Minding the Gap: Lacking Technology Inquiries for Designing Instruction to Retain STEM Majors

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Introduction

While there are many lines of research within science, technology, engineering/computer science, and mathematics (STEM) education, we argue that the most pressing and crosscutting problem remains how researchers can showcase ways to provide equitable and inclusive learning experiences that engage a more diverse population of learners, providing a foundation for later STEM participation as professionals and citizens. There is now a well-established tradition of calls for increased capacity in STEM fields, due in part to the dynamic demands and increasingly technical nature of the world and workplace (Augustine, 2006). Many such demands are expressed as an urgent need (Langdon, McKittrick, Beede, Khan, & Doms, 2011) or related to a particular field in STEM as needing more workers (Xue & Larson, 2015). However, others have argued there is not a shortage of STEM graduates at all (Charette, 2013). Regardless, the focus on a STEM pipeline has done little to diversify the STEM workforce, leading some to advocate for the term *pathways* instead of pipelines; the term pipeline suggests a single narrow route, while pathways suggest multiple routes of growth, as well as a diverse set of points where entry to the STEM field is plausible (Cannady, Greenwald, & Harris, 2014).

In turn, this shift in language becomes representative of the larger shift in educational research that emphasizes the importance of relevancy of research to practice

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(Gutiérrez & Penuel, 2014) and the challenges of urban education more broadly related to diverse students' learning affordances being leveraged (Emdin, 2016). Tolbert, Schindel, and Rodriguez (2018), in turn, argue that STEM and science education research should be evaluated in terms of its transformative potential, a critique that extends past concerns about the boutique nature of many research projects that build vitas but do not lead to lasting change (Barab & Squire, 2004). With this position in mind, this chapter first presents the barriers and drivers of change within STEM education before illuminating the ways research on technology and learning designs might play a role toward more equitable and inclusive STEM learning. Through this structure, our goals for this chapter are to highlight the most current research in the field of STEM education, elaborate on the challenges in providing novel learning experiences for diverse youth, and describe the affordances of this recent literature in pursing equitable STEM education for all.

Barriers and Drivers of Change

In K-12 settings, reform-oriented STEM standards have been strong drivers of change, while assessment practices and textbook publishers have tended to create barriers to change. For instance, in the USA, the Common Core State Standards for Mathematics (National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010) and the Next Generation Science Standards (NGSS Lead States, 2013) have brought a new focus to STEM *practices*. This focus has been supported through both national and private funding agencies and the research that these agencies approve for funding opportunities. Unfortunately, textbooks tend to conserve traditional STEM education approaches, despite strong evidence that changes should be made (Sherman, Walkington, & Howell, 2016), while also not considering the many opportunities afforded through the integration of current technological advancements. The question remains: How can we mediate this reality?

The global trend of increased reliance on standardized testing as a means to evaluate teachers and schools has led to less and lower-quality science teaching, especially for those from groups already underrepresented in STEM fields (Aydeniz & Southerland, 2012; Peters, 2014). Even with advances in technology and learning analytics, most assessments still predominantly measure conceptual understanding, rather than STEM practices. Even more so, when national assessments do adopt a scientific practices framework for evaluation, the context in which the application of these practices is situated is often geographically and historically foreign to those students who have been underserved by these standards (such as youth of color from low economic communities; Basile & Lopez, 2015). These realities, in turn, encourage STEM teachers to focus on concepts at the expense of practices, as well as remain centered on a myopic view of learning related to the normative center of schooling (Leonardo & Broderick, 2011) that disregards the impact that cultural relevancy has on scientific practices (Brown, 2017). This strategy, sometimes pressed onto teachers in the form of scripted curricula by school and district leaders seeking to improve school evaluations (Timberlake, Thomas, & Barrett, 2017), can make it challenging to do transformative research and improve the learning experiences for all students. This is not only true for K-12 education, though; postsecondary education also shares this problem.

