What Have We "Learned" from Maker Education Research? A Learning Sciences-base Review of ASEE Literature on the Maker Movement

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Introduction

This purpose of this paper is three-fold: first, to highlight and synthesize established connections between Maker Education research and the Learning Sciences; second, to employ systematic literature review methods to “describe the state of knowledge or practice” [1] regarding Maker research within the Engineering Education community; third, to understand how this body of Engineering Education-based Maker research has (or has not) leveraged relevant theoretical and pedagogical frameworks from the Learning Sciences.

During the last decade, the Maker Movement[1] has emerged as a significant driver of educational reform efforts in universities and K-12 schools, as well as in informal learning environments, such as museums and libraries [3]. Whether it’s offering project-based courses that utilize digital fabrication technologies, opening a campus makerspace, or starting STEAM (Science, Technology, Engineering, Art, and Mathematics) clubs, educators and administrators are devoting increasing amounts of time and resources to “Maker Education” [4]. In addition, non-profit organizations like Fab Foundation [5] and Maker Ed Initiative [6] are now providing educational institutions with guidance and training on for implementing Maker Education programs.

Due to this rapid adoption, Maker Education has become a topic of interest for a range of academic disciplines; research has appeared in fields as disparate as Library Sciences [7], Human-Computer Interaction [8], [9], Science and Technology Policy [10] and Educational Technology [11]. The effects of the Maker Movement have likewise been felt within the Engineering Education community. Since 2013, when the American Society for Engineering Education (ASEE) accepted its first paper to directly address Making, over 150 Making-related posters and papers have been presented at subsequent conferences. ASEE has also authored two reports [12], [13] on the ways in which Making has supported engineering education as well as the potential roles that it might play in the future.

The diffusion of Maker Education research has worked in favor of constructing diverse kinds of knowledge, but at the expense of developing coherent theory, pedagogy, and practice. Even within Engineering Education, the aims, theoretical approaches, and methods used to study Maker Education vary widely. Given that a significant body of literature has been amassed, we believe it is an opportune time to take stock of what has been learned through Maker Education research. As an initial step towards a larger multidisciplinary study, this paper will focus on assessing the state of Engineering Education literature on Maker Education and synthesizing it with theoretical frameworks established within Learning Sciences research.

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[1] The Maker Movement refers to “a social phenomenon that combines the Do-It-Yourself ethos of the 1960s, the power of internet-based knowledge-sharing platforms, and the democratization of digital fabrication technologies” [2]. The capitalized terms “Making”, “Makers”, and “Makerspaces” refer to the activities, people, and community workspaces identified with the Maker Movement.

Research Questions

To better understand the state of Maker Education research within the Engineering Education community, we conducted a study with the following two central research questions:

RQ1. What are the prominent trends, contexts, and topics of Maker Education research conducted within the ASEE community?

RQ2. How does this body of research relate to, draw on, support, or expand the theoretical and pedagogical Maker-oriented frameworks established within the Learning Sciences?

The Historical and Theoretical Roots of Maker Education in Learning Sciences

In this section, we will provide three lenses which emerge from the Learning Sciences' approach to studying the Maker Movement. This set of schemas will act as both a point of departure and object of reflection for understanding the learning-oriented research into Making conducted within the field of Engineering Education.

Maker Education: a Technology-Powered Extension of Progressive Education

Although the term "Maker Education" implies that current efforts to provide students with hands-on, learner-centered, and exploratory learning opportunities is derivative of the Maker Movement, much of the seminal literature on the topic presents a different narrative. In these writings, Maker Education is presented, not as an outgrowth of the recent technology-driven, DIY social phenomenon, but as a natural extension of a long and well-established lineage of educational philosophy.

The roots of Maker Education have been traced back as far as the eighteenth century [14], when Rousseau and Pestalozzi conceived of learning as an innate ability that could be cultivated in children by giving them the freedom to explore. Martinez and Stager also cite the work of Montessori, Dewey, Vygotsky, and others whose work converged on a set of beliefs about education that focused on active engagement, personal investment, exploration, socialization, and problem-solving. To this list, Blikstein [15] adds critical pedagogy scholars Illich and Freire, giving particular credit to Freire's criticism of the decontextualization of curriculum and his advocation for education as a form of empowerment. These ideas, taken together, largely underpinned the Progressive Education movement [14] which evolved throughout the early and mid-twentieth century and which set the stage for the work of Piaget and Papert, who are often looked to as the "founding fathers" of Maker Education.

