville, 2012). When using analyzed data generated from learners' engagement with technology, educators can not only make sense of the outcomes and the impact of using such technology, but can also characterize the student learning process and make data-driven decisions to adapt the environment to better support student learning (Xie, Zhang, Nourian, Pallant, & Hazzard, 2014). However, it is unclear to what degree the feedback should be provided by the computer itself, and to what degree the computer should provide information to the instructor to interpret and interact with the learners.

In engineering, randomized computer-generated "rolling problems" have been introduced for exams in large enrollment courses (West, Silva, and Herman, 2015) and to create individualized homework problems for textbooks (Vahid, Edgcomb, & Strawn, 2016). These type of personalized problems have evolved from simply changing the numbers within the same skeletal problem statement to developing more and more sophisticated methods to apply to other problem features that make them more like "new" problems from the perspective of the learner. With these problems, like contrived back-of-the-chapter problems of old, educators need to better understand the degree that students engage with core disciplinary concepts and the degree they can anticipate problem features and patterns to "game" the assessment process.

Technology-based assessments also offer the opportunity of assessing 21st century competencies such as problem-solving, critical thinking, or design skills ([DOEd], 2010). The open-ended nature of these processes make them difficult to assess. For example, design skills can neither be assessed as a product nor as a simple test (Vieira, Goldstein, Purzer, & Magana, 2016); the steps the students follow to reach a solution is as important as the final solution itself. Specifically for the case of design skills, by analyzing process data logged through a computer aided design tool, Xie and collaborators (Xie, Zhang, Nourian, Pallant, & Bailey, 2014; Xie, Zhang, Nourian, Pallant, & Hazzard, 2014) identified (a) differences in students' design processes based on gender, (b) different ways in which students interact with the software, and (c) differences on students' design processes after being exposed to an instructional intervention. Likewise, by analyzing logged process data, Vieira and collaborators (2016) identified students' approaches to experimentation in engineering design, and Goldstein and colleagues (2015) assessed students' idea fluency in their design process.

However, there is a significant amount of work to be done, particularly on identifying how interaction, process and learning data can result in instruction and feedback tailored for particular learning outcomes (Cheville, 2012).

Technology and Datasets for Engineering Education Research

Effective practices and guidelines for interpreting and acting on learning and process data are needed. In order to take advantage of the vast amount of data using information technologies, we recommend going beyond traditional narrow forms of assessments with the goal of understanding the learning processes and their nuances (Pellegrino, Chudowsky, & Glaser, 2001) and moving towards embedded or stealth assessment where the data is provided as part of the core learning activity (Shute, 2011). To this end, data must be handled and shared properly and mechanisms to guide this process are highly needed. Such mechanisms should consider not only technological aspects, but also policy aspects such as ownership, privacy, security, and confidentiality.

As learners engage with technology, they leave a trail of ways in which they use the technology (interaction and process data) and the outcomes and the impact of using such technology (learning data) (Borgman et al., 2008). In conjunction, advancements in natural language processing techniques, machine learning, educational data mining, and learning analytics can result in new ways of making meaning of these complex process and learning data (e.g., Borgman et al., 2008; Haudek et al., 2012; Worsley & Blikstein, 2014; Xie et al., 2014). These methods can support the development of domain-specific theories of learning, and the characterization of different aspects of learning processes at the level of individuals, groups, and institutions.

