Advancing the State of the Art of STEM Integration

Tamara J. Moore
Purdue University

Karl A. Smith
University of Minnesota and Purdue University

The inaugural issue (Volume 1, Number 1, 2000) of the *Journal of STEM Education* (then titled *Journal of SMET Education*) included an article by Norman Fortenberry titled "An examination of NSF's programs in undergraduate education." Fortenberry provided a comprehensive summary of the National Science Foundation (NSF) undergraduate education and training programs, which he categorized in five areas for impact in SMET education – curricula and institutions, faculty, courses and laboratories, diversity, and students. He concluded, "With sufficient resources, NSF can both strengthen its core programs and address unmet needs and opportunities. Unmet opportunities can be grouped into five areas: (1) systemic reform of curricula and institutions, (2) high-quality instruction by faculty, (3) educational research, materials, and methods, (4) emphasis on meeting the needs of diverse student populations, and (5) student support (p. 4)." Since Fortenberry's call for embracing research (area 3), discipline-based education research has advanced through the efforts of a rapidly increasing community of researchers, the emergence of engineering education research (and more broadly STEM education research) centers and programs, and reports, such as, the 2012 National Research Council (NRC) report, *Discipline-Based Education Research* (DBER; NRC, 2012a).

Discipline-based education research in science and engineering has continually advanced in the past ten years. Engineering education research (EER) has been on the fast track since 2004 with a dramatic rise in the number of PhDs awarded and the establishment of new programs, even entire EER departments (Benson, Becker, Cooper, Griffin, & Smith, 2010). The rapid advancement of EER has been documented in a series of editorials (Smith, 2006; Streveler & Smith, 2006; 2010) and EER Networking sessions at American Society for Engineering Education conferences. Smith and Streveler have organized and facilitated Engineering Education Research and Innovation (EER&I) networking meetings at each ASEE annual conference since 2010. Each session was attended by between 40 and 60 representatives of engineering education research and innovation programs, departments and centers. At ASEE 2014 the networking sessions will be held at the EER Lounge, which is part of the Engineering Education Research and Innovation space in the Exhibition area.

The 2012 National Research Council's *Discipline-Based Education Research* (DBER) report captures the state-of-the-art advances in our understanding of engineering student learning and highlights commonalities with other science-based education research programs. The DBER report is the consensus analysis of experts in undergraduate education research in physics, chemistry, biology, geosciences, astronomy, and engineering. The study committee also included higher education researchers, learning scientists, and cognitive psychologists. Editorials on the DBER report have been published in ASEE Prism (Singer & Smith, 2013a) and the *Journal of Engineering Education* (Singer & Smith, 2013b). A recent special issue of the *Journal of Research on Science Teaching* was devoted to Discipline-Centered Postsecondary Science Education Research.

Now that the EER community has been established and is growing, it is time to explore the next major advancement, STEM integration, and the *Journal of STEM Education*, which was established in 2000, is the ideal venue to present this editorial. Research-to-practice efforts on STEM integration are the central organizing feature of the University of Minnesota STEM Education Center, established in 2009 by co-founders Tamara Moore and Gillian Roehrig and currently led by Karl Smith and Kathleen Cramer. Our purposes for this editorial are to summarize STEM integration in both K-12 and undergraduate education with a focus on U.S. and international trends. We will feature known best practices and programs both in classrooms and in research around STEM integration.

What is STEM integration?

In general, integrated STEM education is an effort to combine the four disciplines of science, technology, engineering, and mathematics into one class, unit, or lesson that is based on connections among these disciplines and real-world problems. More specifically, STEM integration refers to students participating in engineering design as a means to develop relevant technologies that require meaningful learning through integration and application of mathematics and/or science. STEM integration gets its roots from the progressive education movement of the early 1900s (e.g., Dewey, 1938) and more recently the socio-cognitive research movement (NRC, 2000). Therefore, high quality integrated STEM learning experiences include, but are not limited to, the following: engage students in engineering design challenges that allow for them to learn from failure and participate in redesign, use relevant contexts for the engineering challenges to which students can personally relate, require the learning and use of appropriate science and/or mathematics content, engage students in content using student-centered pedagogies, and promote communication skills and teamwork (Moore, Guzey, & Brown, 2014). Implementation of STEM integration can involve one or more instructors (Roehrig, Moore, Wang, & Park, 2012), one or more classes (Berlin & White, 1995), and can require differing lengths of time to complete (Isaacs, Wagreich, & Gartzman, 1997).