According to Vossoughi and Bevan [16], Piaget's theory of Constructivism "refers to the ways in which understanding is constructed by the individual learner through a wide variety of experiences". Knowledge can only be built on and understood in reference to prior knowledge, a notion derived from Piaget's work on genetic epistemology [17]. Martinez and Stager point out that Constructivism renders the new notion of "personalized learning" redundant, since "all learning is personal". Yet they also note that "learning is often socially constructed" and that "talking and working with others is one of the best ways to cement new knowledge" (2013, p.

31). In practice, Constructivism provided synthesis, explanation, and validation of many of the values that had been developed and espoused for decades by Progressive educators.

Constructivism had radical ramifications for epistemology as well as pedagogy; if knowledge is constructed by the knower, then education cannot be conceived of as a process of transmission of information from teachers to students. Papert coined the term *Instructionism* [18] to describe the traditional schooling model which takes this latter view as a given. Papert would further the project of Constructivism by positing that learners construct knowledge even better when they are engaging in the construction of physical things [19].

Blikstein, Martinez, and Pang [19] place Papert at the center of "three seismic events in research: child development, artificial intelligence, and technologies in education" [19, p. xiv] and frame his research as the crucial connection between Piaget's work and current educational technology trends[2]. In the foreword of his seminal book *Mindstorms: Children, Computers, and Powerful Ideas*, Papert recounts his early childhood experiences tinkering with gears and says that these interactions "did more for my mathematical development than anything I was taught in elementary school" [20, p. vi]. He then puts forth a provocative thesis: that computers could simulate an unlimited number of physical interactions—far more than any set of gears—essentially acting as an infinitely-reprogrammable Constructivist learning machine.

In 1968, Papert was part of a Massachusetts Institute of Technology (MIT) research group that designed the first computer programming language for children, LOGO, a radical act given that the average person people had little interaction with computers at the time [14]. Throughout the eighties and nineties, he continued to explore ways for learners to use computers as "objects to think with" [20, p. 23] and cofounded the MIT Media Lab, an interdisciplinary research center whose members developed and popularized much of the technology that is currently associated with Maker Education, from Makey Makey microcontrollers to the kid-friendly, visual programming language of Scratch [21].

Another off-shoot of the MIT Media Lab was the Center for Bits and Atoms, a group that emerged out of Neil Gershenfeld's popular class "How to Make (Almost) Anything" and that led to the creation of the first Fabrication Laboratories or "Fab Labs", high-tech workshop spaces that promoted the public's use of digital fabrication technologies, like laser cutters, CNC-mills and 3D-printers [5]. These efforts occurred roughly in parallel with the explosion of North American hackerspaces and makerspaces [22], thus becoming another force for accelerating the growth of the Maker Movement. These spaces, and their value as sites of teaching and learning, will be discussed more in-depth in the next section.

This historical narrative serves to illustrate that connections between Making and educational theory are not only well-established but also deeply woven into the foundation of the Maker Movement itself. Understanding this provides a better appreciation for the outsized focus on

[2] Papert is considered so influential to current Maker Education efforts that Martinez and Stager (2013) titled a section of their book "Seymour Papert: Father of the Maker Movement" [14, p. 17]. This highlights a fascinating reversal of the common interpretation of Maker Education as being derivative of the Maker Movement [10].

teaching and learning within the Maker community and at Maker Faires, public festivals where Makers show off their creations [23].

Makerspaces: Potential Sites for Communities of Practice and Learning

Makerspaces have become one of the most visible and popular manifestations of the Maker Movement. Since 2008, hundreds of makerspaces have opened up all around the country in schools, museums, libraries, as well as through independent organizations [24]. Sheridan et al. [25] define makerspaces as "informal sites for creative production in art, science, and engineering where people of all ages blend digital and physical technologies to explore ideas, learn technical skills, and create new products." These spaces are as varied as the organizations that host them, ranging from a classroom that provides grade school students afterschool access to LEGOs, hand tools, and craft materials to a new, seven-story building that promotes innovation and entrepreneurship at a major research university [26].

