Integrating Discovery-Based Research into the Undergraduate Curriculum: Report of a Convocation

DETAILS

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INTEGRATING DISCOVERY-BASED RESEARCH INTO THE UNDERGRADUATE CURRICULUM

Report of a Convocation

Committee for Convocation on Integrating
Discovery-Based Research into the Undergraduate Curriculum

Division on Earth and Life Studies and
Division of Behavioral and Social Sciences and Education

The National Academies of
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Preface

Most currently working scientists remember fondly their first "summers in the lab" as a high school or undergraduate student—those first opportunities to really "be a scientist," to be part of a research group raising questions and seeking answers. Excitement, hard work, confusion, moments of insight, drudgery, were all part of the experience. Social scientists have repeatedly documented that such experiences are the most powerful means to encourage students to persist in the sciences during their undergraduate years, and to seek employment and/or graduate training in the sciences on graduation. As we become teachers we try to impart that same excitement, and as we become professionals in a lab we seek approaches to mentor the students who join us. But the opportunities to do so are highly constrained by the limited resources available in time, lab space, materials, and funds for student support.

Hence many of us found the declaration of the President's Council of Advisors on Science and Technology that we should, as national policy, "advocate and provide support for replacing standard laboratory courses with discovery-based research courses" both exciting—and challenging! Bringing research experiences into the academic year course structure will provide opportunities to reach many more students. It also immediately changes the support mechanisms available, as faculty are "on salary" during the academic year, which is frequently not the case during the summer. But at the same time, the challenge is enormous. The goal of engaging large numbers of students requires rethinking about both the laboratory curriculum <u>and</u> research designs.

Quite a few science faculty members have been experimenting with such an approach, more so during the last decade, creating "CUREs" or "CREs" (Course-based Undergraduate Research Experiences) across the scientific disciplines. Thus tested models are available, and there is a growing literature on the efficacy of this approach, both for students and for faculty. However, there have been no formal convocations to explicitly examine the potential opportunities and challenges to involving more students in research by modifying courses in this fashion. A conversation with Jo Handelsman, then Chair of the Board on Life Sciences (BLS) at the National Academy of Sciences, generated enthusiasm for holding a convocation on this topic, with the explicit goal of producing a report that would be useful to faculty and college/university administrators who were thinking of initiating or expanding efforts of this type. The goals of the convocation would be to (1) try to identify and showcase a variety of models, for which there are assessment data, for creating and expanding undergraduate course-based research opportunities, particularly those that can reach large numbers of students; (2) provide an overview of the most pertinent scholarly literature regarding the efficacy of such efforts; (3) consider some of the major barriers, and address how these might be overcome, looking in particular at the needs of underrepresented students; and (4) discuss what features of the research experience are important for maximum impact, and the mechanisms to support these features in a course-based structure with large numbers of students. We were fortunate to gain support from the Leona M. and Harry B. Helmsley Charitable Trust, the Howard Hughes Medical Institute, and the Alfred P. Sloan Foundation to make this Convocation a reality. The convocation was held at the National Academy of Sciences in May 2015.

The following narrative is a report of that meeting, an attempt to capture the acquired experiences (both positive and negative) of practitioners of this relatively new educational strategy, insights from those assessing these efforts, and thoughts of administrators (from colleges and universities, from scientific societies, and from funding agencies) who have observed our early attempts. The members of the organizing committee were able to identify and showcase exemplary examples from across the scientific and engineering disciplines. These examples were presented in break-out sessions, and are described briefly in the boxes that occur throughout the text. The examples illustrate courses based on a research project designed for students from freshmen to seniors, in all types of two- and four-year institutions. Several are designed to remove the barriers created by hesitation on the part of the students, or selectivity on the part of faculty members. These strategies can benefit underrepresented student groups, including minority, economically disadvantaged, and first-generation college students, who often do not know how to seek out such opportunities—or why they should. Some students, particularly those who have been historically underrepresented in STEM, may never have had an opportunity to see how research can be directly connected to addressing real world problems, and thus may view research-based experiences as irrelevant to their goals and aspirations. A research course centered on a community need or ecological concern can be attractive to these students. Equally important, the CRE approach, which allows a student to embark on the adventure in a class with friends and peers, can look and feel much more comfortable to students than entering a research lab dominated by grad students and/or postdocs. Thus the use of CREs has great potential for helping to bring more underrepresented students into the profession.

