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Feature
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Insights from a Convocation: Integrating Discovery-Based Research into the Undergraduate Curriculum

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INTRODUCTION

Recommendation 2 of the February 2012 report *Engage to Excel* from the President's Council of Advisors on Science and Technology (PCAST, 2012) urges the science, technology, engineering, and mathematics (STEM) education community and funding agencies to "advocate and provide support for replacing standard laboratory courses with discovery-based research courses." The report justifies this recommendation as follows:

> Traditional introductory laboratory courses at the undergraduate level 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.… Engineering curricula in the first two years have long made use of design courses that engage student 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. (pp. iv–v)

This recommendation has engendered wide discussion and motivated formation of a committee at the National Academies of Sciences, Engineering, and Medicine to organize a convocation to explore opportunities and challenges of developing, implementing, and sustaining course-based undergraduate research experiences (CUREs), one mechanism for reaching large numbers of undergraduates. This column reviews the considerations leading up to the May 2015 convocation and summarizes the report that emerged (National Academies of Sciences, Engineering, and Medicine, 2015).[1]

Emerging evidence (cited in the PCAST report and elsewhere) indicates that engaging students in research as early as possible during their undergraduate years is one of the best strategies for supporting and retaining undergraduates in STEM. Until recently, undergraduates have primarily participated in research through apprenticeships, wherein an individual faculty member (or one of their graduate students or postdoctoral fellows) supervises the work of one or several students. Apprenticeships can be beneficial and even life and career changing for many students, yet their one-on-one design inherently limits the number of students who can participate. Providing *all* beginning STEM students with an individualized mentored

[1]The report is available for purchase or free download of a PDF at www.nap.edu/catalogue/21851.

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research experience in an apprentice-style program is not possible, given the large numbers of students. Faculty members (and other potential mentors from industry or elsewhere) have limited time, space, and resources to support undergraduates in their research activities. Most institutions have allocated only enough human and financial resources to involve a small fraction of their undergraduates in such experiences (PCAST, 2012). Students who seek out such positions are generally those who are already interested in research. Competition for a limited number of slots excludes many students, including students who have little knowledge of science career structures or who may not have performed well in traditional academic studies but who are capable of engaging in a research experience. For all of these reasons, students from populations historically underrepresented in STEM fields may especially be precluded from gaining an apprentice-style research experience (e.g., National Research Council 2007, 2011; Locks and Gregerman, 2008; National Academies of Sciences, Engineering, and Medicine, 2016). The PCAST report urges that access to a research experience during the undergraduate years should be seen as a pedagogical necessity for all students rather than a privilege for a small number of undergraduates.

Acting on this recommendation, many undergraduate STEM educators have been experimenting with different strategies for engaging more students in research experiences. There are now a number of different tested and emerging models available, and their successes suggest that this broad goal can be achieved through CUREs.[2] Traditional "cookbook" laboratories are being replaced with discovery-based research and related activities. These are occurring both in laboratories associated with lecture courses and in stand-alone laboratory courses, using on-campus, off-campus, and online resources. A CURE allows undergraduates to engage in research either collectively or individually as part of a regularly scheduled course. Recent efforts have been aided by the Web, which can provide access to large data sets in topics from genomics to environmental monitoring, remote access to research-grade instruments, access to the scientific literature, and the means to build project consortia and to link student and faculty researchers at dispersed sites.

If appropriately constructed, managed, and mentored, CURES may be able to provide students with many of the same benefits acquired from summer apprentice-style research experiences (e.g., Shaffer *et al*., 2014). But CUREs also may provide additional advantages:

– By exposing more students to research and the nature of science earlier in their academic career, they can encourage students to explore the nature of various STEM topics and careers not otherwise considered.
– Course-based approaches may be a more effective and accessible starting point for many students, including minority, low-income, and first-generation college students (Bangera and Brownell, 2014).
– Faculty members may be able to undertake research that would otherwise be difficult or impossible (e.g., Leung *et al*., 2015; Pope *et al*., 2015).
– CUREs can provide all participating students with a greater ability to use scientific thinking in other aspects of their lives.

