Foundation Workshop on Transforming Undergraduate STEM Education: Brief Topical Summaries

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Engage to Excel: Producing One Million Additional College Graduates with Degrees in Science, Technology, Engineering, and Mathematics

President's Council of Advisors on Science and Technology (PCAST). Report to the President: Executive Office of the President. February 2012.

Summary prepared by Martin Storksdieck, Director, Board on Science Education, National Research Council

This report presents very specific recommendations about actions to be taken at the institutional level, by faculty and campus leaders and by stakeholders at the national level on how to improve undergraduate STEM education. The first two years of college are identified as the most critical to the retention and recruitment of STEM majors. These two years share features at all types of 2- and 4-year colleges and universities—community colleges, comprehensive universities, liberal arts colleges, research universities, and minority-serving institutions. STEM courses during the first two years of college have an enormous effect on the knowledge, skills, and attitudes of future K-12 teachers and therefore influence K-12 teaching. For these reasons, the report focuses on actions that will influence the quality of STEM education in the first two years of college.

The case for change is made by contrasting two kinds of learning experiences for students at that level.

> *Traditional introductory laboratory courses generally do not capture the creativity of STEM disciplines. They often involve repeating classical experiments to reproduce known results, rather than engaging students in experiments with the possibility of true discovery. Students may infer from such courses that STEM fields involve repeating what is known to have worked in the past rather than exploring the unknown. Engineering curricula in the first two years have long made use of design courses that engage students' creativity.*
>
> *Recently, research courses in STEM subjects have been implemented at diverse institutions, including universities with large introductory course enrollments. These courses make individual ownership of projects and discovery feasible in a classroom setting, engaging students in authentic STEM experiences and enhancing learning and, therefore, they provide models for what should be more widely implemented.*

This brief quote reflects the extensive collective of *models for what should be more widely implemented* presented in this report, with full documentation of or links to studies that demonstrate the effectiveness of research-based learning approaches. It is a compendium of strategies for transforming undergraduate STEM learning at the college level.

Retaining 35% more students than currently in STEM majors is the lowest-cost, fastest policy option to providing the STEM professionals that the nation needs for economic and societal well-being, and will not require expanding the number or size of introductory courses, which are constrained by space and resources at many colleges and universities.

The reasons students give for abandoning STEM majors point to possible retention strategies. These reasons include uninspiring introductory courses, math requirements, and unwelcoming atmosphere from faculty in STEM courses. Consequently, better teaching methods are needed to make courses more inspiring, provide more help to students facing mathematical challenges, and to create an atmosphere of a community of STEM learners. Traditional teaching methods have trained many STEM professionals, including most of the current STEM workforce. But a large and growing body of research indicates that STEM education can be substantially improved through a diversification of teaching methods. These data show that evidence-based teaching methods are more effective in reaching all students. However, transforming STEM education in U.S. colleges and universities is a daunting challenge. The key barriers involve faculty awareness and performance, reward and incentive systems, and traditions in higher education. The report recommendations aim at addressing the most significant barriers:

Recommendation 1: Catalyze widespread adoption of empirically validated teaching practices.

- Establish discipline-focused programs funded by Federal research agencies, academic institutions, disciplinary societies, and foundations to train current and future faculty in evidence-based teaching practices.
- Create the “STEM Institutional Transformation Awards” competitive grants program at NSF. 1-3 Request that the National Academies develop metrics to evaluate STEM education.

Recommendation 2: Advocate and provide support for replacing standard laboratory courses with discovery-based research courses.

- 2-1 Expand the use of scientific research and engineering design courses in the first two years of postsecondary education through an NSF program.
- 2-2 Expand opportunities for student research and design in faculty research laboratories by reducing restrictions on Federal research funds and redefining a Department of Education program.

Recommendation 3: Launch a national experiment in postsecondary mathematics education to address the mathematics-preparation gap.

- 3-1 Support a national experiment in mathematics undergraduate education at NSF, the Department of Labor, and the Department of Education.

Recommendation 4: Encourage partnerships among stakeholders to diversify path-ways to STEM careers.

- 4-1 Sponsor at the Department of Education summer STEM learning

programs for high school students.
- 4-2 Expand the scope of a Department of Labor Program and focus an NSF program to encourage pathways from 2-to 4-year institutions.
- 4-3 Establish public-private partnerships to support successful STEM programs. 4-4 Improve data provided by the Department of Education and the Bureau of Labor Statistics to STEM students, parents, and the greater community on STEM disciplines and the labor market.

Recommendation 5: Create a Presidential Council on STEM Education with leadership from the academic and business communities to provide strategic leadership for transformative and sustainable change in STEM undergraduate education.

The full report can be found at:
http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-engage-to-excel-final_2-25-12.pdf

Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering

Division of Behavioral and Social Sciences and Education (DBASSE) at the National Academy of Sciences

Preparing a capable workforce and a science-literate citizenry – one able to navigate decisions about health care, energy use, the environment, and other issues – requires effective education in science and engineering. But policy and education leaders have expressed persistent concerns that science and engineering courses are not providing U.S. undergraduates with the high-quality education they need. Moreover, college students drop out of science and engineering majors at higher rates than other majors.

Efforts to improve teaching and learning in science and engineering can be informed by discipline-based education research (DBER). DBER is a field of inquiry emerging in disciplines across academia, including several disciplines of science and engineering. Often motivated by the goal of improving instruction, DBER scholars investigate how people learn the knowledge, concepts, and practices of a particular discipline. A DBER scholar in physics, for example, might investigate how students learn such concepts as force or acceleration and try to identify effective ways for instructors to teach these concepts.

The National Science Foundation asked the National Research Council to convene a committee to consider the status, contributions, and future directions of DBER in undergraduate physics, chemistry, biology, geoscience, and astronomy, as well as in engineering. The committee's findings and recommendations are presented in its report, *Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering.*

What is Discipline-Based Education Research (DBER)?

