STEM Education:
Time for Integration

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STEM is more than shorthand for a collection of science, technology, engineering, and mathematics fields, and therein lies the promise of this domain for twenty-first-century education. Boundaries between STEM disciplines are blurring as students and practitioners seek to understand the natural and designed worlds. Our students come to us at an incredibly exciting time as secrets of the Neanderthal genome are unlocked, synthetic life is constructed, the first quantum machine debuts, distant planets are explored, and climate change challenges us to find creative solutions.

The potential of interdisciplinary work across STEM fields is captured in *A New Biology for the 21st Century* (NRC 2009a). Although the report focuses on biology, parallels can be drawn in other STEM fields. Integration of the physical sciences, computer science, biology, engineering, science education, and mathematics is viewed as foundational for a deeper understanding of biological systems. These inputs lead to science-based solutions to societal problems, including in the areas of health, environment, energy, and food, which then inform further research (NRC 2009b). *The Engineer of 2020* report calls for "an engineering profession that will rapidly embrace the potentialities offered by creativity, invention, and cross-disciplinary fertilization to create and accommodate new fields of endeavor, including those that require openness to interdisciplinary efforts with non-engineering disciplines" (NRC 2004, 50).

Preparing students to work at the interfaces calls for a new way of contemplating STEM education. As *A New Biology for the 21st Century* notes, "The New Biologist is not a scientist who knows a little about all disciplines, but a scientist with a deep knowledge in one discipline and a basic 'fluency' in several" (NRC 2009a, 20). Thus the challenge is to provide undergraduates with an education deeply rooted in their chosen STEM field and situated in a broader interdisciplinary context. Project Kaleidoscope's *What Works in Facilitating Interdisciplinary Learning in Science and Mathematics* summarizes a three-year, twenty-eight institution exploration and implementation of interdisciplinary STEM learning, offering strategies for leadership, learning, and campus culture to support interdisciplinary learning at the undergraduate level (PKAL 2011). Quality STEM learning and literacy are goals for all students and increasingly non-STEM jobs require some element of STEM capability.

Whether a new integrated STEM education will enhance student participation in science is an open question. Higher Education Research Institute (HERI) data reveal that underrepresented minorities' aspirations to an undergraduate STEM major are comparable to white and Asian students, yet completion rates are substantially lower (NRC 2010a, 46). While 24.5 and 32.4 percent of white and Asian students, respectively, who started college in 2004 completed a STEM major in four years, only 15.9, 13.2, and 14.0 percent of Latino, black, and Native American students, respectively, who enrolled as STEM students completed a STEM degree in the same time period. Overall there is increasing participation of women in STEM fields, although computer science has actually seen a decrease in female graduates in recent years. And, it's not only the underrepresented groups that we are failing to successfully engage in STEM at the undergraduate level. Overall completion rates for white and Asian students in STEM are substantially lower than in non-STEM fields.

A generation of Americans has passed through K–16 since the publication of *A Nation at Risk*, but a twenty-first-century workforce, high-quality STEM teachers, and a STEM-literate public are still elusive (National Commission on Excellence in Education 1983). Clarion calls for STEM education reform have drawn attention and action in more recent years. Yet, *Rising Above the Gathering Storm, Revisited* (NRC 2010b), found that despite a five-year effort by the public and private sector to implement the committee's

original recommendations, America's competitive position has deteriorated further and there have been few gains in mathematics and science in K–12. Educate to innovate is the new mantra, echoed in the National Science Board's *Preparing the Next Generation of STEM Innovators* (2010) with numerous recommendations for K–12 science education, including differentiated instruction and accelerated coursework, as well as rigorous STEM teacher preparation. The President's Council of Advisors on Science and Technology released *Prepare and Inspire: K–12 Education in Science, Technology, Engineering, and Math (STEM) for America's Future*, a visionary document on ways to enhance K–12 STEM education, and is preparing a report on postsecondary STEM education focusing on the transition to college and the first two undergraduate years (PCAST 2010).