In higher education settings, professors have been notably resistant to change in the types of pedagogy, curriculum, and assessments provided to postsecondary students. Due to the nature of how STEM disciplines are typically taught in these contexts (such as large lecture halls with hundreds of students using the dissemination model of teaching), students who express self-efficacy in creative problem-solving tend not to persist, suggesting a need for curricular and programmatic changes (Atwood & Pretz, 2016), yet more effective strategies are slow to be adopted (Borrego & Henderson, 2014). This is not to say that attempts to resign postsecondary learning environments in STEM are not present in the literature (see Boda & Weiser, 2018). Rather, this has led to funding agencies having a major influence on these types of changes in both K-12 and higher education settings. The most recent funding priorities in postsecondary STEM education have emphasized technologies and openly licensed materials—a significant opportunity in STEM education to include participation from all students. However, this has come at a cost, as education policies have simultaneously deemphasized teacher professional development (Pareja Roblin, Schunn, Bernstein, & McKenney, 2018).

Given the abundant evidence that K-12 and postsecondary instructors need support to integrate technology effectively (Herring, Koehler, & Mishra, 2016; Svihla, Reeve, Sagy, & Kali, 2015) and that they may not be confident engaging their students in STEM practices (Marshall, Smart, & Alston, 2017; Stroupe, 2015), teacher professional development should be a central focus and one that can effectively be folded into research partnerships with teachers (Koh, Chai, & Lim, 2017; Pareja Roblin et al., 2018). Likewise, for higher education faculty to change, supports are needed that align to institutional reward structures, such as being supported to engage in discipline-based education research (Singer & Smith, 2013). Focusing on systemic change—rather than boutique or individual efforts—may be the key to lasting change (Kezar, Gehrke, & Elrod, 2015), a view taken up by the National Science Foundation's program to revolutionize engineering and computer science departments (Ingram, Litzler, Margherio, & Williams, 2017).

We argue that researchers should consider these barriers and drivers of change as they build on key insights from STEM education research. These considerations could include engaging students at all levels in agentive STEM practices with appropriate scaffolding based on learners' personal epistemologies (Barger, Wormington, Huettel, & Linnenbrink-Garcia, 2016), building on students' cultural practices and experiences to leverage motivational factors that influence learning (Brown, 2017; Kumar, Zusho, & Bondie, 2018; Lee, 2003), and incorporating technology in contextually relevant and thoughtful ways (Boda & Brown, 2019; Metcalf, Grotzer, & Dede, 2015; Miller & Roehrig, 2018).

Engaging Learners in Agentive Practices

To understand how to support students' participation and learning from STEM practices, researchers typically conduct classroom-based studies, often using design-based research to understand how a learning design functions in context. A number of recent meta-analyses have provided greater clarity on the value of long-used designs. For instance, in general, active learning techniques result in greater learning gains compared to traditional lecture-based instruction (Freeman et al., 2014), and participating in STEM practices confers an advantage for learning, retention, and understanding (Kuhn, Arvidsson, Lesperance, & Corprew, 2017). These gains are also typically higher when student engagement with STEM practices is scaffolded (Kang & Keinonen, 2018; Korur, Efe, Erdogan, & Tunç, 2017; Qureshi, Vishnumolakala, Southam, & Treagust, 2017), though more research is needed on the impact of various types of scaffolding (Lazonder & Harmsen, 2016). Recent research on scaffolding has also raised concerns that directive scaffolding may produce learning gains in the short term, but may also have lasting negative attitudinal impacts (Roll et al., 2018). This has led some to argue for a need to explore alternatives to directive scaffolding, such as supports for individually relevant discovery practices, which is a stance that aligns with the focus of, and purpose for, STEM practices that was illuminated in the prior section.

Engaging students in STEM practices requires more agentive STEM learning experiences and highlights a need for research that investigates how to support students to direct their own use of STEM practices in ways that are contextually and culturally relevant to their lived realities—the ways they understand the world outside of formal learning contexts. Specifically, this means investigating metacognitive, affective, self-efficacy, and self-regulative supports and how these relate to students' learning in particular contexts. To engage with this process of applying scientific practices to localized and/or sociopolitical issues that students face, researchers need to be engaged with the nature of their own positionality, their relationship to the students they seek to serve, and define their research purposes in ways that are guided by a relationality that is designed purposefully in these experiences (Tolbert et al., 2018).