However, large-scale undergraduate research, especially for first- or second-year students, is not yet the norm on most campuses, particularly at those institutions with more traditional views of classroom teaching and reward and incentive systems or those with little or no on-site research. To make this recommendation from PCAST a reality, faculty and administrators need to be convinced of the feasibility, efficacy, cost efficiency, student benefits, and overall value of the approach.

Because so many questions remain to be addressed regarding CUREs, the Board on Life Sciences, in collaboration with the Board on Science Education of the National Academies of Sciences, Engineering, and Medicine received support from three private foundations (see *Acknowledgments*) to develop an initiative that could further explore and elucidate the opportunities, barriers, and realities of CUREs as a potentially integral component of undergraduate STEM education. In response, a two-day national convocation was organized by a committee appointed by the National Academies and was held in Washington, DC, from May 11 to 13, 2015. Participants explored the following questions:

- What models have been developed to engage larger numbers of undergraduates in research using an academic year course-based format? Is this general strategy viable for all STEM disciplines and all class levels, from freshman to senior? Are minority-serving institutions participating, and are these models effective in reaching underrepresented students?
- Is the evidence base currently robust enough to identify best practices for implementation, considering different goals and different approaches? What are the most important challenges?
- Can these best practices serve as drivers of institutional cultural change, tackling some of the present barriers to access, and are there examples where they have done so?
- Is it possible to scale up to all students, without losing essential elements of the research experience?
- How do we promote and insure access and equity for all students in such initiatives?
- Can we recommend best practices for dissemination, for "start-up" support? What are the most cost-effective strategies?
- Can a shared research agenda help resolve some of these questions?

A common theme—equity and access issues for *all* students, with an emphasis on students from those populations that historically have been underrepresented in STEM—was emphasized throughout the convocation.

The presentations and discussions that occurred at this convocation resulted in a summary report (Figure 1). The organizing committee selected 12 existing CUREs, presented as case studies, and others were described during the panel

[2]These kinds of research experiences are given different names and acronyms depending, e.g., on whether they are offered during the academic year or during the summer. In this paper, we have adopted the term "course-based research experiences" (CUREs) for consistency. The National Academies report provides additional information about differences in terminology.

Figure 1. Cover of the convocation report.

discussions (Table 1); these provide insights into the use of this strategy in a variety of settings, highlighting opportunities and challenges encountered. The committee also commissioned a paper from Dr. David Lopatto, Grinnell College, which focuses on assessment issues and is included as an appendix in the report. An extensive set of references is integrated into the convocation report. All participants also were invited to display posters of their work on course-based research opportunities, and the posters remained available throughout the event.[3] Thus, the convocation created a rich compendium of reference materials on CUREs brought together in the report and on the website, both of which are freely available.

In this *Feature*, the authors describe activities at the National Academies aimed at understanding models and mechanisms for engaging undergraduates in research at scale and identifying the current state of knowledge and practice related to undergraduate research. We hope that the convocation report will stimulate broader conversations about the role of undergraduate research experiences for all students in undergraduate STEM education. Accordingly, the three foundations that supported the convocation also have provided financial support for follow-up dialogue through workshops at meetings of various scientific societies, including the American Society for Cell Biology and the Genetics Society of America.[4] The convocation, publication, and follow-up dialogue are all helping to inform a larger, more in-depth National Academies consensus study on undergraduate research experiences, including all mechanisms—CUREs, apprentice models, internships, and others. That study is being supported by the National Science Foundation's Division of Undergraduate Education. The committee's report should be available by Fall 2016.[5]

OVERVIEW OF CONVOCATION THEMES

Multiple themes emerged during the convocation, including those laid out by the committee (see bullet points above) and others raised by other participants. An important topic throughout the convocation was the critical characteristics of CUREs. Dr. David Asai from the Howard Hughes Medical Institute proposed that students should know that they are engaged in working on a real scientific problem, that their work matters to the community, and how their discoveries are contributing to the field. According to Asai, CUREs should permit students to encounter and confront problems that are important and timely; their work should contribute to advancing or refining knowledge, rather than simply repeating or "rediscovering" something that is already known. How to structure CURES that can help students advance to this level of discovery, particularly students who enroll in CUREs early in their undergraduate careers and may have only a single exposure to this kind of experience, engendered a great deal of discussion.