Notably, the activities that take place in makerspaces often blur or transcend the distinction between formal and informal learning, with training seminars and peer-led workshops occurring without traditional class structures and, conversely, activities often considered to be "play" being designed intentionally into makerspace-based curricula. Utilizing a comparative case study methodology, Sheridan et al. [25] sought to uncover the ways in which makerspaces functioned as environments for learning. They chose three radically different makerspaces: a large, membership-based space largely geared for experienced makers, a repurposed church basement that provided young adults and less experienced makers with free access to a limited supply of tools, and a museum-based space that was designed for families with young children.

Sheridan et al. [25] employed Lave and Wenger's notion of Communities of Practice as an initial theoretical lens for the study. Since Communities of Practice are comprised of "people who work in a common domain and through their participation in the community share knowledge and experiences" [25, p. 509], the authors theorized that, by considering Making as a common domain, they would find commonalities between different settings and activities. While shared practices did emerge, the authors note in their findings that the community of practice paradigm does not fully encompass the formalized methods of sharing knowledge and skills, nor did it address the need for makers to develop independent habits of mind that supported their activities.

One of the major themes that emerged from this analysis centered on the diversity of learning arrangements. The core community members occupied a variety of supporting roles that helped novices move from engaging in legitimate peripheral participation [27] to becoming experienced Makers. Some of these roles were informal, though in the case of the museum makerspace, many of the activities were formally facilitated by staff and volunteers. Another notable finding was that learning was not independent of Making and, in many instances, the learning-oriented social activities centered on a particular project were just as important as the project itself. This suggests that some makerspace interactions may fit well into Scardamalia and Bereiter's notion of Communities of Learning, which are primarily concerned about increasing the group's collective knowledge and promoting a culture of learning [27].

It is worth pointing out that none of these spaces were part of formal educational institutions and, as such, were not bound by the traditions and structures of classes, grades, or standardized curricula. Sheridan et al.'s [25] findings point to a central tension in promoting Maker Education within schools: the diversity of approaches, interdisciplinary projects, skill levels, age groups, and knowledge-building social interactions that make makerspaces successful learning communities are fundamentally incommensurate with the institution of modern schooling. This tension appears to be closely related to the one present in promoting Constructivist pedagogies within traditional educational institutions, a challenge that Progressive educators have been dealing with for decades. The fact that Maker Education has made considerable in-roads into schools despite institutional obstacles is undoubtedly one of the reasons that Constructivists have aligned themselves with the Maker Movement.

Maker Mindset: Promoting Growth-Oriented and Intrinsically-Motivated Learning

In *The Promise of the Maker Movement for Education*, Martin [3] considers the Maker Movement to be composed of three main elements: tools, community, and mindset. As noted by Sheridan et al., the use of Maker tools in a makerspace leaves out a critical element – the habits of mind of the Makers themselves! Martin provides a framework which links Dougherty's conception of a "Maker mindset" [4] to four elements crucial for education and provides some ways they relate to established LS concepts. According to Martin, Maker mindset is defined by being playful, growth-oriented, failure-positive, and collaborative. These categories are somewhat overlapping and largely rest on notions of growth mindset [28] and intrinsic learning motivation [27].

The Maker Mindset is a powerful construct as it highlights individual learners' capacities that may be promoted or utilized through the execution of Maker-based curricula or within a Makerspace, though they are not the explicit focus of these previously-described lenses. At the same time, by focusing solely on these characteristics there is a danger in losing sight of the fundamentally situated nature. In other words, Maker Mindset is useful for describing the emergent qualities of Makers-as-learners, though potentially misleading if conceived of as discretely-achievable learning objectives.

Research Design and Method

This study was conducted using both systematic literature review methods well as thematic analysis. Borrego et al. [1] provides useful guidance for constructing systematic literature reviews specifically geared for engineering education and it significantly informed the design and structure of this study. The process for determining the inclusion criteria for the literature we reviewed closely followed Borrego et al.'s [1] three-step protocol.