Learners' self-efficacy (i.e., confidence in their competencies) and a "sense of belonging" (i.e., relationality to the content being learned) predict higher outcomes in science, especially for students from groups that are underrepresented in STEM (Chemers, Zurbriggen, Syed, Goza, & Bearman, 2011; Hilts, Part, & Bernacki, 2018). Thus, providing students with opportunities to engage in STEM practices gives them a chance to evaluate their interest in STEM careers (Mody, 2015). When students participate in STEM practices authentically, they experience emotions related to their engagement, such as feeling excitement about an insight or frustration about an unexpected result. Such emotions are endemic to professional practice realities and epistemological challenges students will likely face as practitioners should they choose to pursue STEM careers (Jaber & Hammer, 2016). Adding onto these studies in attempts to leverage technological innovations, investigations into how students manage these types of discovery learning in online environments suggest that environments should be designed to focus on learning rather than minimizing feelings of frustration or maximizing fun (Adler, Schwartz, Madjar, & Zion, 2018). This, however, also requires stakeholders in STEM education to recognize and ameliorate any barriers some populations may face in their active participation with these novel learning experiences.

Building on Students' Cultural Practices and Experiences

While many studies cite broadening participation as a goal, few tackle these issues directly (Svihla, Marshall, Winter, & Liu, 2017). Doing so typically requires careful, in-depth qualitative analyses and/or sample sizes large enough to permit quantitative disaggregation by subgroup. Recently, more STEM education research has taken a social justice stance, partially in response to systemic inequalities that have become more visible through increasingly punitive uses of standardized testing and recognition that traditional instruction systematically underserves non dominant youth. For example, qualitative analysis of diverse classroom mathematics instruction clarifies that commonplace instructional strategies systematically exclude students who do not conform to the expectations of the mainstream culture regarding who is good at math and what that looks like in K-12 classrooms (Louie, 2017). This has led more scholars to consider frameworks such as culturally responsive and sustaining pedagogies, Native and Indigenous science, intersectionality, and, more generally, focus on the roles that context and cultures play on the process of learning (Bang & Marin, 2015; Boda & Brown, 2019; Kolonich, Richmond, & Krajcik, 2018; Leyva, 2017; Paris & Alim, 2014). In turn, researchers are increasingly using research methods that engage students as co-researchers (Birmingham et al., 2017) to gain a more holistic understanding of how these learning experiences can be changed for the betterment of all demographics learning STEM disciplines.

Indeed, the importance of social context and community is underscored in recent research on engaging students from groups that are underrepresented in STEM. Designing consequential learning experiences (Calabrese Barton & Tan, 2018) that matter in students' lives and communities, such as through environmental projects, can lead to deep engagement (Birmingham et al., 2017; Schindel Dimick, 2016), especially when content is intertwined with cultural and community views and histories (Bang et al., 2014). Moreover, engaging students' cultures can support their participation in practices and development of identity in STEM (Meyer & Crawford, 2015) and may help students to have some ownership or authority over their learning. This, in turn, can contribute to the development of learners' identities in STEM and help them envision themselves as STEM practitioners (Brown, 2017; Langer-Osuna, 2017; 2018), which supports their persistence in STEM degrees (Carpi, Ronan, Falconer, & Lents, 2017).

Involving students in meaningful learning experiences that invite them into new STEM learning experiences can reignite lost interest (Jack & Lin, 2014).

This matters because interest often predicts effort (Patall, Vasquez, Steingut, Trimble, & Pituch, 2016) and persistence in STEM. There is no clear age by which such interest needs to be cultivated, meaning efforts to develop interest can be usefully invested along the entire educational trajectory (Maltese, Melki, & Wiebke, 2014). More research is needed on instructional designs that are based in equitable and inclusive teaching, including asset-based approaches, early interventions that reduce opportunity gaps, and theoretical frameworks that include equity and inclusivity (NCTM Research Committee, 2018). Through these research agendas, STEM education for all is seen as attainable, especially when considering the affordances of educational technologies and their capabilities to improve student learning beyond traditional learning models.