DBER is not a single research field, but a set of related fields that have emerged in multiple disciplines over several decades. Each field of DBER is tightly coupled to its parent discipline – such as physics, astronomy, or biology – and is chiefly interested in how students learn the concepts and practices of that discipline. However, DBER scholars across all disciplines share similar research approaches and draw on similar theories about learning. And scholars in all DBER fields seek to improve teaching and learning with findings from empirical research.

The long-term goals of DBER are to:

- understand how people learn the concepts, practices, and ways of thinking of science and engineering;
- understand the nature and development of expertise in a discipline;
- help to identify and measure appropriate learning objectives and instructional approaches that advance students toward those objectives;

- contribute to the knowledge base in a way that can guide the translation of DBER findings to classroom practice; and
- identify approaches to make science and engineering education broad and inclusive.

Key Findings from DBER

The committee found that important and productive work is happening in DBER, and that DBER scholars have generated findings that hold promise for improving undergraduate science and engineering education. These findings, which have emerged from DBER in many disciplines and which complement findings from research on human learning and cognition, include:

- **Involving undergraduate students actively in the learning process enhances their learning more than traditional lectures**. Examples of effective, research-based approaches include making lectures more interactive, having students work in groups, and incorporating authentic problems and activities.
- **Students have incorrect understandings about fundamental concepts in all disciplines, particularly phenomena that are not directly observable, such as those that involve very large or very small scales of time and space.** For example, students often have difficulty understanding processes that involve deep time, such as Earth's history or natural selection. In addition, many learning challenges in chemistry result from students' difficulties in understanding that matter is made up of discrete particles. DBER in physics has identified instructional techniques that may help – for example, using "bridging analogies" that link students' correct understandings to the situation about which they harbor a misconception.
- **Students are challenged by important aspects of a given domain that can seem easy or obvious to experts.** In problem solving, for example, students tend to focus on the superficial aspects of a problem rather than its deep structure. Students in all disciplines also have trouble understanding representations like graphs, models, and simulations. These challenges pose serious impediments to learning in science and engineering, especially if instructors are not aware of them. Several strategies appear to improve problem-solving skills, such as providing support and prompts – known as "scaffolding" – as students work their way through problems.

Increasing Use of DBER Findings

Discipline-based education research has not yet prompted widespread changes in teaching practice among undergraduate faculty in science and engineering, despite its potential to do so. To improve learning outcomes for their students, current faculty in science and engineering should adopt teaching strategies that research has shown to be effective. Institutions, disciplinary departments, and professional societies interested in improving undergraduate education should support faculty efforts to do so.

In addition, these institutions and groups should work together to prepare future faculty, helping them understand the findings of research on effective teaching strategies and how students learn. Institutional leaders should include evidence-based teaching strategies in the professional development of early-career faculty, and they should include teaching effectiveness in evaluation processes and reward systems throughout faculty members' careers.

However, changing the teaching practices of large numbers of undergraduate faculty will not be easy. Simply informing faculty of evidence-based approaches does not seem to produce changes in teaching practices. Efforts to translate DBER into practice are more likely to succeed if they focus on changing faculty conceptions about teaching and learning, recognize the cultural and organizational norms of the department and institution, and work to address those norms that pose barriers to teaching practice. Faculty are unlikely to change their teaching approaches without opportunities to reflect on their own teaching practice, compare their practice to more-effective research-based approaches, and decide on their own to adopt new practices.

Future Directions for Research
Future studies in DBER fields are needed to gain a better understanding of:

- **Whether and how students' learning and response to different instructional approaches varies by key characteristics.** Those characteristics include gender, ethnicity, socioeconomic status, and whether or not they are majoring in the field.
- **Students' learning in a wide variety of undergraduate course settings.** Existing DBER provides excellent insights into students' understanding of introductory course material, but less is known about learning in upper-division courses or in laboratory and field settings.
- **Students' learning over time.** Longitudinal studies would enhance understanding of how students' knowledge transfers (or fails to transfer) from one setting to another. Such studies could also shed light on how and why incorrect beliefs persist or re-emerge over time, and why students either persist in or depart from science and engineering majors.
- **More nuanced aspects of instruction.** Research has demonstrated that student-centered learning can be more effective than traditional lecture. Now, DBER should be expanded to identify teaching techniques that can, for example, promote conceptual change in students, help them use visualizations and solve problems, and improve their metacognition (awareness of their own learning process and when to shift learning strategies).
- **Concepts and cognitive processes that cut across disciplines.** In addition to discipline-specific questions, cross-cutting concepts – such as energy or systems – and concepts that students have difficulty understanding in many disciplines (such as concepts that involve very small or large scales of measurement, or deep time) also merit research attention.

- **The translational role of DBER.** To achieve the goal of increasing the use of DBER in teaching practice, some scholarship needs to focus on organizational and faculty behavioral change.

Advancing DBER as a Research Field

DBER scholars have made notable inroads in establishing venues for publishing and in gaining recognition from their parent disciplines. Each field of DBER has one or more professional organizations that support education research through policy statements, publications, and conferences, and all of the DBER fields have at least one peer-reviewed journal for their work. Despite this progress, DBER scholars still face challenges. For example, becoming established in a new and interdisciplinary research field such as DBER is time consuming and not straightforward, and so early-career faculty members may not appear as productive to tenure committees.

As an emerging field, DBER now needs:

- **A robust infrastructure for research that includes adequate and sustained funding for research and training.** Currently, funding across the fields of DBER is uneven. Adequate support to enable the growth of DBER includes funding for the research identified above, training for future DBER scholars, support for ongoing professional development for active faculty, and funding for initiatives designed to translate DBER findings into practice.
- **Venues for peer-reviewed publication.** The number of venues for publishing empirical research has expanded as the DBER fields have matured, though the journals vary in their standards for research.
- **Continued recognition and support within professional societies**. The fields of DBER have all been recognized by professional societies in the parent discipline as valid and important fields of research; continued support is important for advancing research and attracting scholars to the specialty.
- **Additional venues where DBER scholars can share their research findings;** some professional conferences have already emerged.