We started by doing a wide-range, preliminary search of the terms "Maker", "Makerspace", and "Maker Movement" within a university database, limiting search results to peer-reviewed articles that appear in Engineering Education-focused journals. It quickly became apparent that Making has not been the central topic of investigation for many articles at this level of publication. For example, the *Journal of Engineering Education* has only published one article to-date that directly investigates learning in Makerspace environments [29]. We decided to rescope our study to look at papers from major Engineering Education conferences. We found that the volume and diversity of topically-relevant papers contained through ASEE's PEER database presented itself as an ideal and well-bounded dataset.

Using the keywords mentioned above along with exclusionary clauses that filtered out incidental uses of the term "Maker" (e.g. "policy-maker", "decision-maker", etc.), our first dataset was comprised of approximately 164 papers. This number was greatly reduced by excluding 88 papers from the Manufacturing Division's "Make It!" poster sessions, which were primarily focused on the documentation and description of student projects. After eliminating double-entries and articles erroneously categorized, the titles and Abstracts of the remaining 68 papers were used to determine which ones had a central focus on learning. We then deviated from the standard systematic literature review practice and, rather than fully excluding all non-learning-focused papers from the study, we undertook a coarse-grain analysis of all Making-centered papers, looking at their general topic, context of the study, target age group, and topic of interest.

For the papers with an explicit learning focus, we then subjected them to a careful thematic analysis, utilizing a two-cycle coding process [30] that started with open coding and then utilized the a priori learning-oriented frameworks noted above to organize the inductive codes and generate overarching themes.

Results

The coarse-grain analysis of the 68 Making-centered papers revealed several notable trends and patterns within the Engineering Education community. First, there has been a steady increase in presenting papers related to Maker Education, with an average increase of approximately 6 papers per year since 2013 (see Fig. 1). This suggests that Maker Education is becoming a topic of increasing interest, not only to practitioners of Engineering Education but also researchers.

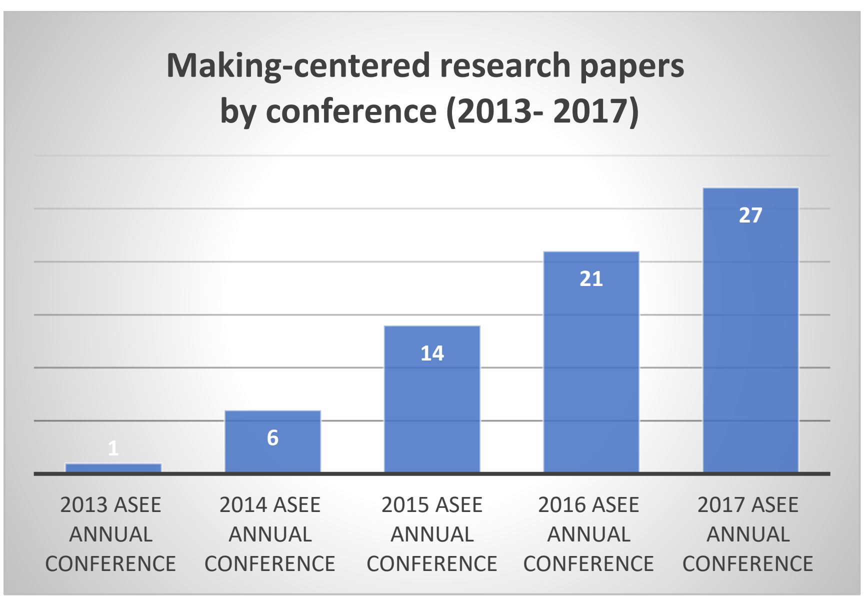

Figure 1. Graph depicting growth of Maker Education research

This analysis also revealed that Making-related papers were largely concentrated in four divisions: K-12 & Pre-College Engineering, Design in Engineering Education, Entrepreneurship & Engineering Innovation, and Educational Research and Methods. Approximately 60% of the papers analyzed were presented within these divisions (See Fig. 2). While this does suggest that some divisions may be naturally well-suited for hosting Maker Education research, it is worth noting that the other 40% were spread across 16 other divisions.