Engineering education researchers have used longitudinal datasets to answer research questions about how students navigate through required engineering curriculum and what courses or policies present obstacles for graduation (Ohland & Long, 2016). For instance, when used with historical data along with university regulations to identify performance probabilities, graduation and passing rates for engineering students can be computed (Caro, González, & Mira, 2014). In tandem, advances in educational data mining and learning analytics can now enable ways to use data for improving teaching and learning. For example, data mining techniques, such as classification methods, have been used for prediction purposes on student performance in examinations (Yadav & Pal, 2012). Rawson and Stahovich (2013) captured time-stamped record of students' solutions to their homework assignments using a smart pen. They quantified the total amount of ink written and the time of the day at which the student homework was done, and used those metrics to characterize homework habits and correlate them with the final course grade. They concluded that by the end of the third week of the quarter, it was possible to explain a significant amount of the variance in final course grade by considering homework habits. Machine learning algorithms have also been used to generate models that predict potential dropouts from engineering majors (Pal, 2012). Results from those predictions could help educators take on-time action in helping lower performing students with additional support (Yadav & Pal, 2012). However, while technology tools show promise in identifying students who are at risk, more work is needed to identify effective ways to interact with these students to change those behaviors.

Engineering education researchers have recognized the need for better ways to share research data, but tensions exists regarding legal, regulatory and ethical considerations (Cheville, 2016). Issues associated with ownership of the data along with and privacy implications have also been identified (Johri, Yang, Vorvoreanu, & Madhavan, 2016). Other challenges for adoption of sharing practices relate to technical and cultural barriers (Gilmore, Adolph, Millman, & Gordon, 2016). Because of the clear value in using and reusing data for discovery purposes, engineering education researchers have started to devise principles and heuristics to guide the sharing of data (Cheville, 2016). Ongoing efforts also include devising methods to help researchers move from sharing to enabling partnerships (Adams, Radcliffe, & Fosmire, 2016).

Recommendations

We urge engineering educators and curriculum designers who have successfully taken advantage of technology-based assessments to share lessons learned and effective practices, tools, and methods for providing formative feedback. For example, when gaps in student learning are observed, what are strategies for instructors to respond? What role do advances in machine learning, artificial intelligence, and learning analytics play in adaptive or personalized feedback? We recommend continued development of technology and feedback mechanisms to support engineering faculty in (a) identifying the effects of pedagogical changes, (b) adapting instruction according to students' prior knowledge and performance, and (c) advising students based on predictions of future learning and retention. Critically, exemplary implementations along with lessons learned of such assessments need to be shared with the wider community to help members evolve in their instructional practice.

To take advantage of the vast amount of data using information technologies for research, we recommend that engineering educators and engineering education researchers go beyond traditional narrow forms of outcomes assessments with the goal of understanding the learning process itself (Pellegrino et al., 2001). For instance, "stealth assessment," assessment embedded into the instructional environment, can serve both purposes (Shute, 2011). With these data, inferences can be made about how to support the learning process as well as how students achieve competency (Shute & Ventura, 2013). However, care should be taken in over relying on computer-enabled methods. Learning is complex and requires human interpretation that goes beyond the capability of technology (Worsley & Blikstein, 2014). Computer-enabled methods should be used as complement to qualitative approaches of data analysis where, for instance, human-scored students' processes can be used as an input to technology-based assessment tools (Worsley & Blikstein, 2014).

Finally, we recommend that funding agencies identify and implement monitoring programs to ensure that research data and other products resulted from federal funds are made available to the research community following guidelines promised and approved in the proposal (i.e., data management plans). It is also recommended to *university administrators* and *investigators* to implement and follow proper procedures for data to be handled and shared properly. Effective practices to guide data sharing and handling process require deliberate effort and are highly needed.

Issue 5: Alignment of Technology with Instructional Practice: Faculty Beliefs and Pedagogical Knowledge

We argue that programs, strategies and mechanisms are needed to address faculty pedagogical beliefs, to help develop faculty technological pedagogical content knowledge, and to connect the two. Faculty pedagogical attitudes and beliefs are a vital first step toward technology acceptance and eventually productive integration. Additionally, in order to adopt technology effectively, it is essential for instructors to develop sufficient knowledge of pedagogy and technology, and align that with the appropriate disciplinary (content) knowledge.