We also learned how a well-designed CRE-based research program utilizes many recognized mediators of student learning, for example by allowing students to pursue projects of personal interest, and/or by providing instructional support (setting up the dimensions of the project) while requiring them to make critical decisions as they analyze data. Several examples illustrated how creating a "parallel problem" is a good strategy: devise a situation in which students can be taught a common set of tools for data generation / data analysis, but each student (or sub-group) has a distinct problem to solve—a different virus, a different part of the genome, etc. Projects that address local issues, including environmental problems, are often engaging. Students who participated in the convocation remarked that a classroom structure that emphasizes collaboration, one that clearly places the faculty member in the role of mentor, contributed to their learning. It was pointed out that large classes can actually be an advantage because more data can be gathered. For example, each experiment can be repeated independently several times to establish a large data set, determine whether the phenomena observed originally are replicable, and address issues of variability in the data using statistical methods.

While scaling up provides a number of challenges, convocation participants learned about a variety of creative solutions. To overcome lab limitations, faculty and students are using the campus itself (or a local field station) as the laboratory; they are accessing sophisticated instruments remotely; and they are making use of increasing numbers of sophisticated data bases that are publicly available through the internet. To overcome limitations in personnel, faculty are building hierarchical mentoring systems reminiscent of the Peer-Led Teaching and Learning strategy,[1] and are experimenting with virtual internships. To help more faculty adapt their research interests to the CRE format, lab module templates are being established, and new types of teaching labs designed and built or created by restructuring old labs. Indeed, some institutions already have embraced the notion that all undergraduates, in all disciplines, should be involved in some aspect of discovery, i.e. should learn how new knowledge is created in their field. This is, after all, the arena in which the college/university outshines the MOOC (Massive Open Online Course). As stated by Jim Gentile, one of the moderators at the convocation, "Undergraduate research is quality education." Despite some current barriers (which are discussed throughout this report), the CRE might be one way forward to help democratize quality education in the many different institutions for *all* undergraduates.

However, many questions and challenges remain. It was pointed out that many of the published assessments of CREs rely solely on self-reported student responses. While self-reporting is an appropriate way to determine whether faculty have successfully imparted their own enthusiasm for science, one would also like to know more about the student's development of process skills, and the long-term impacts of such efforts in improving learning, self-efficacy, and transferable knowledge and skills. The use of consortia across many campuses can facilitate research on the impact of this intervention. Developing good CREs requires substantial effort, and both administrators and faculty would like to have better documentation of the costs and benefits (monetary and otherwise). A range of assessment instruments was discussed and some presenters and participants in the ensuing discussion made clear that additional work is needed to better understand and reach agreement within the community about ways to assess CREs, adjusting for program goals and objectives. An evaluation of costs and benefits will need to take into account the impact on graduation rates, job satisfaction and income resulting from graduation with a science degree. A consensus study currently being undertaken by the National Academies of Sciences, Engineering, and Medicine is examining a range of models for providing undergraduate students with discovery-based research experiences, including CREs. That study will be able to investigate in greater depth some of the issues raised at the Convocation, and the discussions from this convocation may help inform that study (See also Box 1-4.)

I think all participants left the Convocation impressed by what has been accomplished to date in using CREs to improve science education. No doubt the effort has been facilitated by the on-going efforts to bring active learning strategies into the college/university science curriculum. Engaging students in discovery-based research is the ultimate active learning strategy—teaching science by having students do science.