There are two different ways to integrate content and engineering thinking: context integration and content integration. Context integration refers to an integration of engineering design as a motivator to teach some disciplinary content (usually mathematics and/or science). The learning goals are not about the engineering per se, but rather engineering design as a pedagogy to help students learn the content. Content integration refers to an integration of engineering thinking and mathematics/science content where learning multiple areas including engineering are part of the learning objectives for the activity or unit. Here, the learning goals would include mathematics and/or science content but also include engineering learning as a desired outcome (Moore et al., 2014). Whether a learning activity is content or context integration depends upon where emphasis is placed. For example, the NanoRoughness Model-Eliciting Activity is an activity that can serve both purposes. The problem is set in an engineering context where the students are working for a company that is developing coatings for hip-joint replacements. The student teams need to design a way to measure the roughness of coatings at the nanoscale given atomic-force microscope images of coating materials. In a context integration implementation of this activity, a statistics instructor might use the engineering context as a motivator but focus heavily on the ways students use the ideas of sampling, central tendency, and variance that are required to de-

velop the procedure for measuring roughness (Hjalmarson, Moore, & delMas, 2011). Whereas, a first-year engineering instructor might want to take a content integration approach calling attention to the engineering design thinking by helping the students recognize the iterative engineering thinking used in the development of their roughness model, using the engineering context to bring out the chemistry concepts by focusing on the minimization of wear on the hip joint coating highlighting the molecular structure of the coatings, and the statistical analysis methods needed in the roughness model (Moore & Hjalmarson, 2010). Context and content integration approaches to STEM integration are useful to help students recognize the interconnectedness of the STEM disciplines. Smith and Karr-Kidwell (2000) state that the goal of an integrated STEM education is to be "a holistic approach that links the disciplines so the learning becomes connected, focused, meaningful, and relevant to learners" (p. 22), and both of these approaches are useful to achieving these ends.

Current Status of STEM Integration

STEM integration is taking hold in both the K-12 and postsecondary arenas. The current movement in K-12 education to integrate engineering design into science education is evidence that the ideas of STEM integration are taking root. The document *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (NRC, 2012b) outlines a broad set of expectations for K-12 science education students. Through these expectations, the framework documents a new vision for K-12 science education that includes engineering enterprises as well as scientific ones.

The recently published *Next Generation Science Standards* (NGSS; NGSS Lead States, 2013), which are academic science standards that were developed based on *A Framework for K-12 Science Education* (NRC, 2012b), require elementary and secondary science teachers to use engineering design pedagogies as one method for teaching science content. At the minimum, this represents a context integration approach to learning science, but it also represents an opportunity to develop and foster content integration approaches, which give relevance to all content areas and are more representative of the problems that our society faces. As states in the U.S adopt NGSS and as other countries consider the integration of engineering into the precollege curriculum, the need for understanding how learning progressions for engineering design and relevant science content objectives work together becomes more imperative.

Initiatives that focus on STEM integration are becoming more and more prevalent. Emphasis is being placed on researchers and practitioners to consider STEM integrated curricula and pedagogies. We are now seeing STEM focused articles and entire issues in research and practitioner journals (e.g., *School Science and Mathematics* - Volume 112, Issue 1; *The Science Teacher* - Volume 80, Issue 1; and *Mathematics in the Middle School* - Volume 18, Issue 6). Curricula have been and are being developed to address the need for integrating STEM meaningfully. The National Research Council report, *Successful K-12 STEM Education: Identifying Effective Approaches in Science, Technology, Engineering, and Mathematics* (2011), describes models of schools across the country that focus on integrated STEM ideas.