Supporting STEM Learning with Educational Technologies

Researchers have emphasized that technologies are neither inherently good nor are they bad, but rather that the pedagogical uses of technological advances must be considered to truly highlight their promises and impacts (Clements & Sarama, 2017). Educational technology can both scaffold students' engagement in STEM practices and contribute to equitable and inclusive learning. Here, we review recent research that provides a foundation for educational technology use, prior to discussing more transformative possibilities on the horizon.

To understand the relative impact of four approaches to improving science learning—providing extensive professional development about inquiry, technologies to support conceptual understanding, science kits, and textbook innovations—Cheung, Slavin, Kim, and Lake (2017) conducted a meta-analysis that found professional development and technology had the greatest impact. However, given that the largest barrier to K-12 teachers adopting technology is their beliefs about what effective teaching and learning looks like (Ertmer, Ottenbreit-Leftwich, Sadik, Sendurur, & Sendurur, 2012), thus the approach that professional development models take to educate STEM instructors should be carefully considered. Combining these two strategies—technology and professional development—may be particularly useful to help teachers understand both the strengths and limitations of appropriate technology use (McKnight et al., 2016). This combination has also been shown to enhance instructor buy-in for such novel learning experience integrations (Buabeng-Andoh, 2012; Potter & Rockinson-Szapkiw, 2012).

A key role for educational technology has been to provide scaffolding within learning environments where previous models of scaffolding may not have leveraged the affordances of technology use in the classroom. For instance, in secondary classrooms, programs like the Web-Based Inquiry Science Environment (WISE; wise.berkeley.edu/) have been shown to enhance content acquisition compared to traditional learning environments and also to narrow achievement gaps (Raes, Schellens, & De Wever, 2014). Such environments typically support students to learn from computer simulations using metacognitive scaffolding (Moser, Zumbach,

& Deibl, 2017). Additionally, some interactive textbooks blur the lines between textbook and learning environments like WISE, providing automated formative feedback and distributed practice through quizzes and interactive simulations, a strategy that has proven successful in introductory undergraduate STEM courses (D'Angelo et al., 2014; Edgcomb et al., 2015). Other technologies like mathematics games and online mathematics homework tools provide similar supports—automated feedback and repeated practice—to significantly increase performance on standardized tests (Bakker, van den Heuvel-Panhuizen, & Robitzsch, 2015; Roschelle, Feng, Murphy, & Mason, 2016).

In higher education settings, the movement from face-to-face to blended or entirely online settings has frequently resulted in positive outcomes, in part because faculty receive professional development to make the transition (Baepler, Walker, & Driessen, 2014; Bernard, Borokhovski, Schmid, Tamim, & Abrami, 2014; Bernard, Broś, & Migdał-Mikuli, 2017; Spanjers et al., 2015). In doing so, faculty have incorporated research-based strategies, such as more frequent formative assessment and distributed practice. Like many uses of online courses, serious educational games support learning through feedback and reflection, while also enhancing engagement through realistic context, story, and interactivity (Ravyse, Blignaut, Leendertz, & Woolner, 2017). When aligned to curricula, such games can support the development of STEM practices (Wallon, Jasti, Lauren, & Hug, 2018). However, like many curricular innovations, implementation can enhance or minimize learning (Wilson et al., 2018). While well-designed and well-implemented games can result in narrowed achievement gaps (Schacter & Jo, 2016), comparison of gains related to high-quality science instruction and a game designed to cover the same content showed that students performed equally in both conditions, raising concerns over whether the benefits outweigh the high cost of designing such games (Sadler, Romine, Menon, Ferdig, & Annetta, 2015). However, more research is needed on long-term impacts and other impacts of educational uses of games (Sadler et al., 2015).