Many faculty commonly hold low digital literacy, which limits their ability to effectively integrate technology into their teaching practice (NMC, 2014). Part of the problem relates to the lack of effective faculty professional development. However, deeper challenges that exacerbate this issue relate to: (a) faculty attitudes and pedagogical beliefs that may influence the decision and the ways faculty integrate technology in the classroom (Ertmer, 2005); (b) faculty development of technological pedagogical content knowledge (Mishra & Koehler, 2006); and (c) faculty perceptions of usefulness and ease of incorporating technology (Nolen et al., 2009; Venkatesh & Davis, 2000). A rewards system that systematically and increasingly values research activities over teaching activities can limit the effort faculty are willing to devote to improving their teaching practices (Fairweather, 1993).

Faculty Attitudes and Beliefs

Faculty attitudes and beliefs are a vital first step toward technology acceptance and eventually integration (Dusick, 1998; Ertmer, 2005). Faculty attitudes and pedagogical beliefs relate to suppositions, opinions, commitments, expectations, and ideologies that they hold about technology (Ertmer, 2005; Hermans, Tondeur, van Braak, & Valcke, 2008). Faculty first need to identify the value of technology in helping them achieve instructional goals they perceive to be important (Watson, 2006). Faculty also need to develop their knowledge about technology to a point where they are confident using it (Faseyitan, Libii, & Hirschbuhl, 1996; Wozney, Venkatesh, & Abrami, 2006) and overcome levels of anxiety when using the technology (Johnson, Wisniewski, Kuhlemeyer, Isaacs, & Krzykowski, 2012). Importantly, faculty need a clear understanding about how technology can enable student achievement of meaningful outcomes (Angeli & Valanides, 2009).

The way that pedagogical beliefs influence technology integration has been hypothesized as follows: faculty with more instructor-centered pedagogical beliefs will implement more traditional or "low level" technology uses, whereas teachers with more student-centered (e.g., constructivist) pedagogical beliefs will implement more "high-level" technology uses (Ertmer & Ottenbreit-Leftwich, 2010; Roehrig, Kruse, & Kern, 2007). Two studies were identified that provide some insights about engineering faculty pedagogical beliefs and some of the forms in which they use technology for teaching and learning. Middleton and colleagues (2015), identified that faculty can hold student-centered beliefs, teacher-centered beliefs, and non-discriminatory beliefs. In addition, faculty apply pedagogies that correlated significantly to their attitudes; faculty with student-centered beliefs engaged in more learner centered practices than either teacher-centered faculty or non-discriminating faculty. As related to engineering faculty uses of technology, it was identified that faculty commonly use Internet for simplistic static tasks (e.g., posting of syllabi) as opposed to dynamic more complicated ones (e.g., online discussion forums) (St. Clair & Baker, 2003). Faculty also reported that easiest tools to use were more commonly used and at the same time were perceived as most effective and efficient. On the other hand, the hardest tools to use were used less often and were perceived as not so effective and efficient (St. Clair & Baker, 2003).

An initial step towards change in pedagogical beliefs that help faculty become comfortable with using the technology for teaching and learning can be addressed via faculty development programs (Faseyitan et al., 1996). However, knowing about pedagogical methods, learning theories, or principles of good instruction does not mean that faculty will adopt them (Lin, Yu, Wang, & Ho, 2015). For example, a study that investigated the effect of an online faculty development program to lead to a change in faculty beliefs and intentions towards more student-centered learning revealed that after the training, faculty indeed decreased their *intention* towards knowledge transmission models. However their practice did not become more student-centered as a result of participation in professional development (Rienties, Brouwer, & Lygo-Baker, 2013). What has been identified as a predictor of shifts in pedagogical beliefs from more instructor-centered to student-centered approaches is faculty identifying changes in their students' learning (Levin & Wadmany, 2005), such as the case presented by Moore and colleagues (Moore et al., 2015) through the use of Model-Eliciting Activities.