Research in STEM integration is also being given emphasis. The recent joint report of the National Academy of Engineering (NAE) and the National Research Council, *STEM Integration in K-12 Education: Status, Prospects, and an Agenda for Research* (NAE & NRC, 2014) describes theoretical models of STEM integration with the purpose of shaping research and practice of STEM integration at the K-12 level, with particular emphasis on curriculum design and assessment development. This work came out of the NAE project, *Toward Integrated STEM Education: Developing A Research Agenda* (2013), which resulted in the above report that provides a structured research agenda for "determining the approaches and conditions most likely to lead to positive outcomes" of STEM integration. A related report, *Developing Assessments for the Next Generation Science Standards* (NRC, 2013), includes recommendations for classroom and larger-scale assessments that are related to STEM integration due to the NGSS integration of engineering into science learning. Collaborative research endeavors by groups of faculty, such as the one described for the University of Minnesota's STEM Education Center, are being formed. Faculty positions in integrated STEM education are being created. For example, Purdue University has announced a cluster-hire for K-12 Integrated STEM Teacher Education through which six open-rank faculty positions will be filled with the intention of targeting the issue of STEM integration through research-to-practice endeavors.

With the U.S. and international emphasis on increasing the number of STEM graduates (PCAST, 2012; NRC, 2012c) the integration of engineering into K-12 science standards has excellent potential for encouraging more students to pursue STEM, especially engineering careers, and better preparing them to success in post-secondary settings. The work of Carr, Bennett, and Strobel (2012) and Moore, Tank, Glancy, Kersten, and Ntow (2013) have documented the status of the integration of engineering in K-12 across the US through assessment of academic standards documents showing the trend of integrating engineering into science and mathematics is increasing in the United States. Research from around the world is also showing trends for increasing K-12 STEM integration initiatives. Researchers such as Dr. Lyn English of Queensland University of Technology in Australia, and Dr. Nicholas Mousoulides of University of Nicosia in Cyprus are studying STEM integration interventions in classrooms as well (e.g., English & Mousoulides, 2011).

Undergraduate STEM Integration

STEM integration currently has much less presence in undergraduate STEM education than in K-12; however, there are signs that this may be changing. Fairweather (2008) argues in his summary report, Linking Evidence and Promising Practices in Science, Technology, Engineering, and Mathematics (STEM) Undergraduate Education for a National Research Council workshop,

> ". . . although faculty in STEM disciplines vary substantially on a broad array of attitudinal and behavioral measures (Fairweather & Paulson, 2008) careful reviews of the substantial literature on college teaching and learning suggest that the pedagogical strategies most effective in enhancing student learning outcomes are not discipline dependent (Pascarella & Terenzini, 1991; 2005). Instead, active and collaborative instruction coupled with various means to encourage student engagement invariably lead to better student learning outcomes irrespective of academic discipline (Kuh, 2008; Kuh, Kinzie, Schuh, & Witt, 2005; Kuh, Kinzie, Buckley, Bridges, & Kayek, 2007). The assumption that pedagogical effectiveness is disciplinary-specific can result in "reinventing the wheel," proving yet again that pedagogies engaging students lead to better learning outcomes (p. 4-5)."

A pedagogical shift that has taken hold in undergraduate STEM education is the use of cooperative learning and this shift has excellent potential for increasing STEM integration. Cooperative learning was introduced nationally to engineering educators at the 1981 Frontiers in Education Conference in Rapid City, SD (Smith, Johnson, & Johnson, 1981a); a little over 30 years after Morton Deutsch's pivotal article (Deustch, 1949). The 1981 paper was based on David and Roger Johnson's pioneering work (Johnson & Johnson, 1974) as identified by Karl Smith in the mid-1970s as a promising practice for engineering education. Also in 1981 an article, *Structuring Learning Goals to Meet the Goals of Engineering Education* (Smith et al., 1981b), was published in the Journal of Engineering Education. Cooperative learning is now embraced by many engineering faculty (Smith, 2011), and its use is increasing by faculty at large as indicated by the UCLA Higher Education Research Institute Survey of Faculty as shown in Table 1 (DeAngelo, Hurtado, Pryor, Kelly, & Santos, 2009). The adoption of cooperative learning provides a foundation for science, technology, engineering, and math faculty to embrace STEM integration.