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FOR MORE INFORMATION…This brief was prepared by Division of Behavioral and Social Sciences and Education (DBASSE) based on the report *Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering*. The study was sponsored by the National Science Foundation (NSF). Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not reflect those of NSF. Copies of the report are available from the National Academies Press, 500 Fifth Street, N.W., Washington, DC 20001; (800) 624-6242; http://www.nap.edu.

STEM Retention and Drawing in Underrepresented Groups

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There is much political support for increasing the number of U.S. undergraduates who complete majors in STEM fields. Proposals often seek to expand the "pipeline" of entering freshmen by improving K-12 science and mathematics education, with some concentrating upon growing minority groups that have long been underrepresented among STEM majors. Such efforts can only be for the good, since basic understanding of science, mathematics, and technology now is central to an informed citizenry who can navigate the increasingly technical challenges being faced by advanced societies, whether or not such knowledge is essential to any individual's day-to-day work.

Large percentages of entering freshmen indicate they intend to pursue STEM majors, although substantial fractions of these end up not completing such majors. This means that increasing completion/retention among entering freshmen who already are interested in, and prepared for such majors may offer a highly leveraged strategy for increasing the number and percentage who graduate with STEM majors, compared with alternative efforts to encourage more to enter into such degree programs.

Available data on persistence and completion of STEM majors are somewhat murky. It does NOT seem to be true that completion rates in STEM majors are lower than those for non-STEM majors; if anything STEM completion rates appear to be somewhat higher. U.S. completion rates appear to be lower than in other countries, but this comparison is clouded due to the liberal arts format of much undergraduate education in the U.S., which enables (even encourages) entering freshman to easily shift out to other majors during their first two years. This is a very different structure from those of undergraduate education in most other high-income countries, in which first-year students often have already specialized and then pursue more focused and narrow further studies with real limitations on changing to other fields.

Notwithstanding the ambiguities, it appears that completion rates in U.S. STEM majors could be substantially higher. Even small increases would produce considerably larger numbers of STEM graduates, some of whom would be expected to pursue graduate studies and enter the STEM workforce while others could make use in other careers of the analytical and problem-solving capabilities that are so essential in STEM disciplines. The effects upon underrepresented groups could be proportionately even larger. This suggests potentially large benefits of attending to aspects of current undergraduate STEM education that may be discouraging persistence and degree completion among entering freshmen intending to pursue STEM majors. Candidate foci for such attention include:

- Early gateway courses in mathematics and science – to what extent are they discouraging entering freshmen and in effect encouraging them to change their intended majors to non-STEM fields?
- Incentives for STEM faculty that militate against strong commitments to the highest quality of teaching and mentoring of undergraduates contemplating STEM majors.
- The very lengthy preparation required for entry into STEM careers, coupled with the uncertain and often unattractive career paths in many STEM fields.

Gateway courses: Many who have examined these issues believe that "gateway" courses for freshmen and sophomores in science and mathematics have evolved over time in ways that unintentionally lead many intending entering students to shift out of STEM majors.[1] Decisions by intending STEM majors to shift out to other fields may be increased by inadequate commitment to mentoring on the part of some faculty involved in teaching of these gateway courses, and even by alleged "weeding out" behaviors that suggest that only the most committed underclassmen should consider continuing into a full major program. There is now substantial experience and evidence based on alternative approaches, including well-designed experiments with alternative instructional modes and procedures, coupled with encouraging results from some specially-tailored programs that focus upon underrepresented minorities.

Faculty incentives that limit attention to undergraduate teaching: Pursuit of increased external funding and higher rankings over time appear to have led many universities to incentivize their faculty to focus their time and energy toward research, and hence unintentionally to de-emphasize the importance of successful undergraduate instruction and mentoring. (This is of course less true of the high-quality 4-year colleges that are another perhaps unique feature of U.S. higher education, though even in these institutions incentives favoring research have increased.) These institutional incentives combine with non-institutional incentives from STEM disciplines at national and international levels that also favor research and publication over high-quality undergraduate teaching. Meanwhile, the parallel availability of graduate students, who can be financed at low cost as teaching assistants (TA's) during these times of financial stringency in higher education, also has tended to increase dependence upon often inexperienced graduate students to staff entry-level courses.

Career paths for STEM majors: Finally, decisions by undergraduates to shift out of the STEM majors that they originally intended to pursue may be affected by the uncertain and often unattractive prospects of STEM career paths. Indeed Carnevale

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[1] Seymour, E. and Hewitt, N., 1997, Talking about leaving: Why undergraduates leave the sciences. Boulder. Westview.

et al. find that many STEM graduates pursue their careers outside of STEM occupations, which they describe as "diversion" to more attractive career paths.[2]

It also is important to distinguish between those STEM fields related to engineering and computing/IT occupations on the one hand, vis-à-vis careers in science and mathematical fields. Non-academic employers of engineers and computing/IT professionals usually hire from among those completing BS/BA degrees, rather than requiring additional graduate-level studies as in the sciences. Yet the industries involved also are prone to powerful and relatively short cycles of booms and bust, and many of those who enter employment in such industries face prospects of short and uncertain careers -- employers who are forced to downsize but later begin to hire again often prefer to recruit younger and less expensive engineers and computer professionals for which there are ample supplies of temporary visa-holders from countries with lower expectations as to wages and benefits. Indeed, enrollment by U.S. students in degree programs tend to rise and fall with these industry boom and bust cycles, but usually lagged by several years. It is also important to recognize that large fractions of employees in the IT sector have degrees in fields other than computer science and information science, and also that many graduates in computer and information science are employed in occupations other than computing and information technology.[3]

Meanwhile, in most fields of science the PhD and often a subsequent postdoc are required for initial hiring, implying post-baccalaureate study of 5-7 years for PhD and 2-5 years for a postdoc. Even after this extended period of 5-12 years, career prospects remain uncertain due to the vagaries of public and corporate funding for research and development. Perversely from the point of view of maximizing retention and completion, these career challenges may be being conveyed to prospective undergraduate STEM majors by teaching assistants who are themselves graduate student and postdocs.