I would like to thank the Organizing Committee; the NAS staff who worked with us to obtain funding, put together the program, and captured the results; and the speakers and participants at the convocation for a lively meeting. I also thank Steve Olson, the writer who worked with the committee to weave all of the discussion from verbatim transcripts into the narrative that is

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[1] Additional information is available at https://sites.google.com/site/quickpltl/.

provided here. We hope that this resulting report will be of help to those interested in considering the introduction or expansion of CREs in their curriculum.

Sarah C. R. Elgin
Committee Chair

Acknowledgments

This workshop report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Academies of Sciences, Engineering, and Medicine Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published workshop report as sound as possible and to ensure that the workshop report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the process. We wish to thank the following individuals for their review of this workshop report:

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Although the reviewers listed above have provided many constructive comments and suggestions, they did not see the final draft of the workshop report before its release. The review of this workshop report was overseen by **William B. Wood** (Member, NAS; Professor Emeritus, University of Colorado, Boulder). Appointed by the National Academies of Sciences, Engineering and Medicine, he was responsible for making certain that an independent examination of this workshop report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this workshop report rests entirely with the authors and the institution.

The committee thanks all of the presenters, discussants, and facilitators who helped make this convocation a success. We also thank all of the other people who attended the convocation for their rich contributions to the sessions and the conversations which ensued throughout the event.

The meetings staff at the National Academy of Sciences Building, where the convocation was held, were especially helpful in accommodating our many requests for various room configurations and for making last-minute changes to those configurations. We appreciate their flexibility and professionalism.

We also sincerely thank the program officers with whom we worked throughout this project: Ryan Kelsey and Sue Cui from the Leona M. and Harry B. Helmsley Charitable Trust, David Asai and Cynthia Bauerle from the Howard Hughes Medical Institute, and Elizabeth Boylan from the Alfred P. Sloan Foundation. Their encouragement and support are deeply appreciated.

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1
Introduction and Overview of the Convocation

Background

Students who participate in scientific research as undergraduates report gaining many benefits from the experience. They rate their time doing research highly and are more likely to continue studying science, technology, engineering, and mathematics (STEM) (Eagen et al., 2013). They say that participating in research broadened their academic and professional networks, taught them how to think like a scientist, and boosted their enthusiasm for research (Laursen et al., 2010; Lopatto, 2010). Especially for women and for minorities underrepresented in STEM fields, involvement in research can make the difference between students with declared interests in STEM remaining in these disciplines versus pursuing alternative education and career goals (Committee on Science, Engineering, and Public Policy, 2011).

However, undergraduate research done independently under a faculty member's guidance or as part of an internship (the "apprenticeship" model), regardless of its individual benefits, is inherently limited in its overall impact. Faculty members and sponsoring companies have limited time and funding to support undergraduate researchers. Most institutions have available (or have allocated) only enough human and financial resources to involve a small fraction of their undergraduates in such experiences (e.g., PCAST, 2012). Students who seek out such positions are generally those already interested in research, who have high grade point averages, or who may have interacted previously with a faculty member. Thus, competition for a limited number of slots excludes many students, including students with less than stellar academic transcripts and those unfamiliar with the recruiting process, who nonetheless may be highly qualified. All of these factors constrain participation, particularly by members of groups historically underrepresented in STEM fields, many of whom could benefit considerably from being involved in research (e.g., National Research Council 2007, 2011, Locks and Gregerman, 2008; see also description of SEA-PHAGES in Box 3-1).

In recent years, an alternative approach has gained increasing attention (Corwin et al., 2014, 2015). Many more students can be involved as undergraduate researchers if they do scientific research either collectively or individually as part of a regularly scheduled course. Course-based research experiences have been shown to provide students with many of the same benefits acquired from a mentored summer research experience, assuming that sufficient class time is invested (Shaffer et al., 2014). But research-based courses have several additional potential advantages. By exposing more students to research, they can encourage some students to pursue careers that they otherwise might not have considered. Course-based approaches can involve many more students from groups underrepresented in research, including minority, low-income, and first-generation college students (Bangera and Brownell, 2014). This strategy also potentially

Box 1-1
Recommendation #2 from the President's Council of Advisors on Science and Technology

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

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 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.