In his address as the keynote speaker at the convocation, Dr. James Gates, professor of physics at the University of Maryland, College Park, a member of the National Academy of Sciences and cochair of the committee that authored *Engage to Excel* (PCAST, 2012), provided a historical perspective of the relationship of research in science and technology to the nation's economy and well-being (chap. 2 of convocation report). During the latter half of the 19th century and most of the 20th century, average educational levels in the United States were higher than in other countries, which he argued fueled the economic engine of this country. Educational levels of people in the United States are now lower than those in most other developed countries, and median household income has fallen, especially during the past 30 yr. Given the increase in available information and changes in the nature of work, Gates argued that today's workers will need to continually relearn and retool their skills over their working lifetimes. He emphasized and provided details about how emerging approaches to education, including efforts to allow larger numbers of students to engage in discovery-based

[3]Copies of posters, PowerPoint presentations, the meeting agenda, a list of participants, and a video of Lopatto's discussion of his commissioned paper, as well as resources selected by the organizing committee and suggested by convocation participants, are available at www.dropbox.com/sh/lhxz8fokljbwe7i/AAAiwXqUmbshQurCxzCzIehga?dl=0.

[4]The list of meetings where these dialogues will occur as of the date of publication of this article and copies of presentations from sessions already completed are available at http://dels.nas.edu/global/bls/Year-of-Dialogue.

[5]Additional information about this study is available at http://sites.nationalacademies.org/DBASSE/BOSE/CurrentProjects/DBASSE_090473.

Table 1. Case studies presented in the report by name, discipline, focus, and reach (individual faculty vs. national partnerships)