The above brief discussion suggests a number of promising ways forward. Funders might consider supporting careful studies assessing the relative importance for persistence/completion in STEM majors of gateway course quality, of faculty incentives for high-quality undergraduate teaching and mentoring, and of student knowledge and/or concern about STEM career paths. Such studies could be designed to address whether the importance of these might differ for student groups that currently are underrepresented among completing STEM majors. Another valuable initiative would be to explore whether current academic STEM major programs might be incrementally modified in ways that would maintain very high scientific standards but also enable undergraduates to be more flexible in

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[2] Carnevale, A. P.. Smith, N., and Melton, M., 2011, STEM. This report contains numerous useful definitions and references regarding persistence to degree and student career choices. STEM is comprised of a full report, a state report, and an executive summary. All can be accessed at cew.georgetown.edu/STEM

[3] Salzman, H., Kuehn, D., and Lowell,B.L., 2013, "Guestworkers in the high-skill U.S. labor market: An analysis of supply, employment, and wage trends" (Washington, D.C.: Economic Policy Institute, 2013).

planning careers based upon their STEM knowledge. This might best be done by finding ways to build better connections among such degree programs with industries and employers outside of academe. The rapid expansion of Professional Science Master's degree (see www.sciencemasters.com) programs around the country suggest that improved articulation between graduate STEM curricula and non-academic employers can offer strong encouragement to students, and the same could be said for improved articulation between associates degrees and four-year baccalaureate institutions.

Guess Who's Coming to College: Shifting Demographics and What They Mean for Higher Education

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This paper focuses on exploring the current and future make-up of those who will enter higher education who will need "next generation STEM education" to support global citizenship and to enable some portion of these entrants to serve as the talent pool for STEM. As we consider the course and curricular improvements and pedagogical transformation needed to increase access to and success, especially in gateway courses, it will be important to note how these might address the needs of the student populations to be served.

"**The future ain't what it used to be**." *Yogi Berra*

Over half of children under the age of one on July 1, 2011 were minority (U.S. Census Bureau, 2012). On that basis alone we would expect that the high school graduating class of 2029 and beyond (and thus, the entering college freshman classes) would be mostly comprised of "minority" students. Many other variables, including the opportunities made available to students and the behaviors and choices of the students, would affect this prediction. These would include:

- The likelihood of members of each demographic group completing high school
- The likelihood of their completing high school "college-ready"
- The likelihood of members of each group attending college
- Other sources of enrollees that might be tapped by institutions, including "returning" students, international students and immigrants

These factors will be very much affected by the conditions they will experience and opportunity structures made available between birth and age eighteen (National Center for Education Statistics [NCES], 2012a).
Given the structure of academic programs in most colleges and universities we can assume that the audience for gateway courses would likely include most, if not all, entrants. If we wished to consider the "customer base" for majors in college STEM programs, we would also need to factor in the makeup of the "STEM eligible" pool and the likelihood of members of different racial/ethnic groups choosing to study within a STEM field (Malcom-Piqueux & Malcom, 2012, 2013; NCES, 2012b).
Another demographic aspect to be considered is the sex composition of the college going population and, in the case of STEM, the likelihood of their majoring in different fields of STEM. At present women are about 57% of those enrolled in college (National Science Foundation [NSF], 2013; NCES, 2012b). Even where they have the background to enter and succeed in STEM, women have a lower rate of doing so, driven in part by what we **don't** do to attract these women to study and careers in STEM (Ceci & Williams, 2010; Morgan, Gelbgiser, & Weeden, 2013; Wang,

Eccles, & Kenny, 2013). Any national need to increase the STEM workforce that might arise would need to include strategies for increasing immigration, and/or expanding participation of under-participating groups—women and minorities, who together comprise some 70% of the domestic talent pool. An additional source of talent would include students with disabilities, who are some 10.8% of the college going population (NCES, 2012b).

According to data from the National Center on Education Statistics (2012b), the percentage of American college students who are members of minority groups has been increasing over the decades as the population of these students has increased. "From 1976 to 2010 the percentage of Hispanic students rose from 3 to 13 percent, the percentage of Asian/Pacific Islander students rose from 2 to 6 percent, and the percentage of Black students rose from 9 to 14 percent" (NCES, 2012b, p. 279). At the same time the percentage of White students went from 83 to 61 percent (and most of these students are women). International students, a significant part of the graduate population, especially in STEM, are a very small percentage of the undergraduate population; their participation level increased from 2 to 3 percent (NCES, 2012b).

Growth in overall population does not translate "perfectly" into growing presence in higher education. Latinos are now almost 17% of the population, while 13% in higher education (U.S. Census Bureau, 2013; NCES, 2012b).

Enrollment and degree completion continue to be adversely affected by low socioeconomic status and minority group membership; these factors also affect the type of postsecondary institution attended with greater enrollments in 2-year colleges. For every racial/ethnic group except Asians, females have a higher 6-year graduation rate than their male counterparts (61 vs. 56 percent) (NCES, 2012a).

"We made too many wrong mistakes." *Yogi Berra*

1. **The educational value of diversity, capturing the advantage—**The magnitude of the global challenges we face around issues such as climate change, energy options, food security and health coupled with the coming demographic shifts have the potential to invigorate and re-define higher education. The question is whether we are prepared to address these challenges and seize the opportunities these changes will present.

2. **Cultivating rather than weeding—**Attitudes about who is "worthy" and instructional practices grounded in "separating wheat from chaff" will need to be replaced with strategies that allow students to address their full potential and become the problem-solvers of tomorrow. Classrooms would need to become "learner centered."

3. **What is to be taught and the context of instruction—**Decisions about what is taught and what is important to know are faculty decisions. Where student and faculty cultures and values diverge, tensions about relevance to students may emerge.

4. **All institutions, "minority serving"—** In the mid-1960's Historically Black colleges and Universities (HBCUs) enrolled over half of African American students in higher education. Today that figure is 13% and falling. Yet HBCUs "over-perform" especially in graduating students in fields such as engineering, physics and mathematics (Czujko, Ivie, & Stith, n.d.). These institutions, along with those whose mission is to serve Hispanic and/or American Indian, Asian American, and Pacific Islander students, are a small fraction of all institutions. As minority student populations (except Latinos) are primarily to be found **outside** of so-called Minority-Serving Institutions (MSIs), there is a clear need for the rest of higher education to learn how better to support success by these students and to become "minority-serving".