PCAST, 2012, pp. iv-v

can generate major benefits for faculty. It can provide faculty members with ways and means to do research that would otherwise be difficult or impossible to undertake (e.g., Pope et al., 2015, Leung et al., 2015). It has the potential to be an accessible strategy for community colleges or 4-year institutions with limited lab space and resources. It can inculcate in participating students, regardless of whether they ultimately choose STEM tracks or careers, a greater ability to use scientific ways of thinking in their professional and personal lives. Even more broadly, it has the potential to transform undergraduate education by using experiential learning to motivate students to invest in learning deeply and meaningfully.

As described throughout this report, course-based approaches to providing undergraduates with research experiences have gained increasing use in the past decade, particularly following the release of the report on improving undergraduate STEM education from the President's Council of Advisors on Science and Technology (PCAST, 2012). The present effort explored one aspect of Recommendation #2 in the PCAST report (Box 1-1) as well as numerous efforts to improve STEM instruction at the college level through the utilization of active learning strategies (e.g., Handelsman et al, 2005; American Association for the Advancement of Science 2011, 2015; Freeman et al., 2014, National Research Council, 2015). The PCAST report calls for converting regularly scheduled lab courses to a research focus, but does not develop that idea in detail. By bringing together a number of current examples, this convocation attempted to extend the discussion of this general strategy.

While such efforts have been undertaken at many colleges and universities across the nation, the majority of undergraduate STEM students are still enrolled in more traditional courses with standard laboratories. The slow pace of acceptance and implantation of the research format could be due to a lack of familiarity with the approach, or the result of skepticism on the part of some faculty and administrators as to the effectiveness of this strategy compared with more traditional course offerings. Some may incorrectly view this shift as emphasizing process skills at

Box 1-2
Statement of Task

An *ad hoc* committee will organize a convocation that will examine the research evidence on the efficacy of engaging large numbers of undergraduate students who are enrolled in traditional academic year courses in the life and related sciences in original research, civic engagement around scientific issues, and/or intensive study of research methods and scientific publications at both two- and four-year colleges and universities. The convocation also will explore issues such as the benefits and costs of offering students such experiences and the ways that such efforts may both influence and be influenced by issues such as institutional governance, available resources, and professional expectations of faculty.

The committee will develop the agenda for the convocation, select and invite speakers and discussants, and moderate the discussions. One committee-authored workshop report will be prepared in accordance with institutional guidelines. As part of this project, if resources allow, committee members and staff will also offer briefings, presentations, and workshops at professional society meetings and related venues in the year after the final report is published.

the expense of the acquisition of content knowledge. This is a false dichotomy; students involved with research must master specific bodies of knowledge or content to successfully undertake that work. And research in human learning emphasizes that expertise in any domain is built on a combination of content knowledge along with the ability to use and connect that knowledge in ways that novices in that domain cannot (e.g., National Research Council, 2000).

Will the benefits justify the investment in personnel, equipment, and physical infrastructure required to maintain such efforts? How should faculty efforts in this teaching format be recognized and rewarded compared with more traditional approaches? What other administrative changes (e.g., in course scheduling) would be needed?

To explore the potential benefits and challenges of more widely adopting course-based research for all undergraduates, the Board on Life Sciences (BLS) and the Board on Science Education (BOSE) of the National Academies of Sciences, Engineering, and Medicine held a convocation in Washington, DC, on May 11-13, 2015, entitled “Integrating Discovery-Based Research into the Undergraduate Curriculum.” Box 1-2 provides the approved Statement of Task that guided the committee in organizing the convocation.