Factors such as technology awareness, perceived technology affordances to achieve learning outcomes, and perceived usefulness and ease of use, may determine intention to use technology and subsequently, integration (Taylor & Todd, 1995). Researchers have argued that university faculty do not choose to use technology in the classroom even though they feel some technologies can improve students' learning (Ajjan & Hartshorne, 2008). For instance, a predictor for technology integration for learning is faculty perceived value of technology use (Wozney et al., 2006), along with perceived usefulness and compatibility (Ajjan & Hartshorne, 2008). That is, faculty may make value judgements in regards to technology affordances to help them achieve instructional goals they perceive to be important (Watson, 2006). The more valuable faculty perceive a particular technology is in helping them achieve instructional goals, the more likely they are to use it (Ertmer & Ottenbreit-Leftwich, 2010). Other predictors for technology integration relate to faculty self-efficacy and confidence in achieving specific learning outcomes with technology (Faseyitan et al., 1996; Wozney et al., 2006), as well as the level of anxiety experienced when using the technology (Johnson et al., 2012). For instance, low personal knowledge about technology may result in stress or anxiety (Kersaint, Horton, Stohl, & Garofalo, 2003). On the other hand, when faculty believe that the technology is easy to use and compatible with the way they work, their likelihood of integrating it into the classroom increases (Ajjan & Hartshorne, 2008). Developers could better align innovative technologies to the real needs and practices of faculty through processes such as the "customer discovery" interviews that are central to the I-Corps L program (Guerra & Smith, 2016)

Faculty Knowledge

Studies in higher education level have identified significant correlations between technology literacy and integration into pedagogical practice (Georgina & Hosford, 2009; Georgina & Olson, 2008). Specifically, low personal knowledge about technology may be a strong barrier to technology implementation (Kersaint et al., 2003). In addition, educational researchers have identified that in order to improve student learning with technology, it is essential for instructors to properly orchestrate the interplay among content, pedagogy, and technology use. Effective technology integration for meaningful learning requires that educators comprehend the technology tools themselves, along with the specific affordances of each tool enable for conceptual understanding, problem solving, design thinking, or other desired outcomes (Angeli & Valanides, 2009). This interplay among faculty content, pedagogy and technology knowledge has been referred to as Technological Pedagogical Content Knowledge (TPCK) (Mishra & Koehler, 2006).

The TPCK framework has emerged as a form to represent educators' knowledge on how to integrate technology into their teaching and learning activities (Abbitt, 2011). It was developed as an extension of Shulman's (Shulman, 1986) pedagogical content knowledge (PCK). One of the criticisms of the TPCK framework is that it is complex and difficult to measure (Archambault & Barnett, 2010). Specifically elements of the TPCK framework are difficult to tease out (Shinas, Yilmaz-Ozden, Mouza, Karchmer-Klein, & Glutting, 2013). However, clear distinctions have been identified for technology knowledge (Archambault & Barnett, 2010; Shinas et al., 2013). Similarly, valid and reliable instruments have recently been developed that allow faculty to self-report about their own TPCK (Yurdakul et al., 2012) and students to indicate their views about their university professors knowledge in technology-supported classroom environments (Shih & Chuang, 2013).

In general, however, understanding of what technology knowledge is needed and the degree that faculty exhibit such knowledge is sparse. A survey study of 360 engineering faculty from eight institutions reported on faculty knowledge of specific technologies for teaching and learning (Chen, Ellis, Lockhart, & Hamoush, 2000). While common technologies such as email, word processing and the Internet were widely used by engineering faculty, they reported little skill in more specific class-specific technology uses such as developing multimedia modules, Java applets, or even creating web pages for a course or holding electronic help-sessions or office hours using conferencing or collaboration tools. While the landscape has probably shifted somewhat in the years since this study, more work is needed to identify the types of technological knowledge that faculty have (e.g., Magana et al., 2012). Furthermore, valid and reliable ways to measure that knowledge would provide information to allow support strategies to be developed for more effective use of technology.