While the pipeline for STEM professionals leaks in many places, it is clear that the end of high school and beginning of college is a critical juncture. It is essential to consider both the culmination of the high school years and the start of college, as well as the critical role of community colleges. Encouraging responses to the lack of alignment of precollege and college experiences include the Science College Board Standards for College Success (CBSCS-S), focused on college and workplace readiness. *Exploring the Intersection of Science Education and 21st Century Skills* aligns with those elements in the CBSCS-S and calls out adaptability, complex communication/social skills, non-routine problem solving, self-management/self-development, and systems thinking (College Board 2009, 3; NRC 2010). Like the CBSCS-S, the Common Core Math Standards focus on college and work readiness. Overall, some coherency in learning goals is emerging from a range of STEM communities at both the college and precollege levels.

CONVERGING ON SHARED STEM LEARNING GOALS

At the broadest level, a set of essential learning outcomes developed as part of AAC&U's Liberal Education and America's Promise (LEAP) initiative, are shared across the STEM disciplines. These become contextualized when situated within disciplinary core concepts and science practice or process skills. Scientific understanding and knowledge are growing at an unprecedented rate and a substantial barrier to effective science learning is mile-wide and inch-deep coverage in curricula, without attention to unifying principles. Critiques of the older Advanced Placement (AP) curriculum underscore the emphasis on broad coverage and insufficient cognitive challenge, while the evidence points to the effectiveness of focusing on a few core concepts and integrating learning about science concepts and practice (NRC 2002, 2007). Intertwined strands of learning were first introduced in the context of mathematics learning and later emphasized in the new *Common Core Mathematics Standards* (NRC 2001). *America's Lab Report* also found strong evidence for interweaving content and process in integrated instructional units where laboratory learning is integrated into the flow of instruction (NRC 2005). Integrated instructional units are at the core of the recommended design principles for laboratory learning which were integrated into the National Science Teachers Association laboratory guidelines and have been implemented at both the precollege and college levels.

The *Conceptual Framework for New Science Education Standards*, developed by the National Academies Board on Science Education, informs a full set of internationally benchmarked standards (2011a). The report reflects a commitment to key, core concepts and the importance of science practice—a substantive shift away from lengthy lists of facts.

Agreement upon the most fundamental concepts and practices may provide greater curricular coherence. For example, in biology the four big ideas in the revised AP curriculum are parallel in content to the five core concepts for biological literacy for undergraduates as outlined in *Vision and Change in Undergraduate Biology Education* (AAAS 2011). Similar alignment is found with the science practices in both. Scientific Foundations for Future Physicians(SFFP) establishes competencies relevant to both concepts and science practice for premedical and medical students (AAMC 2009). At the undergraduate level, these competencies align with and expand upon the *Vision and Change* core concepts and practices, replacing the prior notion of course taking versus competencies.

The integrated nature of STEM is reflected in the shared core concepts for biology students. The physical sciences and mathematics are deliberately included. The importance of modeling is called out in *Vision and Change* and SFFP, and included in the Common Core Mathematics Standards at the high school level. The SFFP competencies are largely interdisciplinary and offer a starting point for cross-disciplinary conversations that may benefit a larger population than the targeted premedical population.

At the undergraduate level, learning goals within a STEM discipline reflect the deep disciplinary understanding required of students, as well as cross-cutting goals within and beyond STEM. Clear articulation of goals has multiple benefits. Colorado University's Department of Molecular, Cellular, and Developmental Biology applied learning goals at the level of courses, reducing redundancy to maximize students' progression through the major. As part of a PKAL regional network, fourteen colleges and universities in the Portland PKAL network (PortPKAL) are collectively exploring reforming their intro-

ductory science courses using the SFFP competencies. ABET, the engineering accrediting agency, has eleven learning outcomes for all engineering students ranging from applying mathematics, science, and engineering knowledge to understanding ethical responsibility. ABET outcomes are aligned with workforce needs. And, across the STEM disciplines, learning outcomes are a first step towards asking whether or not an approach is working. A further push to align learning goals with assessment approaches comes from higher education accrediting agencies.

PROMISING PRACTICES IN STEM EDUCATION

In the interstices between goals and assessments live curriculum, program development, and implementation. While beginning with clear learning outcomes in mind is good practice, getting to the desired outcomes is a distinct challenge (NRC 2011b). A growing body of evidence for effective pedagogies comes from the emerging field of discipline-based education research (DBER), with a study on the state of the research and the field in process at the NRC. DBER researchers use both their deep disciplinary expertise and education research tools to understand how to support student learning. Detailed reviews of the state of astronomy, biology, chemistry, engineering, geoscience, and physics education research are available at http://www7.nationalacademies.org/bose/DBER_Homepage.html.