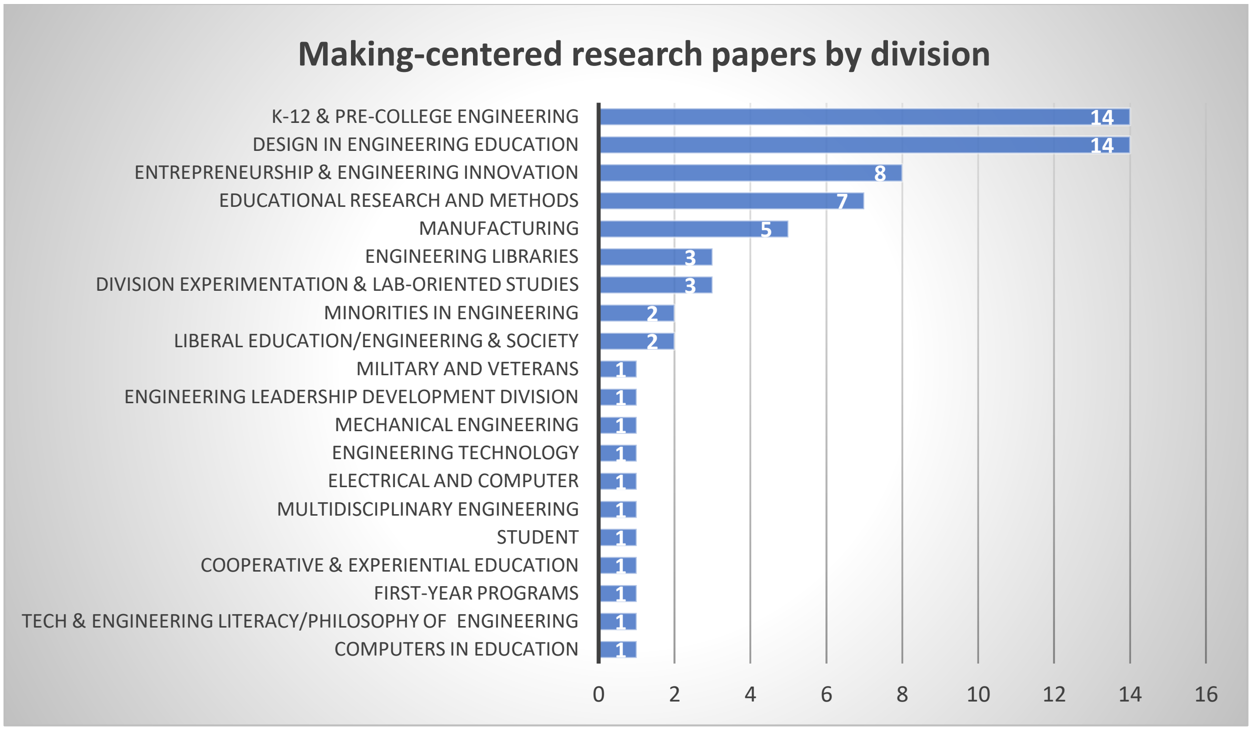

Figure 2. The variety of ASEE divisions that have accepted Making-centered papers

With regards to the contexts of the studies, the data indicate that university classes and Makerspaces are, by far, the most heavily studied site for Maker Education research (See Fig. 3), with 28% and 26%, respectively. The Makerspace category included any communal workshop space aside from formal engineering shops or laboratories (e.g. Innovation Hubs, Fab Labs, Maker Labs, etc.). Like the distribution of research papers within divisions, there were a large number of contexts with only a few papers in each. This suggests that, although Maker Education practices may be taking place in a variety of venues, many of these contexts are only starting to be explored through research.