Organization of the Convocation

When this project was originally conceived, the plan was to focus on the life sciences, since members of this discipline have been very active in developing course-based research experiences. However, in discussions with the sponsors and others, the committee and staff were convinced that the purview of the convocation should be expanded to include representatives and exemplars from other STEM disciplines as well as including representation from the diverse types of institutions that constitute higher education in the United States. Thus, the final composition of the organizing committee and the exemplars selected represent this broadened purview and includes an international exemplar, in this case from the City University of Hong Kong.

Accordingly, the convocation brought together a diverse group of presenters and discussants, including faculty and administrators from institutions of higher education, funders of curriculum innovation (both private foundations and public agencies), undergraduate students from local 2- and 4-year colleges and universities, leaders of disciplinary societies, leaders of pertinent departments and agencies of the federal government, and others with additional expertise in various models of undergraduate research experiences. The group was asked to examine the evidence for potential benefits from broad utilization of course-based research, the drawbacks and challenges associated with this approach, barriers to its adoption, and ways of overcoming these barriers as warranted. Box 1-3 lists some of the questions that were given to all participants at the convocation. Since many of these issues are cross-cutting, discussion of all of them occurred throughout the convocation and thus appears in various parts of this report.

Appendix A provides the agenda for the convocation. Appendix B contains a paper commissioned by the organizing committee from David Lopatto, professor of psychology at Grinnell College. This paper offered convocation participants an overview of the evidence base supporting discovery-based approaches to undergraduate education and a perspective on ways that such approaches might be sustained and expanded based on the kinds of metrics employed to assess their effectiveness and efficacy.[2] Appendix C lists the attendees at the convocation, and Appendix D gives brief biographical sketches of the organizing committee members and convocation speakers.

Convocation speakers and participants were invited to display posters describing their work related to course-based undergraduate research experiences, and 18 participants exhibited a total of 21 posters.[3] In addition to Lopatto's commissioned paper, the organizing committee identified a number of seminal research papers and other resources related to undergraduate research experiences. Electronic versions of the posters, presenters' PowerPoint files, the aforementioned additional research papers, and links to additional resources all were made available to convocation participants through the web.[4]

The convocation was generously supported by grants from the Leona M. and Harry B. Helmsley Charitable Trust, the Howard Hughes Medical Institute (HHMI), and the Alfred P. Sloan Foundation, each of which had representatives at the meeting. In their brief welcoming remarks, Elizabeth Boylan from the Sloan Foundation emphasized the need for "feasibility, efficacy, and value" in course-based research, while Ryan Kelsey from the Helmsley Charitable Trust stressed the need to produce a report that "will be something that people can do something with." And HHMI's David Asai identified three criteria that course-based research should satisfy:

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[2] David Lopatto was unable to attend the convocation in person but made a video for one of the plenary sessions to provide an overview of the content of his commissioned paper. This video is available for viewing through a hyperlink at https://www.dropbox.com/s/jm4ogrdw5auy95c/LINK%20TO%20VIDEO%20BY%20DAVID%20LOPATTO%20DISCUSSING%20HIS%20COMMISSIONED%20PAPER.pdf?dl=0.

[3] Posters are available for viewing at https://www.dropbox.com/sh/kvk84w1psqhbok3/AACIr5U5HYZ2igdOXCE0KKcca?dl=0.

[4] Available at https://www.dropbox.com/sh/lhxz8fokljbwe7i/AAAiwXqUmbshQurCxzCzIehga?dl=0/.

1. Students should know that they are engaged in a real scientific problem.
2. Students should know that the work they are doing matters to the scientific community
3. Students should know how their discoveries are contributing to the field

Thus, according to Asai, students should be working on a problem that experts in the field consider to be important and timely, and their work should contribute to advancing or refining knowledge, rather than simply repeating or "rediscovering" something that is already known.

Because the movement toward broader inclusion of undergraduates in research experiences is still in its early stages of development and scale-up, various terms have been used to describe the movement's goal, including participation in "authentic" or "discovery-based" research. This convocation was not designed to reach consensus on terminology, as emphasized during the opening remarks by Sarah (Sally) Elgin, Viktor Hamburger Professor of Arts and Sciences at Washington University in St. Louis and chair of the organizing committee.