Organizational Support and Faculty Development

Some external factors attributed to faculty not choosing to integrate technology relate to the lack of organizational support, not enough resources, weak leadership in guiding them through the adoption process, and lack of training to develop technology knowledge and pedagogical knowledge (Keengwe, Kidd, & Kyei-Blankson, 2009). Other barriers include the time and effort needed to learn how to use a technology, the planning to incorporate it into a classroom setting, and concerns about negative impacts of instructional innovations on faculty teaching evaluations (Berk, 2005; Kersaint et al., 2003; St. Clair & Baker, 2003). These external factors or barriers can be addressed. Engineering colleges and departments can support faculty efforts with incentives and time to explore technology in order to identify effective ways to use it in the classroom, and get rewarded for doing so (Brownell & Tanner, 2012; Finley & Hartman, 2004; Surry & Land, 2000). Once faculty have used technology for one specific purpose, along with sufficient technical support and colleague-supported training, they are more likely to use technology for other purposes (Jacobsen, 2000; Sahin & Thompson, 2007).

For faculty development, we draw on the literature for development of knowledge for complex pedagogical practices. For example, a qualitative study that measured the effects after a faculty development program aimed at integrating problem based learning (PBL) among 31 faculty revealed transformations on their PCK (Major & Palmer, 2006). After conducting interviews with the 31 faculty and examining their portfolios, Major and Palmer (2006) identified that faculty implementation of PBL encouraged them to critically examine their teaching and learning processes. Another useful example comes from a faculty development program in science education that aimed at implementing a cognitive apprenticeship model (Sunal et al., 2001). Part of the workshop dynamics included an iterative process of exchanging roles from teacher to learner and back again. This exchange of roles allowed faculty to (a) share beliefs publicly, (b) discuss, reflect and observe alternative approaches for teaching in order to create cognitive conflict, and (c) reconstruct ideas related to effective learning and teaching in disciplinary courses. We can draw on this work to develop more effective strategies for faculty development around complex technological practices in the engineering classroom. Specific strategies that faculty have identified as useful are interaction of faculty from different colleges, connections with faculty with similar goals, institutional and administrative support, development of interpersonal skills, participating in action research, and joining external networks of faculty to collaborate and disseminate results (Sunal et al., 2001).

Recommendations

Our recommendations for this issue are addressed to university administration and personnel from units or centers focused on faculty development or instructional innovation programs (e.g., centers for instructional excellence). An effective way to shift beliefs and increase faculty knowledge about technology and how to integrate it effectively into their classrooms starts with participation on faculty development programs, followed by design of learning materials, and then to actual integration of the technology in their classrooms (Doering, Veletsianos, Scharber, & Miller, 2009; Koehler & Mishra, 2005; Koehler, Mishra, & Yahya, 2007). Faculty development programs can not only help faculty improve their knowledge about how to integrate technologies for teaching and learning, but can also help them become comfortable with using the technology for such purposes (Faseyitan et al., 1996). This technology knowledge should go beyond using technology to make classroom management and delivery more effective. Specifically, faculty need to understand how to use technology to facilitate and support meaningful learning that can result in students' connected knowledge and skills readily available for application to real situations (Lawless & Pellegrino, 2007). This recommendation for faculty development programs focuses on strategies designed to improve faculty pedagogical and technological knowledge. We advocate for following the guidelines similar to those developed by the National Effective Teaching Institute (NETI) (Felder & Brent, 2010; Felder, Brent, & Prince, 2011), but adapted so technology integration is considered in the proposed practices.

We recommend that pedagogy-focused faculty development programs specifically address the use of technology in engineering. These programs should incorporate the design of technology-enhanced learning materials, and supports for the actual implementation of the technology in their classrooms. Long-term and organizational benefit can follow if there is a critical examination and reflection of individuals' teaching and learning processes and the creation of communities of practice and mentoring mechanisms.