Initiative (page numbers in convocation report)	Discipline(s) targeted	Local or national in scope?	Brief comments
The Science Education Alliance—Phage Hunters (SEA-PHAGES) (p. 18)	Life sciences	National collaborative	First-year students isolate bacteriophages whose genomes are then sequenced and annotated. Students routinely discover new viruses. Data are collected from multiple sites and made available to all participants. http://seaphages.org
Genome Consortium for Active Teaching (GCAT) (p. 23)	Synthetic biology	National, but with faculty focus on specific topics of interest to them	Data from individual campuses are shared across the initiative. www.bio.davidson.edu/113/113labscedule2015.html
Genomics Education Partnership (pp. 24–25)	Genomics, bioinformatics, and evolution	National collaborative	Focuses on research around *Drosophila* genomes, including sequence improvement, annotation, and analysis of regions of interest. http://gep.wustl.edu
Genome Solver (p. 25)	Microbial genomics and bioinformatics	National collaborative, but permits individual faculty to establish their own protocols under this umbrella	Focuses on analyzing data from the NIH Microbiome initiative. www.genomesolver.org
Place-Based Research (pp. 32–33)	Research on campus-based issues	Currently courses at the University of Wisconsin–Madison	Students conduct research on university issues such as energy use, food supply chains, and waste streams in collaboration with the University's Office of Sustainability. http://nelson.wisc.edu/undergraduate/sustainabilitycertificate/syllabi/env_st_126-spring_2015_syllabus.pdf
Expanding the Use of Online Remote Electron Microscopy in the Classroom to Transform Undergraduate Education (pp. 34–36)	Geosciences	Currently a partnership among four colleges and universities in Florida	Students send samples to instrumentation labs and conduct individual research projects using the data obtained. http://fcaem.fiu.edu/tues
DNA Learning Center (pp. 36–40)	DNA barcoding	Cold Spring Harbor Laboratory, New York	Students employ DNA barcoding to examine and resolve many kinds of questions, including identification of species in a habitat, food labeling. www.dnalc.org
Science Education for New Civic Engagements and Responsibilities (SENCER) (p. 39)	Disciplinary, multidisciplinary, and interdisciplinary	National, with regional hubs that focus on different research issues	Students engage in research based on regional or global issues whose boundaries often extend beyond the STEM disciplines. http://sencer.net; www.sencer.net/Resources/models.cfm
Virtual Internships (pp. 40–42)	Multidisciplinary and interdisciplinary	Individualized by instructors	Provides simulated experiences that give students the opportunity to both take and reflect on their actions to solve real-world problems, and develop ways of thinking about real-world practice. http://news.wisc.edu/uw-to-offer-new-virtual-internships-to-enhance-womens-interest-in-engineering
Vertically Integrated Projects (pp. 41–42)	Engineering, multidisciplinary and interdisciplinary	Currently 15 colleges and universities	Undergraduates have opportunities to participate in research for up to 3 years and help mentor newer members of the group. www.vip.gatech.edu
Rock Art Sustainability Index (RASI) (pp. 46–47)	Anthropology	Mesa Community College, Arizona	Students use the RASI to help determine which local Native American rock panel artworks are in greatest danger of eroding to allow for decisions about how to best use resources for preservation. In collaboration with the National Park Service. http://alliance.la.asu.edu/rockart/stabilityindex/RASI_Overview.html
Center for Authentic Science Practice in Education (CASPiE) (pp. 48–51)	Chemistry	Currently 5 centers	Offers guidance on developing, implementing, and evaluating course-based models of research for first- and second-year undergraduates in chemistry. www.purdue.edu/discoverypark/caspie
Scaffolding for Undergraduate Biology Using Yeast (p. 49)	Biological sciences	North Carolina Central University	Designed to involve students underrepresented in STEM fields with authentic research experiences as part of three introductory biology courses. www.phdavid.com/documents/McDonaldCUREnet2014.pdf
The Nature of Life (pp. 51–54)	Life sciences	University of Minnesota–Twin Cities	A required 2-yr, two-credit course for all entering biology majors that starts in the summer before the students' first year at the university. http://cbs.umn.edu/academics/departments/btl/academics/nol-series

(*Continued*)

Table 1. Continued

Initiative (page numbers in convocation report)	Discipline(s) targeted	Local or national in scope?	Brief comments
Freshman Research Initiative (pp. 52–53)	Multiple disciplines	University of Texas–Austin	Offers first-year students in the College of Natural Sciences an opportunity to conduct original research under the guidance of a research faculty member and graduate students through a three-semester sequence of courses and laboratory work. https://cns.utexas.edu/fri
Community College Undergraduate Research Initiative (pp. 56–57)	Multiple disciplines	National	Exposes community college students to real-world science through hands-on research experiences. Students take an introductory course in which they are taught basic scientific procedures while investigating a specific case study and then work together to investigate questions developed from a case study. www.ccuri.org/content/home
Discovery-Enriched Curriculum (pp. 61–63)	All disciplines	City University of Hong Kong	Institution-wide program that requires all 11,000 students who matriculate to make an original discovery or create intellectual property. www.cityu.edu.hk/provost/dec
Interdisciplinary Science Learning Labs (pp. 63–65)	All disciplines	University of Delaware	Engages undergraduates in all phases of scientific research through the development of facilities that foster the integration of teaching, learning, and research in a holistic learning environment. www.udel.edu/iselab
Center for Interdisciplinary Biological Inspiration in Education and Research (CIBER) (p. 64)	Engineering design inspired by biological structures and functions	University of California–Berkeley	Creates a community of next-generation scientists and engineers who can work together to conceive and execute innovative multidisciplinary work by engaging undergraduates to formulate and execute novel designs in engineering that are informed and inspired by biological principles and phenomena. http://ciber.berkeley.edu
First-Year Innovation and Research Experience (FIRE) (pp. 65–68)	All disciplines	University of Maryland–College Park	Modeled after the Freshman Research Initiative at the University of Texas (see description above), FIRE provides first-year students with authentic research experiences, broad mentorship, and institutional connections, but with an expansion to disciplines beyond the STEM fields. http://fire.umd.edu
Dynamic Genome Project (pp. 66–67)	Genomics and molecular biology	University of California–Riverside	Provides undergraduates with the same types of experimental activities as graduate students while they learn fundamental concepts in genomics and molecular biology in a two-course sequence that is required for biology majors. http://dynamicgenome.ucr.edu