5. **The faculty does not look like the students—**The implications of these demographic shifts for higher education are stunning, beginning with concerns about the implications of the extreme mismatch between faculty demographics and student demographics (Nelson, 2008). Much more attention is needed to diversifying the faculties, enabling faculty to teach diverse student populations and being aware of potential for the cultural mismatch that might occur between a large international faculty relating to U.S. minority and women students.

6. **The price of college—**There is the possibility that some colleges and universities will price themselves out of the market. Student reluctance to take on crippling education-related debt may be greatest for those with the greatest need and the least availability of family support. In addition, as long as employment prospects and salary potential are stratified by race/ethnicity and sex, a legitimate question for any student will be relative "return on investment" (Price, 2004).

7. **College readiness, the need for remediation and the ascendency of 2-year colleges—**Unless and until the structural problems of K-12 education and readiness are addressed, enrollments will have to follow services. Those institutions unable or unwilling to address the learning gaps of high potential students will be challenged to serve diverse populations. Thus, 2-year colleges, as providers of developmental education, are emerging as *de facto* minority-serving institutions (Goldrick-Rab, 2010; Malcom, 2012).

8. **Balancing technology and needs for personal engagement—**Many of the programs and institutions most effective in engaging and supporting students from under-participating populations are those that are "high touch," with a considerable amount of faculty/staff-student interaction (National Academy of Sciences, National Academy of Engineering, & Institute of Medicine, 2011). While technology has potential to serve instruction, a balance will need to be found between "high touch" and "high tech."

If you come to a fork in the road, take it. *Yogi Berra*

References

Ceci, S. J., & Williams, W. M. (2010). Sex differences in math-intensive fields. *Current Directions in Psychological Science*, *19*(5), 275–279. doi: 10.1177/0963721410383241

Czujko, R., Ivie, R., & Stith, J. (n.d.). Untapped talent: The African-American presences in physics and the geosciences. Retrieved from http://www.aip.org/statistics/trends/highlite/minority/africanhigh.htm

Goldrick-Rab, S. (2010). Challenges and opportunities for improving community college student success. *Review of Educational Research*, *80*, 437-469.

Malcom, L. E. (2012). Student Diversity in Community Colleges. In J. S. Levin, & S. Kater (Eds.), *Understanding Community Colleges: Core Concepts in Higher Education Series.* New York: Routledge.

Malcom, L. E., & Malcom, S. M. (2011, Summer). The double bind: The next generation. *Harvard Educational Review*, *81*(2), 162-172.

Malcom-Piqueux, L. E., & Malcom, S. M. (2013). Engineering diversity: Fixing the educational system to promote equity. *The Bridge*, *43*(1), 24–34.

Morgan, S. L., Gelbgiser, D., & Weeden, K. A. (2013). Feeding the pipeline: Gender, occupational plans, and college major selection. *Social Science Research*. Advance online publication. doi: 10.1016/j.ssresearch.2013.03.008

National Academy of Sciences, National Academy of Engineering, & Institute of Medicine. (2011). *Expanding underrepresented minority participation: America's science and technology talent at the crossroads*. Washington, DC: National Academies Press.

National Center for Education Statistics. (2012a). *Higher education: Gaps in access and persistence study* (NCES 2012-046). Washington, DC: U.S. Department of Education.

National Center for Education Statistics. (2012b). *Digest of education statistics: 2011* (NCES 2012-001). Washington, DC: U.S. Department of Education.
National Science Foundation. (2013). *Women, minorities, and persons with disabilities in science and engineering: 2013* (NSF 13-304). Arlington, VA: National Center for Science and Engineering Statistics, National Science Foundation.

Nelson, D. J. (2008). *Nelson diversity surveys.* Norman, OK: Diversity in Science Association. Retrieved from http://faculty-staff.ou.edu/N/Donna.J.Nelson-1/diversity/top50.html

Price, D.V. (2004). *Borrowing inequality: Race, class, and student loans*. Boulder, CO: Lynne Rienner.

U.S. Census Bureau. (2012, May 17). Most children younger than age 1 are minorities, Census Bureau reports [News release] Retrieved from http://www.census.gov/newsroom/releases/archives/population/cb12-90.html

U.S. Census Bureau. (2013). State and county QuickFacts [Data]. *American Community Survey, Population Estimates.* Retrieved from http://quickfacts.census.gov/

Wang, M., Eccles, J. S., Kenny, S. (2013). Not lack of ability but more choice: Individual and gender differences in choice of careers in science, technology, engineering, and mathematics. *Psychological Science*, *24*(5), 770–775. doi: 10.1177/0956797612458937

Barriers to Change in Higher Education: Taking a Systems Approach to Transforming Undergraduate STEM Education

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Universities and colleges are complex organizations, and significant change typically involves a complex process. No single factor or initiative will transform undergraduate education, just as scientific research alone cannot solve such complex problems as obesity. As Fairweather (2008) has explained, "research evidence of instructional effectiveness is a necessary but not sufficient condition…." for faculty to change their teaching practices. Transforming undergraduate STEM education requires multiple facilitators or "levers" pushing for change that can counter-balance the forces that act as barriers (p. 11).

Understanding the barriers (and conversely the facilitators) for transforming STEM undergraduate education requires understanding the overall system in which undergraduate education is situated. The system involves the students engaged in learning and the faculty engaged in teaching, the disciplinary and institutional contexts in which the education occurs, and the external environments (including employers, accrediting agencies, scholarly associations, and government agencies impacting higher education). This briefing paper highlights several important factors affecting education in higher education—each with the potential to be either a lever or a barrier to transforming STEM undergraduate education (Austin, 2011).