Issue 6: Broader Considerations: Technology with a "T"

To this point, we have considered technologies that have been specifically developed for learning engineering (learning innovations), for domain-specific applications to engineering practice, and for instructional design including learning outcomes, assessment, and instructional practice. We have also argued that faculty professional development is a critical component if engineering educators want widespread deployment of these type of effective technology-based instructional practices. Our discussion has focused on intentional uses and specific ways that technology can be enacted in engineering learning environments to improve learning and increase engagement. However, a broader perspective reveals many ways, both obvious and subtle, that technology interacts with the work of engineering students and faculty at the university. In this section, we shift the discussion from developing technologies for specific educational needs towards a broader consideration about the affordances and tensions with technology towards learning engineering. While it is beyond the scope of this article to unpack these issues in detail, they are critical to the conversation of how to approach technology in engineering education.

As illustrated earlier in Figure 1, the specific technologies that have been developed for engineering learning and practice are situated within the broader context of the role technology plays in the lives of humans in the 21st century.[4] Mobile, wired devices that provide broad and ready access to information and to other people have redefined fundamental conceptions of space and time (Castells, 2011; Madhavan & Lindsay, 2014; Standage, 1998). In this section, we address some of the ways that Technology (with a capital "T") impacts the engineering learning environment for the better (e.g., increased access) and for the worse (e.g., access to solution manuals). Capital "T" Technology is what Arthur (2009) refers to as the "entire collection of devices and practices available to a culture" (p. 28). Engineering educators need to understand and negotiate the tensions between Technology as a large and continually changing force in society and their ability to adapt educational systems and develop educational innovations at pace.

With the goal of promoting systemic change towards more productive learning with equitable access for all learners, we draw on Arthur's definition to identify how Technology fits into the cultures of engineering programs and the culture of higher education. At its core, Technology is a cultural phenomenon of interlocking material and social practices (Leidner & Kayworth, 2006; Latour & Woolgar, 2013; Leonardi & Barley, 2008: Pickering, 2010). Engineering faculty and students exist within the broad culture of higher education, and within specific departmental and institutional cultures, and all of these are changing rapidly. Engineering educators need to create technologies and

[4]It is easy to lose sight of how rapidly computer technology is changing, e.g., the widespread use of the personal computer (began in the 1980s), the internet (1990s), and the smart phone (2000s).

enact technology-based practices with the understanding of what culture they want to create. Such strategies need to account for and shift the values, beliefs, and norms that permeate institutions of higher education. Faculty, administrators, students, and researchers need to begin by creating the "time" and "space" to have these conversations. For example, one could argue that a cultural norm typical in Carnegie Research 1 universities is the need for minimally invasive teaching so that faculty have more time for research. This norm is reflected in the rewards structures for tenure, promotion, and merit raises, and also in a growing lower-paid, often marginalized, class of fixed term instructors to carry the teaching load. If it is important to think about Technology as providing affordances that enhance student learning, the engineering education community needs to change the way people think about teaching and the value placed on teaching in the context of their work. In this regard, there may exist tensions between effectiveness and efficiency. Technology should serve to make teaching more effective, not less intrusive - to improve teaching, not commoditize it. This cultural context needs to be considered in developing strategies for faculty development discussed above. Thus, in considering how Technology fits into the educational system, and extrapolating for how it will fit into the system into the future, it is necessary to fundamentally address core issues of organizational identity and organizational learning (Kezar & Eckel, 2002).