research, can help meet the expanding need for workers trained in STEM fields. These points served as the basis for recommendation 2 in the PCAST report.

Assessment and Evaluation of CUREs

A plenary session focused on what emerging research indicates about the efficacy of CUREs on several levels.[6] Student and faculty enthusiasm for CUREs is, at present, largely based on student reports of learning gains and satisfaction with the experience (Auchincloss *et al*., 2014; Corwin *et al*., 2015; Linn *et al*., 2015). However, there are some well-documented studies showing that research experiences improve retention in the sciences (e.g., Locks and Gregerman, 2008; Estrada *et al*., 2011; Schultz *et al*., 2011; Eagan *et al*., 2013; summarized in Corwin *et al*., 2015), and several case studies presented at the convocation reported positive impacts. CURE assessments that use multiple indicators of student learning and program efficacy can provide greater insights concerning achievement of desired learning goals and affective behaviors of students and can offer guidance when starting new courses (Corwin *et al*., 2015; Linn *et al*., 2015); more research of this type is needed.

Many CUREs are designed by individual faculty to align with their own research interests, an approach that has many benefits but results in assessments that are idiosyncratic and difficult to compare (Lopatto, 2010; Linn *et al*., 2015). In contrast, a group of coordinated national efforts (Table 1) have attempted to address these issues by using common assessments, and some positive results have been reported (Jordan *et al*., 2014; Shaffer *et al*., 2014). Speakers pointed out that collaborative projects and/or cooperatives of schools with common program goals and common sets of activities can develop a common set of metrics, providing unique opportunities for assessing their efforts. Moreover, speakers noted the potential for partnerships among state systems of higher education and public and private consortia for fostering the acceptance and institutionalization of research-based courses.

[6]Given the limited amount of time to address many topics during the convocation, no topic was explored in detail. The consensus study now underway at the National Academies of Sciences, Engineering, and Medicine will address many of these issues more deeply. A primary charge to that committee is to examine the robustness of the research literature on assessment of CUREs and other types of undergraduate research experiences.

Leveraging Resources to Provide More Students with Opportunities for Research

A great deal of discussion at the convocation centered on issues of resources and costs of CUREs compared with more traditional teaching laboratories or apprentice-based models of research participation. There are surprisingly few data available on relative costs, and where available, most of the information is incomplete; for example, faculty are often not compensated for mentoring students under the apprenticeship model, so this cost is not recorded, but will be compensated for teaching a CURE. Benefits are also difficult to monetize. However, if CUREs can be demonstrated to increase retention of students, either in STEM or more broadly at the institution, the money from those students' tuition can financially justify the strategy. Several presenters noted that research-based courses were powerful recruiting and retention tools for the departments or colleges that offer them. Several presenters reported that costs for running CUREs, even if slightly more expensive than traditional labs, could be borne by students through a small increase in lab fees. However, undergraduates who participated in the convocation pointed out that even a small increase in fees can be a much larger amount if included in high-interest student loans and could make a difference in their decision to enroll in a discovery-based lab course versus a more traditional one. Some people claimed that the CUREs they designed were less expensive; techniques such as DNA barcoding and synthetic biology open up many avenues at modest cost.