Methods Used in "All" or "Most" Classes	All Faculty 2005 - %	All Faculty 2008 - %	Assistant – 2008 - %
Cooperative Learning	48	59	66
Group Projects	33	36	61
Grading on a curve	19	17	14
Term/research papers	35	44	47

Table 1. The American College Teacher: National Norms for 2007-2008

Closely related to cooperative learning is the increase in focus on "challenge-based learning" (Bransford, Vye, and Bateman, 2002), which is another change needed for STEM integration. Challenges can be presented in many formats, such as, real data and experiences, simulations, and fabricated scenarios. Professional schools – medicine, law, engineering, business – have been using this approach under names such as problem-based learning, case-based learning, and project-based learning. One of the most popular research-based instructional approaches that embraces challenge-based learning is SCALE-UP (Student Centered Active Learning Environment with Upside-Down Programs; http://scaleup.ncsu.edu/). SCALE-UP classrooms have been implemented at North Carolina State University, MIT, the University of Minnesota and the University of Iowa. A recent issue of *New Directions for Teaching and Learning* was devoted to active learning spaces and features the SCALE-UP approach (Baepler, Brooks, & Walker, 2014). While cooperative learning and challenge-based learning programs are a start to STEM integration in undergraduate STEM education, more efforts are needed in this area.

There are some indications that a few undergraduate STEM programs are attempting STEM integration, such as Olin College and Iron Range Engineering; however the extent and depth of STEM integration is much less evident than in K-12. Clearly, there is room for advancement of STEM Integration in undergraduate STEM programs. As engineering educators continue to work to align student learning outcomes, assessment practices, and instruction (or pedagogy) more emphasis on STEM integration will become critically important (Streveler, Smith, & Pilotte, 2012).

How to Make Progress

Progress in K-12 STEM integration needs to come on multiple fronts. Among these are curricula development, teacher and administrator education initiatives, school change initiatives, and policy initiatives. The following highlight some ideas of how to make changes regarding these four issues:

- There is a need for curricula that integrate STEM contexts for teaching disciplinary content in meaningful ways that go beyond the blending of traditional types of understandings. Curricula that integrate STEM are rare for K-12 spaces, and of those that do, even fewer are research-based and have meaningful mathematics and science. Funding to back new research-based STEM integration curricular innovations is needed and should be targeted.
- Teachers and administrators need professional learning experiences that prepare them to work within and develop STEM integration learning environments for K-12 students. Most instructors, teachers, and administrators have not learned disciplinary content using STEM contexts, nor have they taught in this manner, and therefore new models of teaching must be developed if STEM integration is to lead to meaningful STEM learning. Programs should be developed at local and state levels to promote this change in practice. School change is needed to support STEM integration. Schools are set up to silo the disciplines of STEM. This separation is an artifact of history. While it is good to learn each subject as a stand-alone, it is also imperative that students see the interconnectedness of the subjects they are learning.
- Schools need to make structural changes that will allow students to do both - learn the nature of each of the STEM disciplines and learn that they are interconnected in ways that is more like what they will encounter in real-world problems. This will take concerted efforts at local, state, and national levels if this is to be achieved.
- Policymakers need to consider that our ever-changing world requires updates in the manner that we educate our students of the future. The research around STEM integration as one method of teaching K-12 students is very promising. Current policy initiatives that include high-stakes testing only on mathematics and language arts, school improvement measures based solely on scores on these tests, and teacher performance policies that are based primarily on these tests are hurting our education system. Schools and teachers make educational decisions about what and how to teach based on getting their students to perform better on these tests. This results in students not having access to science, technology, or engineering until later in their education, and in our opinion, the mathematics students are taught represent only the procedural nature of mathematics, not the structure of mathematics. In order to help alleviate this problem, policymakers must fully consider what the research is telling us about how students learn, how they engage, and what can lead to more meaningful citizenry.

STEM integration in K-12 has the potential to help students learn more deeply, enjoy the STEM disciplines, and provide them better access to future careers. The above suggestions may help move us forward in achieving these goals.

Although the suggestions above were focused on K-12 STEM integration, similar ideas are applicable for undergraduate STEM, where there is as much or more disciplinary siloing. STEM integration is sorely lacking in undergraduate STEM programs. We hope it will be the next shift.

Froyd, Wankat, and Smith (2012) identified five major shifts in engineering education in the past 100 years:

1. A shift from hands-on and practical emphasis to engineering science and analytical emphasis;
2. A shift to outcomes-based education and accreditation;
3. A shift to emphasizing engineering design;
4. A shift to applying education, learning, and social-behavioral sciences research; and
5. A shift to integrating information, computational, and communications technology in education.