Individual students and faculty members each bring characteristics that can affect the learning environment. Students are the central "ingredient" in undergraduate education. The characteristics that students bring to a class or learning experience (e.g., their educational and personal backgrounds, interests and aspirations, motivations and competing commitments) affect their learning—as barriers or facilitators (Ambrose et al., 2010; Pascarella & Terenzini, 2005). Of equal importance are their teachers, who have the responsibility to scaffold, encourage, and guide student learning. As they make choices about their teaching practices, faculty members are influenced by their own experiences as undergraduate and graduate students, their career stages, the cultures and priorities within their fields, the nature of their appointments (e.g., full-time or part-time, tenure-track or non-tenure-track), and their sense of motivation.

- For example, doctoral education typically has not emphasized preparation for effective teaching (although many universities are showing increased attention to this issue), and doctoral students often report that they receive "mixed messages" about the relative value of directing attention to developing their expertise as teachers (Austin & McDaniels, 2006).
- The nature of appointment can affect a faculty member's teaching practice. For example, a non-tenure-track part-time faculty member may have classes to teach at several institutions, limiting his or her time for class preparation or student meetings.

- An early career tenure-track faculty member may perceive or reason that time spent on teaching could detract from time on research and thus could hinder progress toward tenure.
- Motivation to teach well depends on one's knowledge about teaching and learning and related practices, one's sense of self-efficacy about engaging in teaching (e.g., that one's efforts will be successful), and one's perception that the reward structure matches one's efforts. Some faculty may believe that they lack knowledge and skills, that their efforts are unlikely to lead to some degree of success in terms of their students' learning, or that their efforts will not be rewarded (or will undermine their credibility as researchers) (Austin, 2011).

Disciplinary and departmental contexts matter. Over the past twenty years, some fields have invested much attention to improving undergraduate teaching and learning; others have not. Within departments, various characteristics make a difference in undergraduate education.

- The priorities of department chairpersons affect the messages faculty receive about where to allocate their time. Leaders' decisions also have an impact. For example, the timing of when institutional leaders hire teaching assistants can be a barrier (e.g., if teaching assistant assignments are made just before a course starts, little time may be available for preparation) or a facilitator of change (e.g., if the assignment is made in sufficient time for the faculty member and teaching assistant to prepare for using research-based teaching approaches).
- The characteristics of the courses that faculty are assigned to teach also affect teaching behaviors (e.g., the purpose and sequencing of a course within a department's curriculum, class size, and physical arrangements) (Fairweather, 2008; Fisher, Fairweather, & Amey, 2003; Henderson & Dancy, 2007). For example, whether a course is intended as a "gate-keeper" to determine which students continue in the field may influence the approach to teaching that course. Class size and physical arrangements (e.g., whether furniture can be moved to facilitate conversations) also can affect teachers' choices and the kinds of learning experiences students have.

The cultures of institutions shape the extent of faculty members' attention to teaching, the choice of particular teaching and learning practices, and readiness for or resistance to innovation in teaching. The relative balance between teaching, research, and service varies considerably in institutional missions across community colleges, liberal arts colleges, comprehensive institutions, and research universities, creating differing expectations for faculty members in terms of their allocation of time and effort to teaching (Gappa, Austin, & Rice, 2007). Reward systems, time availability, professional development, and leadership practices are particularly important institutional factors, serving as barriers or levers for change.

- Institutional reward systems—especially whether investing time in effective pedagogy is a positive or negative factor in evaluation for career advancement—constitute a major factor that affects faculty decisions about time spent on teaching (Braxton, Lucky, & Holland, 2002; Fairweather, 1996; 2005; Massey, Wilger, & Colbeck, 1994). Faculty must not perceive time spent on the development of new pedagogues as a negative factor in salary and advancement.

- Whether faculty work assignments provide for time spent on teaching improvement is also an institutional factor related to change. Faculty do not want to adopt teaching methods that are more time consuming than traditional methods; time to learn and implement new approaches to teaching can be a barrier (Henderson & Dancy, 2007). Thus, new strategies must be easy to use and adapt, and faculty must have time to learn to use them.
- Faculty members often are unfamiliar with the research on learning and teaching and how to implement research-based teaching practices; lack of knowledge is a barrier. Thus, growth-oriented, non-remedial, time-effective, accessible, and individually relevant professional development is important (Gappa, Austin, & Trice, 2007).
- Institutional leaders can facilitate or impede transformation of STEM undergraduate education. They communicate goals, allocate resources, impact tenure and promotion processes, initiate campus conversations, and provide symbolic support that signals key institutional priorities.

External bodies also play a role in the transformation of STEM undergraduate education. Accrediting organizations, employers, scholarly associations, and government bodies create expectations about the kinds of learning that are expected and valued. Some organizations within these groups have encouraged transformation of undergraduate education, provided supportive programs or funding for promising initiatives, and encouraged faculty members' attention to improving teaching and learning. In such cases, these organizations serve as factors that counter-balance the barriers discussed above.

Summary: Universities and colleges are complex environments in which many factors facilitate, impede, or influence change. Each of these factors can be a barrier to transforming undergraduate education—or can be handled in ways that facilitate or at least do not impede transformation. Single-lever strategies are unlikely to result in transformation in STEM undergraduate learning. Successful transformation efforts require strategic mobilization of multiple levers for change (Austin, 2011).

References

Ambrose, S., Bridges, M. W., DiPietro, M., & Lovett, M.C. (2010). *How learning works: Second research-based principles for smart teaching*. San Francisco: Jossey-Bass.

Austin, A. E. (2011). *Promoting Evidence-Based Change in Undergraduate Science Education*. Paper commissioned by the Board on Science Education of the National Academies National Research Council. Washington, D.C.: The National Academies.

Austin, A. E., & McDaniels, M. (2006). Preparing the professoriate of the future: Graduate student socialization for faculty roles. In J. C. Smart (Ed.), *Higher education: Handbook of theory and research*, Vol. XXI (pp. 397-456). Netherlands: Springer.

Braxton, J., Luckey, W., & Holland, P. (2002). *Institutionalizing a broader view of scholarship through Boyer's four domains. ASHE-ERIC Higher Education Report*, Vol. 29, No. 2. San Francisco: Jossey-Bass/John Wiley.