Several presenters emphasized that costs for CUREs can be reduced by taking advantage of local resources and partnerships. Specialized analytical instruments can be accessed remotely, often at low cost. Further, every campus needs to collect and analyze data on the operation of their physical plant, on the use of services, and so on, and students can be engaged in the effort. For example, California State University's recent initiative, "The Campus as a Living Laboratory,"[7] and student research undertaken with the University of Wisconsin's food services to better understand food use and waste by students[8] were both described. Some of the costs recovered can be directed back into the student research program (Cathy Middlecamp, University of Wisconsin–Madison, personal observation).

Opportunities and Challenges to Scaling CUREs

The convocation provided many examples of how to restructure a given course as a CURE, but we have little experience in "scaling up" these efforts. Expanding such efforts to all sections of a course or most courses within a department may seem desirable, but the logistics and infrastructure required to do so may seem prohibitive. A great deal of discussion during the convocation thus focused on issues of scaling up of CUREs. Because appropriate mentoring is hard to provide for large numbers, it was pointed out by David Shaffer (University of Wisconsin–Madison) that virtual internships (online challenges that prompt students to take action on a complex problem, reflect on their action, and develop ways of thinking about real-world practice) can enable many more students to participate, reaching more students than would be possible through internships in which students must be at the site of the internship to participate. However, several universities (e.g., University of Minnesota–Twin Cities, University of Texas–Austin; Table 1) are expanding wet-bench CUREs by organizing multiple research "streams," among which a student can choose, using a hierarchical mentoring system. A parallel in engineering is the Vertically Integrated Projects program, described by Edward Coyle (Georgia Tech), in which senior students contribute to mentoring beginning students (Table 1).

Several convocation speakers indicated that research-based courses can help a broad range of students decide whether they would like to pursue additional research opportunities, arguing that at least one such course should be mandatory for all students. Mandatory participation ensures that students who may lack the confidence to pursue such pathways on their own are able to do so (Bangera and Brownell, 2014). However, requiring a research experience also means that some students may feel that they are being forced into something they do not want; the undergraduates present at the convocation noted that students who are working hard to maintain or increase their grade point average may be wary of a process in which the probability of failure may be high and course grades are not based on the usual criteria. Hence, for some students, an effort must be made to show them how a research experience will benefit them.

In a panel on institutional strategies, Goldie Byrd (North Carolina A&T State University) pointed out that department chairs, deans, and other administrators can support CUREs by actively promoting faculty professional development in teaching and mentoring and by supporting faculty time used to develop a CURE. The construction of new instructional spaces or the reconfiguration of existing spaces for CUREs also offers opportunities to change the culture of teaching and learning, as seen in the new Interdisciplinary Science Learning Laboratories at the University of Delaware and described by John Jungck. Efforts toward the establishment of endowments and special funds can send powerful signals to faculty, students, regents, and parents about the value of this kind of work. For those campuses undertaking or contemplating major curricular reforms, open consideration of investing in CUREs may provide opportunities to rethink the integration of research into undergraduate education and to retool the reward system for faculty, a major change strategy utilized by the City University of Hong Kong and described by Arthur Ellis.

Closing remarks stressed that the creation of new knowledge is a major function of universities. By welcoming students into this effort, we make them our partners and provide a sense of belonging in this field. As Robin Wright said in describing the freshman program at the University of Minnesota, "We're talking to them as if they are emerging professional biologists, and we treat them as colleagues." Teaching STEM by having students do research can be viewed as an active-learning strategy—and there is considerable evidence that active-learning strategies work (e.g., Freeman *et al*., 2014). The convocation closed with enthusiasm for using CUREs to expand research opportunities to all students. Jim Gentile, now at the University of Arizona, concluded that

[7]Additional information available at www.calstate.edu/cpdc/sustainability/liv-lab-grant.
[8]Additional information available at http://nelson.wisc.edu/undergraduate/sustainability-certificate/syllabi/env_st_126-spring_2015_syllabus.pdf.

"undergraduate research is quality education." Collectively, the speakers and discussions engendered enthusiasm for several elements related to CUREs, and we hope that this report will be useful for those faculty and schools thinking about or planning to expand the use of CUREs in their curriculum.

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