Future Directions for More Equitable Technology-Enhanced STEM Education

Finding ways to support STEM practices in online learning remains relatively understudied (Jaber, Dini, Hammer, & Danahy, 2018). While inquiry-based learning management systems can scaffold students to participate in STEM practices using simulations and to learn from them (Donnelly, Linn, & Ludvigsen, 2014), it is not yet clear if students learn to transfer STEM practices when the scaffolding is faded. After using such learning designs, do students exhibit *framing agency*—the ability to make decisions that are consequential to their learning and further designing? Can they pose their own questions and design ways to investigate them? Supporting this kind of learning is particularly challenging because of its unpredictability—an area, therefore, that has been difficult for technology to support effectively. When answers do not converge on a single correct path, it is difficult for technologies to provide automated feedback and guidance. Likewise, designing technologies capable of supporting students to make connections between normative, textbook science and students' own, everyday, and cultural experiences remains a challenge. However, supporting teachers to make effective and contextual adaptations that align to students' cultural experiences is more easily accomplished than previously articulated in the field. Educative curriculum materials that are designed to support teachers to make such adaptations would be particularly fruitful (Davis et al., 2014) and serve as a potential area of inquiry for future projects.

In order to realize the promise of new STEM standards that emphasize practices, more development and research on assessments that can equitably measure progress in these areas is also needed. Despite the availability of multimedia, such as interactive simulations, few standardized tests incorporate these, revealing a mismatch between the resources to support learning and the means to measure understanding (Van Rooy & Chan, 2017). As technology continues to play a central role in assessment, researchers must attend to novel ways to equitably help students to share what they actually know. For example, technology might provide scaffolding for students to better ensure they understand what they are being asked, using familiar context and allowing students to use both writing and drawing to respond (Kang, Thompson, & Windschitl, 2014). Significant progress has been made with computer-based and learning analytics assessments of science practices (Gobert, Sao Pedro, Raziuddin, & Baker, 2013; Kuo, Wu, Jen, & Hsu, 2015), but further research is needed to expand such approaches and relate outcomes to particular learning experiences, such as serious games (Westera, Nadolski, & Hummel, 2014). These learning analytics tools can also usher in change by supporting formative data use. For instance, Reinholz and Shah (2018) created a tool to identify subtle inequalities in classroom participation. Such technologies should make it easier for teachers to sensibly collect and use learning data in their instructional decision-making (Cai et al., 2018).

With a now well-established body of research showing that gesture and embodiment can support and reveal learning (Alibali & Nathan, 2018; Lira & Stieff, 2018; Williams-Pierce et al., 2017), advances in wearable technologies are also allowing researchers to explore ways to integrate these into STEM teaching (Lee, Drake, & Williamson, 2015; Norooz et al., 2016). While new technologies offer more accessible ways to engage in STEM, they also risk widening opportunity gaps; any bring-your-own-device approach runs this risk. Likewise, researchers have raised concerns about equitable access to and use of technologies in STEM classrooms (Kitchen & Berk, 2016), including the fact that technologies that end up in schools serving marginalized groups are less likely to include professional development for faculty and less likely to engage learners in agentive ways (Kitchen & Berk, 2017). It is also important to note that access gaps persist in many parts of the world; as of 2017, less than 55% of the world population had Internet access ("Internet World Stats," 2017). This is a tension our field needs to address and treat with critical reflection.

Ultimately, to support transformative uses of technology, researchers will need to collaborate closely with teachers and consider designs that support them to use innovations expansively, while also engaging students agentively (Cai et al., 2017; Davis, Janssen, & Van Driel, 2016; Linn, Gerard, Matuk, & McElhaney, 2016; Rubel & Stachelek, 2018). In order for our learning designs and technologies to be transformative, they must both fit into and modify many resilient structures that maintain inequities—a call over 15 years in the making (Lee, 2003). While continued qualitative and quantitative studies of classroom interventions are needed, research studies should therefore also attend to the systems and contexts at play and how these do or do not change in response to our interventions. Without such contextually dependent modifications that meet the needs of the students we seek to serve, integration of such novel technologies may fall short of responsive and relational applications to support the learning needs of diverse, under-represented populations in STEM.

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