Engaged learners are at the core of practices where Froyd (2008) found strong evidence of both student learning and ease of implementation. The efficacy of approaches that actively engage students in their learning is found in study after study (see Wood 2009). Having students actively engage in their classroom learning, rather than passively processing lectures, aligns well with what we know about how people learn (NRC 1999; NRC 2007). Using learning outcomes and providing students with feedback through systematic formative assessment were also identified as promising practices, along with problem-based learning and case studies. Undergraduate research has been shown to have a number of positive effects on student participants, including increased retention of students from underrepresented groups in STEM fields. Such strategies have been at the core of over two decades of PKAL "What Works" faculty development efforts.

Collaborative learning also scored high in Froyd's analysis. While the evidence for student group work is compelling, there are important, but nuanced, areas with open questions. For example, an important area of inquiry is unpacking why students may be successful in group problem solving but still struggle with their individual efforts (Anderson et al. 2011). Reform teaching pedagogies have enhanced effectiveness in classrooms structured to support student-centered learning across STEM fields. Pioneered with the studio science approach at Rensselaer Polytechnic Institute and further developed and implemented through Beichner's (2008) Project Scale-up, today's students find themselves in high-tech classrooms, seated at large round tables with network access and monitors that allow them to collaboratively view work at the level of the group or entire class. Relatively large-scale studies confirm that structuring the learning environment in this way significantly decreased failure rates and leveled the playing field for men and women. PKAL's Learning Spaces Collaboratory relies on two decades worth of facilities planning to help institutions think creatively and productively about new STEM spaces that will enhance the student learning experience (http://www.pkallsc.org).

Most education research at the undergraduate level has been within disciplines. While much is transferable to learning in an interdisciplinary STEM context, our understanding of what works in specifically enhancing interdisciplinary learning is in the early days. Measuring integrated learning is challenging and instruments like the AAC&U Integrated and Applied Learning Rubric are available for use toward that end (see http://www.aacu.org/value/integrativelearning.cfm.).

FROM EVIDENCE TO CHANGE—DIFFUSION OF INNOVATIONS

No matter how compelling the evidence, it is insufficient to change practice. Fairweather (2008) noted that if more faculty used any of the engaged pedagogies in their teaching, student success in STEM would increase, yet the movement towards twenty-first-century STEM learning has been limited. Learning and teaching centers, including those with a STEM focus, support change at the institutional level. Centers for the Integration of Research, Teaching, and Learning (CIRTL) support graduate students. Within the disciplines, professional development for new faculty can be found in workshop formats, including the Physics New Faculty Workshop and the National Academies and HHMI Summer Institutes for biologists. The biology workshop follows the long standing PKAL model of bringing institutional teams to workshops, in this case pairing a new and a more senior colleague. Within the geoscience community, Cutting Edge provides a hybrid model of workshops and online, community-developed resources that have energized geoscience educators across the country. Disciplinary societies across the STEM fields provide a range of support for faculty to develop as teachers, including collaborative efforts among societies dating back at least to CELS (Coalition of Educators for the Life Sciences) in the 1990s. Both the National Academies and PKAL are actively working with disciplinary societies to enhance professional development for

educators. While much faculty development work occurs within disciplines, PKAL's rich interdisciplinary STEM history provides a vibrant example of positive outcomes when individuals from a range of STEM disciplines and a range of institutional types learn from each other.

There is no silver bullet for STEM education reform. Faculty development efforts show promise, but lack of serious attention to college and university rewards systems provides an ongoing barrier to STEM educational reform at all institutional types (Fairweather 2008). Research on STEM undergraduate education is growing to include a focus on change strategies. Henderson and colleagues (2010) have been leading the way, integrating findings from faculty development and higher education researchers into their work. They classify change strategies into four categories: disseminating curriculum and pedagogy, developing reflective teachers, developing policy, and developing shared vision. Broad scale, meaningful STEM education reform requires not only a solid evidence base, but also a collective will to change and the combined efforts of all stakeholders, including faculty, administrators, and disciplinary societies. ▪

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