Students also bring Technology-mediated cultural behaviors to the engineering classroom. Incoming students are referred to as digital natives, a term that is often interpreted as digital fluency, but more appropriately refers to their habits, values and beliefs (Howe & Strauss, 2007; Kirschner & De Bruyckere, 2017; Oblinger, 2003). In general, this group, the *IGens* (Twenge, 2017) and before them the *Millennials*, is tech-savvy and connected. They are characterized as collaborative (crowdsourcing), prone to multi-tasking (which in fact is not effective), and accustomed to instant gratification[5]. As students, they seek a greater work-life balance than their predecessors and seek more immediate meaning and relevancy to their work. They spend a reported 30% less time studying than their counterparts 50 years earlier (Cheville, 2012). In addition to less time studying, their activity may be less focused as their use of computers and other devices for work and fun often coalesce. They believe that if something is digital, it is everyone's property – an attitude that can lead to conflicts with policies on academic misconduct. However, educators should not lose sight that IGen characteristics can be productive. They bring to the classroom stronger abilities to use information technology and to collaborate than predecessors; both these skills are needed in engineering work. Their outlook that "doing is more important than knowing" can be leveraged in authentic project-based work around engineering design. Finally, we agree with Bennett, Maton, & Kervin (2008) that

[5]Behaviors of instant gratification logically follow the assertion that the internet is compressing or annihilating time and space.

incoming students' relationship with technology may be more nuanced and complex than the digital native characterization implies, and that better understanding is needed to characterize and identify ways that learning environments can be shifted to better fit this and future generations of learners.

A broad perspective is needed to connect the affordances and tensions of Technology with the ends for which education should work. Technology has led to tectonic shifts in the amount of information available to both students and faculty and the ways they can collaboratively work. However, the educational processes and systems at the core of many engineering programs remain intact from the pre-internet era. Engineering education researchers need to better understand tensions between Technology and the core educational processes and systems through which engineers are formed. We illustrate this point with three examples. First, faculty and students may have very different perspectives of the role of homework in learning engineering. Faculty could assign homework from a *process* orientation, thinking that through engaging in problem solving processes of challenging problems, students are elicited to make meaning of core concepts and principles. Thus, homework becomes a central tool in the course design to promote deep learning. On the other hand, students know that homework problem solutions are often only a click (or a text message) away[6]. As time constraints and other stressful factors become salient, they may take a *product* orientation, prioritizing "getting the points" for successful completion to genuine engagement. More subtly, students may believe that access to solutions can be used to "guide" their thinking when stuck, and, even with the best intentions, also circumvent the meaning making that leads to deep learning in working through challenging problems. Second, most engineering textbooks are designed for the pre-internet era where the book needed to serve as both a learning tool and also an encyclopedic resource for future reference. Students have networked information resources now available rendering textbooks as transient tools only needed during the term. This shift together with affordances of Technology towards interactivity and adaptive feedback discussed above necessitates a need to shift conceptions and manifestations of the fundamental role of out of class resources in learning engineering (Lee et al., 2013; Edgcomb & Vahid, 2014). Applying the discussion from Issue 3 above, it is better to think about the resources learners need outside the classroom and use technology to reconstitute those resources to be more effective rather than simply converting a traditional textbook into an electronic format. From such a perspective, resources shift from providing static content to interactively developing conceptual understanding and problem solving skills (Vahid, Edgcomb, & Strawn, 2016). Third, we juxtapose the rich, networked

[6]Technology may address this issue by incorporation of "rolling" problems that change in nature for each learner; however, they may just lead to the next level of a set of students "gaming" homework. An alternative approach is to develop homework activities within learning environments that prompt students to be interested and to see the value of completing the work.

collaborative learning uses of Technology outside of school and the limited, individualized uses in the classroom. This contrast suggests that better alignment of the activities and assessments educators choose in the engineering classroom may lead to higher motivation and more meaningful learning.

Recommendations

Studies are needed that explore how Technology interacts with the cultures of engineering departments, with an emphasis on a systems-level understandings and forecasting. Such research should draw collaborators with a wide range of expertise, including technology and science studies, sociology, and anthropology. Rapid changes in Technology are shifting work practices and social norms. Engineering educators need strategies to keep up with this change. For example, they need to understand better how students use Technology to get their work done and what aspects of work practices might misalign with instructors' conceptions. From such an understanding, educators can develop strategies to redirect unproductive habits and ideas to leverage others. With the constant temptation of connectivity, education researchers also need to characterize the relationships between multi-tasking and deep thinking. Does connectivity form a distraction that subverts complex thinking or can it be an affordance to distribute thinking and enhance learning? Ultimately, educators are responsible for developing learning environments that fit their learners. They must institutionalize processes that allow them to identify shifts in Technology-based social norms and work practices, and respond agilely in ways that better match learners' needs. Importantly, administrators and faculty need to create space at the university to reward and recognize this challenging work.