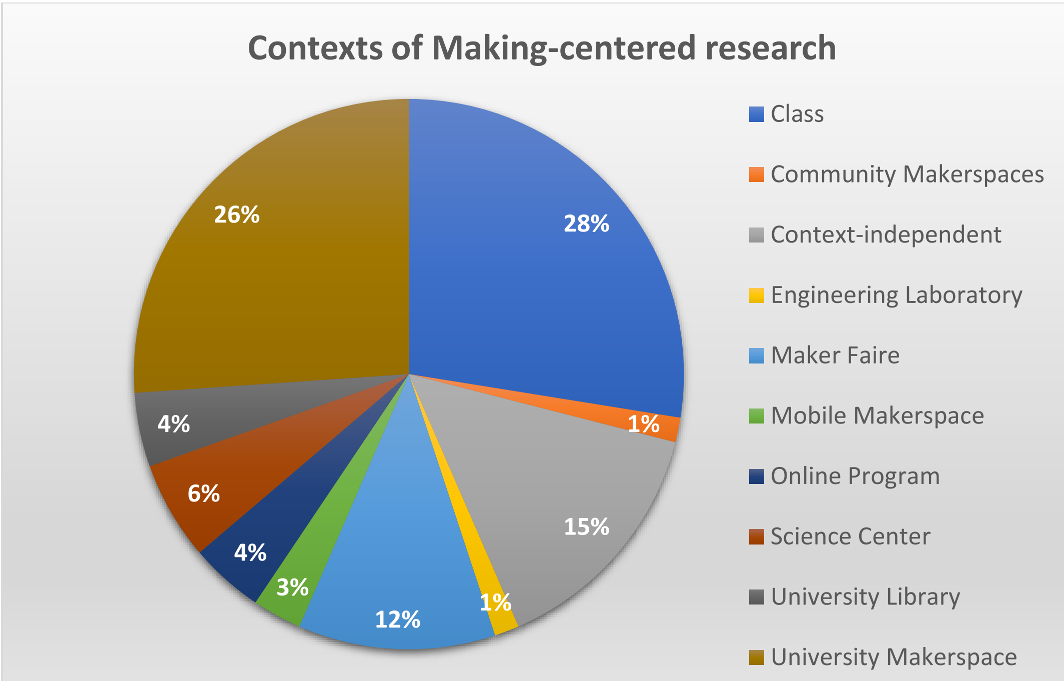

Figure 3. The relative frequency of contexts for Maker Education research

Findings

An iterative qualitative analysis of the articles' contents revealed several major areas of topical focus, which emerged as the following codes:

Learning-focused codes	**Non-learning-focused codes**
Project-based pedagogy	*Technical operation of tools and equipment*
Creative engagement with technology	*Broadening participation: Socioeconomic*
Interest-based pedagogy	*Broadening participation: Non-STEM majors*
Informal/Grassroots learning	*Community-building in makerspaces*
Entrepreneurial pedagogy	*Operating a makerspace*
Career preparation	*Understanding grassroots Maker culture*

Table 1. Majors codes resulting from a qualitative analysis of Maker Education research papers

The thematic findings for the learning-focused set of papers are still emerging; the preliminary results are presented in terms of major themes derived from the content analysis. These categories are by no means exhaustive or fully describe all the papers analyzed; however, they represent prominent trends that intersect with the Learning Sciences-based theory discussed above.

Maker Education: New and Exciting, but Lacking Specific Evidence of Learning Outcomes

While most papers analyzed had some relevance to learning strategies, outcomes, or pedagogies, most did not make significant use of Learning Sciences literature. Out of the 68 papers analyzed, only five made explicit and repeated references to Learning Sciences concepts, terminology, or theoretical frameworks. For the many papers that focused on introducing innovative, project-based pedagogies or bringing new technologies into the classroom, metrics for success were largely based on student interest, engagement, and excitement. Few papers sought to determine specific changes in either technical knowledge or the development of soft skills, but these outcomes were alluded to frequently.

Makerspaces: Engineering Labs Run *for* Students vs. Community Hubs Run *by* Students

As noted above, university or academic Makerspaces were a prominent area of focus for Engineering Education researchers. Many articles related to these spaces were excluded based on their focus on operation or technical capacities. Several studies describe the teaching of traditional engineering content—especially engineering design—but with a greater emphasis on collaboration and entrepreneurship [31]–[33].

Other articles provide evidence that Makerspaces were being conceived of as places that allow for different kinds of knowledge production and social development. Brey et al. [34] discuss the development of a student-run Maker-in-Residence program that brings in craftsman and local “expert Makers” to lead workshops and long-term construction projects. Through these activities a Community of Practice was fostered, notably organized by novices who have self-selected to engage in legitimate peripheral participation [35]. Similarly, Shelley et al. [36] describe an undergraduate-led effort to design and run an Makerspace; rather than use a Makerspace to learn about the engineering design process, they employed their knowledge of design to actually create an interdisciplinary space.