Fairweather, J. (1996). *Faculty work and public trust: Restoring the value of teaching and public service in American academic life*. Boston: Allyn & Bacon.

Fairweather, J. (2005). Beyond the rhetoric: Trends in the relative value of teaching and research in faculty salaries. *Journal of Higher Education, 76*, 401-422.

Fairweather, J. (2008). *Linking evidence and promising practices in science, technology, engineering, and mathematics (STEM) undergraduate education: A status report for the National Academies National Research Council Board on Science Education*. Commissioned Paper for the National Academies Workshop: Evidence on Promising Practices in Undergraduate Science, Technology, Engineering, and Mathematics (STEM) Education.

Fisher, D., Fairweather, J., & Amey, M. (2003). Systemic reform in undergraduate engineering education: The role of collective responsibility. *International Journal of Engineering Education, 19*, 768-776.

Fisher, P., Zeligman, D., & Fairweather, J. (2005). Self-assessed Student Learning Outcomes in an Engineering Service Course. *International Journal of Engineering Education, 21,* 446-456.

Gappa, J. M., Austin, A. E., & Trice, A. G. (2007). *Rethinking faculty work: Higher education's strategic imperative.* San Francisco: Jossey-Bass.

Henderson, C., & Dancy, M. H. (September, 2007). Barriers to the use of research-based instructional strategies: The influence of both individual and situational characteristics. *Physical Review Special Topics- Physics Education Research, v. 3*.

Massy, W., Wilger, A., & Colbeck, C. (1994). Department cultures and teaching quality: Overcoming "hallowed" collegiality. *Change, 26*, 11-20.

Pascarella, E., & Terenzini, P. (2005). *How college affects students; A third decade of research.* San Francisco: Jossey-Bass.

Effective Use of Technology

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Computer technology has long held out the promise of creating a learning environment for students that might allow faster and more thorough learning. From the earliest days of rote drilling systems and the PLATO system[1], the ability of computers to interact with a student and to vary the student's experience depending on how a student responds to questions or challenges has been a distinguishing characteristic. Interactivity is what separates information technology from earlier "broadcast" passive technologies for one-way delivery of information, such as printed books or television[2].

A convergence of multiple factors makes the time now ripe for a major shift in how students learn and how teachers prompt and facilitate their learning:

1. Technology is now widespread among the U.S. population, although there is uneven access to high-quality technology and broadband[3].
2. Technology for learning in its various aspects (computational power, displays, input devices, sensors, mobile touch-screens, etc.) has become remarkably inexpensive compared to expected earnings for educated workers.
3. With losses of state funding to public higher education, the cost of attendance borne by the individual student and the debt loads of students graduating have been going up at rates above inflation.
4. Pressure to improve the quality of education and simultaneously reduce costs have focused institutional attention on use of technology to support learning, particularly in large introductory courses.
5. The fraction of higher education students who have taken at least one course online has been growing rapidly. The advent of MOOCs offered by nationally recognized universities has shifted the public perception of technology-mediated learning.

These factors have brought intense interest to designing learning experiences that are more effective than traditional lecture-homework-tests modalities. Evidence is

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[1] PLATO (Programmed Logic for Automatic Teaching Operations) developed at the University of Illinois, Urbana-Champaign in the 1960's.

[2] Every improvement of access to educational materials has created a new learning opportunity for motivated self-starters. As a celebrated example, we note that Abraham Lincoln had access to books and rich life experiences, but no formal higher education. His certification by success for the Illinois Bar exam allowed him to pursue his career as a lawyer. The question is whether technology can assist and facilitate the learning process for all students, including those who are less motivated or gifted at learning.

[3] As the fraction of instruction delivered by technology increases, close attention must be paid to providing access for those with disabilities.

mounting that well-designed courseware is part of better learning at lower cost per student[4][5][6].

Strategies for effective learning with technology have pursued a number of innovations: the application of learning sciences coupled with artificial intelligence, use of data analytics and "big data" data-mining algorithms, and peer-evaluation/crowd-sourcing. These are components of an adaptive learning system, one in which computer technology presents subject content to a student, and through interactions with the student, forms a model of the student's evolving understanding of the subject. The software uses that model to predict what next presentation or interaction will be most helpful, and it guides the student along the path of active learning that is predicted to be most propitious for that student. In this way the learning process is "personalized" for the student, neither boring nor overwhelming.

A number of producers take advantage of learning science insights[7]. To illustrate, cognitive scientists observe that students are often blocked from learning a concept because they harboring a false version of the concept (e.g., an incorrect algorithm for doing long division that works only in special cases). When a wrong answer from the learner reveals a likely misconception, the software might direct the student to interactions that will surface the failings of the misconception and point to how the correct approach overcomes them. The system gives the student immediate feedback. Many systems also help improve the use of class time by letting the instructor know how the students are progressing, enabling concentration of class time on areas of need.

Intelligent tutors develop successively refined models of a student's knowledge structures, the simplest being the student's degree of mastery of various concepts. Inferences can be made about what would help the student make the next step, and these are translated into recommendations to the student.

When large numbers learn with common software and content, the responses of students to questions form a rich data set from which deductions can be made. Which paths led to rapid success and which to frustrating dead-ends? Data-mining can identify places where new or better material is needed, and it can give personalized recommendations on which ways to turn to succeed, much as Netflix and Amazon recommend products their customers.

Another big challenge for entirely automated interaction is giving sophisticated feedback to students beyond what machine grading can achieve. For example, a MOOC on literature should ask students to write essays, but computer algorithms

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[4] Interactive Learning Online at public Universities: Evidence from Randomized Trials," Bowen et al., Ithaka S+R , May 22012

[5] http://blogs.sjsu.edu/today/2013/sjsuedx-expansion/

[6] See extensive documentation of "course redesigns" at http://www.thencat.org/

[7] e.g., Open Learning Initiative at Carnegie Mellon and Knewton in New York

alone are inadequate to grade them perceptively, and one faculty member is incapable of reading them all. A scaling strategy that has been used is to have other students in the class do peer-review of the work of fellow students. If there are sufficient numbers of energetic and already capable students in a class, an individual might receive good feedback and reasonably reliable assessment. Most faculty are wary of these forms of outsourcing grading to the students themselves.