CLOSING THOUGHTS

This article seeks to address the questions "What are the potential affordances of computer technology (ICCT) to make effective tools for teaching and learning engineering?" and "What tools will scale and propagate?" Often mentioned first is that computers can provide individualized learning pathways combined with feedback on how the learner is progressing. That is, computers make it easier to engage in "what if" scenarios. While such scenarios will undoubtedly occupy space in the educational technology landscape, it is unclear to what extent the social process of learning can be effectively sourced to a computer tool. If we look at history as a guide, humans are often quick to project changes to human social systems from the next technology on the horizon, simply by virtue of the technology itself. For example, a common shared belief was that the telegraph was going to bring world peace because it would allow humans from different nations to readily interact, and thereby understand one another (Standage, 1998). But this optimistic prognosis overlooked the hard social work of developing that shared understanding. Similarly, one could take the perspective that the more general value of computer-based learning innovations is to augment, not replace, the social work done in learning. From this perspective, computer technology allows more possibilities for the interactions that it can foster to do that challenging work.

We have argued that technology-enabled pedagogical systems can fundamentally shift the space where learning occurs. By that, we do not mean that learning becomes any less human, just that there are more possibilities for creating meaningful human interactions,[7] interactions that can foreground conceptual understanding or foreground disciplinary practices. To realize this use, educators need to expand their conceptions of the learning environment at the university. There is a tendency to see technology in terms of the current structures and systems that are in place. The telephone was first considered as a "talking telegraph" and the automobile first as a "horseless carriage." In each of these cases, technology is viewed as making what was once difficult easier. Alternatively, educators might ask how Technology affords paradigmatic shifts in the fundamental ways they do the challenging cognitive and social work of helping students learn engineering.

Ultimately, the ways and degree to which educators choose to reconstitute learning environments in response to Technology change is inextricably linked to their conceptions of learning and knowing. They might consider knowledge as an entity to be transferred and skills development as proceeding through orchestrated behavioral responses to external stimuli. Alternatively, they can view learning as a socially-mediated process where the learner constructs conceptual understanding building on their prior knowledge and experiences through orchestrated activity. Finally, they might say that learning is a sociocultural process of increasingly greater participation in the valued practices of a disciplinary community. These conceptions have implications in the interactions of educational systems with Technology. One perspective might emphasize personalized and adaptive learning where the technology provides a responsive diagnostic agent that directly and immediately responds to the individual learner. Another perspective might prioritize a use of technology to put students in social situations where they make meaning of activity through interacting with one another. Failure to make connections to core learning processes can doom instantiations of technology to the same mistakes as earlier interventions (e.g., see Webel, Krupa, & McManus, 2015).

[7]In the mid twentieth century, Claude Shannon (see Shannon, 2001) connected the concept of entropy to information. From such a perspective, one could argue that the exponentially increasing amounts of information accessible by computer technology leads to many more system "configurations" in any arena it touches, including the professional formation of engineers. But, like with entropy, most sets of configurations tend to be disordered. It takes coordinated input of the right type of work to create "low entropy" configurations that could potentially be quite beneficial to learning engineering concepts, tools, and practices.

In some ways, these juxtaposed commitments harken the early debates during the development of the internet (or ARPAnet) and personal computer (Markoff, 2005). There was one faction that argued stridently for artificial intelligence (that computers should replace human function) and another who advocated for augmentation (computers should support human thinking and activity). Clearly, underlying philosophical commitments provide the impetus for the Technology approaches engineering educators, administrators, and policy makers privilege and where they direct resources.

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