They argue that the first two shifts are completed and the last three are in progress.

The *DBER* study is particularly focused on Shift 4, applying education, learning, and social-behavioral sciences research (Singer & Smith, 2013b).

The next major shift we argue in this editorial will be the re-integration of these five shifts with special emphasis on integrating the practical and mathematical, achieving the outcome of integrative STEM thinking, situating much of the work in an engineering design context, and basing the work on education, learning, and social-behavioral sciences research.

As a pioneer in STEM education scholarship, we see the *Journal of STEM Education* as a principal venue for documentation advancing the state of the art of STEM integration.

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Tamara J. Moore, Ph.D., is an Associate Professor of Engineering Education at Purdue University. Dr. Moore's research is centered on the integration of STEM concepts in K-12 and higher education mathematics, science, and engineering classrooms in order to help students make connections among the STEM disciplines and achieve deep understanding. Her research agenda focuses on defining STEM integration and investigating its power for student learning. She is creating and testing innovative, interdisciplinary curricular approaches that engage students in developing models of real world problems and their solutions. Her research also involves working with educators to shift their expectations and instructional practice to facilitate effective STEM integration.

Tamara is currently working on two National Science Foundation supported projects: The STEM Integration CAREER Project and the EngrTEAMS Project. The goal of the STEM Integration CAREER project (CAREER: Implementing K-12 Engineering Standards through STEM Integration; NSF – EEC/CAREER, #1055382) is to understand different mechanisms of integrating engineering content and standards into K-12 classrooms through STEM integration. Through this funding, a "Framework for Quality K-12 Engineering Education" has been developed. The framework will be used as a tool for evaluating the degree to which academic standards, curricula, and teaching practices address the important components of a quality K-12 engineering education. Tamara is the Principal Investigator of the EngrTEAMS (Engineering to Transform the Education of Analysis, Measurement, and Science in a Targeted Mathematics-Science Partnership, NSF – MSP, #1238140) project, which works with teachers to increase science and mathematics learning through engineering for 15,000 students in 4th-8th grades. It provides summer professional development and curriculum writing workshops to allow teachers to design curricular units focused on science concepts, meaningful data analysis, and measurement. Tamara is the co-chair of the Focus on Engineering Writing Team for the National Association for Research in Science Teaching Position Paper for the Next Generation Science Standards and was awarded a Presidential Early Career Award for Scientists and Engineers (PECASE) in 2012.

Karl A. Smith, Ph.D., is Cooperative Learning Professor of Engineering Education, School of Engineering Education, at Purdue University. He is also Emeritus Professor of Civil Engineering, Morse-Alumni Distinguished Teaching Professor, Executive Co-Director STEM Education Center, and Faculty Member, Technological Leadership Institute at the University of Minnesota. Karl has been actively involved in engineering education research and practice for over forty years and has worked with thousands of faculty all over the world on pedagogies of engagement, especially cooperative learning, problem-based learning, and constructive controversy. His research and development interests include building research and innovation capabilities in engineering education; faculty and graduate student professional development; the role of cooperation in learning and design; problem formulation, modeling, and knowledge engineering; and project and knowledge management and leadership. He is a Fellow of the American Society for Engineering Education and past Chair of the Educational Research and Methods Division.

Karl is PI of the NSF Workshop: Innovation Corps for Learning (I-Corps-L): A Pilot Initiative to Propagate & Scale Educational Innovations (NSF DUE-1355431). He has been co-PI on two NSF Centers for Learning and Teaching (CLT), including the Center for the Advancement of Engineering Education (CAEE), and co-PI on a NSF-CCLI-ND—Rigorous Research in Engineering Education: Creating a Community of Practice. He served on the Committee on the Status, Contributions, and Future Directions of Discipline-Based Education Research that produced the National Research Council Report, *Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering*. He has written eight books including *How to model it: Problem solving for the computer age; Cooperative learning: Increasing college faculty instructional productivity; Strategies for energizing large classes: From small groups to learning communities; and Teamwork and project management, 4th Ed.*