Overall, these papers suggest a tension between conceptions of Makerspaces as sites of traditional engineering learning guided by “top-down” teaching versus sites of peer-supported, interest-driven exploration guided by “bottom-up” community development. Similar tensions were the focus of Tomko et al.’s [37] study of student-to-student and student-to-faculty social interactions in a university Makerspace.

Maker Mindset: A Foundation for Thinking like a 21st-Century Engineer

The explicit characteristics attributed to the Maker Mindset, as well as related qualities, were heavily referenced and explored in the literature. Several papers reference self-efficacy [38], extrinsic motivations for learning [39], and adaptive expertise [40]. In looking at the connections between these so-called “soft skills” and professional engineering qualifications, Wigner et al. [41] conducted an in-depth analysis of the Maker Mindset’s connections to ABET accreditation standards. These studies cumulatively suggest that the Maker Mindset is closely linked with key attributes associated with the “Engineer of 2020” [42].

Discussion

The multidimensional nature of Making allows a variety of disciplines to engage with Maker practices in many ways. At the same time, this diversity has allowed for the formation of research “islands” and “gaps” in which Maker-related phenomena are parsed through the standard divisions established within the world of engineering education. Consider the fact that the terms “Making”, “Maker Movement”, and “Makerspace” are not included as key terms in the most recent edition of the Engineering Education Research Taxonomy [43], while Making-related topics appear in virtually every major taxonomic category (see Table 2). The diffusion of Making-related topics in so many different arenas suggests that the Making is not only relevant to Engineering Education broadly, but also that it may be necessary to consider additional methodologies and categories of research that take a more holistic approach. Bill and Fayard [44] attempt that kind of undertaking by describing how the Communities of Practice learning framework might be employed to both shape the design and layout of a university makerspace while also fostering an entrepreneurial and innovation student culture. Such a study might fit well under a new subheading in the taxonomy: *Learning environment—makerspace.*

Examples of Making-related topics in the Engineering Education Research Taxonomy (Finelli, n.d.)	
1.d.i.4	*Student assessment tools: portfolios*
2.a.iii.1.b.i	*Designing via rapid prototyping*
3.b.ii.1	*Diversity in individual learning styles*
5.e.vi,vii	*Learning environment— communities and studios*
7.e.vi-viii	*Mutual, problem, and project-based learning models*
8.d-f,k	*Outcomes: creativity, critical thinking, entrepreneurship, innovation*

Table 2. Selected taxonomic subcategories that relate to Making-centered research

Conclusions and Future Work

Given the current state of the research field, Engineering Educators should feel encouraged to build on and extend constructs based in Learning Sciences that have traditionally received less consideration within higher education research. The rapid establishment of university Makerspaces is an opportune time to reevaluate existing pedagogical practices and implement Learning Sciences-based theory when making curricular changes. The previously-mentioned areas of tension raise important questions: If communities are not formed within Makerspaces, how are these spaces providing qualitatively different learning opportunities than traditional engineering shops? Can “top-down” spaces effectively cultivate the valuable social, emotional, and cognitive benefits that emerge organically in grassroots Maker communities?

While the literature reviewed above should act as a useful starting point for having larger conversations about the state of Maker Education research within Engineering Education, a great deal of work has been done outside of the discipline that may be useful to Engineering Education researchers. That being said, the interdisciplinarity of Learning Sciences research combined with the inherently trans/a-disciplinary nature of Maker practices [16], [25] complicates the standardization of Maker Education concepts and terminology. A recent meta-analysis of 43 Maker-related research projects [45] exemplifies the immense challenge of comparing studies that vary in duration, participant number, conceptual framing, and data type (i.e. qualitative and/or quantitative) in addition to the wide range of technical skills, settings, participant demographics, and goals of the Maker activities under investigation.

Additionally, there are bodies of literature that clearly speak to elements of Maker Education (art and design education research, for example) that, due to the historical divisions of research fields, have not been translated into the Learning Sciences or Engineering Education. To accomplish this monumental task, appropriate and rigorous methodologies that utilize interdisciplinary analysis methods will need to be employed.

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