To this point the biggest leaps in effectiveness and quality appear to be in blended mode, the “flipped classroom” model in which technology is the channel for delivery of information and foundational exercises, and group time in classrooms is devoted to social learning interactions stimulated by an instructor. Both online and in the classroom, the student must be engaged in active learning, receiving immediate feedback, and being challenged in that student’s fruitful zone of learning.

What Does the "MOOC Tsunami" Mean for Reforming Undergraduate Education?

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Columnist David Brooks characterized the growth of online education at universities – enabled now by improvements in broadband internet access and new handheld and tablet devices – as a "tsunami." The tsunami is being driven by "MOOCs" – massive online open courses" – a new term less than two years old. It seems increasingly clear that internet-driven content will dramatically change universities.

Will efforts at undergraduate education reform use this new toolset, and couple it to what we are now learning about learning science? Can we realize two revolutions – an online revolution tied to a face-to-face classroom education revolution – both tied to advances in learning science?

What Online Ed *Can Do*

Online learning arguably can be a supporting pillar for an education transformation. It can provide a dynamic new set of tools for visualization, representation, reinforcement and assessment. Online features enable dynamic visualization of data and the ability to interact with that data, allowing the ability to identify new data patterns and influencing factors. It also allows new ways for mapping the content and core ideas of a field, with new possibilities for representation of both information and knowledge. It can also be a great tool for real time assessment of content acquisition, with the ability to improve reinforcement of content.

The continuous assessment capability uses feedback loops tied to repetition of areas not understood, so online can convey information and content, reinforcing both. The traditional lecture is static, not dynamic and interactive, and so allows little of this. Importantly, online education, adequately implemented with interactive features, could disrupt the traditional lecture and so force the restructuring of face-to-face learning into more seminar-like, interactive classrooms.

What Online Ed *Can't Do*

However, vital education components will remain face-to-face at least for a long time to come. The development of oral expression, presentation and advocacy skills and the organizing of expertise through expression and interchange will likely remain face-to-face. These are crucial aspects of learning. Online simply can't handle these features well; online discussion groups at this stage of the technology are not a substitute.

A second critical area of learning is written analysis. Machine evaluation of written papers is improving, and edX, for example, has a team working on this technology. However, although software can capture key words and rubrics supplied by faculty – established concepts – it will not be good at out-of-the-box new ideas, or analytic

evaluation of ideas with fresh approaches. For a very long time to come, writing will require human assessment except for the more straightforward assignments.
A third learning area is research, where online capabilities will be problematic. Performing research is central to learning-by-doing in science; it is what scientists do. While computer simulations and modeling can capture elements of how to perform research, in the end the student needs to be at a lab bench interacting with a research team on project-based learning. Online features can enhance research – data visualization and display and computer simulations, for example, can be critical tools. MIT has an "iLab" for high school science students allowing them to run real experiments online on real MIT equipment, for example. But in the end research appears to have critical face-to-face dynamics that will be hard to replace.

What Remains *Face-to-Face*
To summarize, the social features of exchanges in classroom and seminar build student involvement in learning; interactive online features still can't fully substitute for face-to-face intensity. Learning still requires human scaffolding – for discourse, for argumentation, for mentoring, for making the case, for research, for making the conceptual leap. There is also no getting around the reality that research still requires place – for face-to-face engagement by investigator teams. The internet and computing, and the cyberspace they enable, are best viewed as new allies of these teams, not substitutes. We will continue for the foreseeable future to need physical research spaces for the critical accompanying learning. The internet will change everything but won't necessarily kill everything.

Blended Learning
The advent of online education means that a least for the foreseeable future, learning will be on the "human-machine symbiosis" approach first advocated by J.C.R. Licklider in his seminal 1960 article that forecast so much of the future of computing. In this approach, machines (online education) will do what they are good at – content, information, and their assessment – and teachers will do what only they can do – mentoring, directing discussion, pushing expression of expertise, and evaluating written analysis.

This means that a new blended learning model will prevail. For now.
But the technology will change. Online technology's interactive social and evaluation features will evolve. With increasing broadband capability we can further build online discussion groups, and the videos will be increasingly be able to use high definition capability for improved realism. There will still not be the personal intensity of the classroom, with its competitive pressure, its emotional and friendship ties to classmates, its mentor relationship with the teacher.
As noted, machine writing evaluation will get better. Even now for shorter papers – where software can increasingly evaluate word use and the capture of rubrics and core concepts – it is providing the same grade as a teacher grader 85% of the time. And as noted, research can be complemented by online simulation and modeling, and can offer online access to lab equipment and the ability to run experiments online. Boundaries between online and face-to-face will continue to shift.

For now, however, online assessment offers a particularly important tool. If we do it well, it can teach us about learning in ways that could drive educational reforms in online and face-to-face education. To achieve this, we will have to systematically apply both what we now know and what we learn about learning science to improve both online and face-to-face environments. If we fail to do this, the potential online revolution will be elusive.

Summary

Because online higher education cannot adequately capture key aspects of learning – particularly oral expression, written analysis and research skills - the learning revolution (for the foreseeable future) will be blended, both online and face-to-face. Just as the interactive and more dynamic features of online education must be optimized to realize its potential, face-to-face will need to be thoroughly reorganized to be optimal – with more personal exchange, more focus on writing and oral discourse, more problem-solving, and more support for online work. Online offers an opportunity to drive overdue reforms in face-to-face learning; two learning revolutions may be at hand.

The online tsunami has started but online courses that fail to incorporate what we understand about the best instructional approaches won't work well. Online learning has an important role, which can promote an education transformation – it can be a critical tool, as discussed, for visualization, for representation, for reinforcement and for assessment. But it will need human scaffolding – for discourse, for argumentation, for mentoring, for making the case, for research and for making the conceptual leap. It's the human-online symbiosis – the right blend of students, teachers and teams with online capabilities - that will be the enabler for a new generation of science learning.