However, several participants observed that the type of experience being discussed implies involving students in as many phases of a research process as time permits, including the development of questions to be addressed (for which answers are currently unknown), designing a protocol to address those questions, collecting and analyzing data, reaching conclusions based on those data and defending those conclusions, participating where possible as co-authors of a peer-reviewed publication, and/or presenting their work at student symposia or professional meetings. This kind of research experience differs from more traditional teaching laboratories where the outcomes are already known or predetermined, often referred to as "cookbook" labs. It also differs from what have come to be known as "inquiry" labs, where students have freedom to design and conduct their own investigations but the results are already known, or not of particular interest to the scientific community. While course-based research often takes place within a framework established by a faculty member, who lays out the overall research goals, it also differs from technical work where students are assigned specific tasks (e.g., maintaining research colonies, collecting data points) with no responsibility for data analysis and little, if any, knowledge of the scientific questions guiding the research. Additional discussion of these issues is provided in Chapter 3.

In this report, "research-based courses" or "course-based research" are used interchangeably to describe efforts to introduce research experiences within individual courses during part or all of an entire term or semester. These labels also refer to research programs that extend beyond the timeframe of an individual course or that might involve students in undertaking service- or community-based work on or off campus. In all cases, "research-based" implies that such programs incorporate the attributes of discovery described above. (See also Figure 3 in Linn et al, 2015 for the differences between course-based experiences and apprentice-style undergraduate research experiences more generally.)

Organization of the Convocation Report

This report of the convocation covers both the formal presentations of speakers (reviewed in Chapters 2 through 6) and the rich discussions that occurred during question and answer sessions,

Box 1-3
Questions Examined During the Convocation

(While these questions were considered throughout the Convocation, the note in italics following each question indicates where in the report this issue is considered in greatest depth)

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 students underrepresented in STEM fields? *These questions are addressed through a series of case studies, presented throughout the report.*

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? *See Chapter 3.*

Can best practices be recommended for dissemination? For start-up support? What are the most cost-effective strategies? *See Chapters 4 and 6 on leveraging resources.*

Is it possible to scale up to all students without losing essential elements of the research experience? *See Chapter 5.*

How can access and equity for all students be promoted and ensured in such initiatives? *See Chapters 5 and 6.*

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? *See Chapter 6.*

Can a shared research agenda help resolve some of these questions? *Considered throughout the report.*

in the reports of representatives from the breakout groups that took place during the convocation, and in several open-ended discussion sessions (summarized in Chapter 7). Issues that arose during discussion sessions that relate directly to the presentations are incorporated into the summaries of the speakers' remarks in Chapters 2-6.

Chapter 2 (Historical Context for Course-Base Research: The Need for Improved Science Education) summarizes the keynote presentation by University of Maryland professor James Gates, who placed research-based courses into a broader historical context and introduced the case for expanding the use of this approach in STEM curricula.

Chapter 3 (Promising Practices and Ongoing Challenges) examines promising practices and ongoing challenges in establishing and running research-based courses, providing an introduction to the major issues associated with the approach.

Chapter 4 (Leveraging Available Resources to Create Greater Access to Research Opportunities) presents several case studies that demonstrate how one can leverage available resources for research-based courses to engage larger numbers of students without incurring large additional costs.

Chapter 5 (Rewards and Challenges of Scaling Up) builds on this idea of cost effectiveness by examining some of the broader issues involved in scaling up course-based research to include most or all of the students in a department, college, or institution.

Chapter 6 (Institutional Strategies and Funding Structures) considers the institutional support that is necessary for research-based courses to succeed, including changes in the broader culture of institutions, including perceptions of students, faculty members, and administrators.

Finally, Chapter 7 (Observations from Convocation Participants) summarizes the broad points made during the discussion sessions of the convocation. This chapter is organized thematically, so it serves as a review of the major issues discussed during the convocation and as a guide for future discussions. This chapter also includes the reflections of four undergraduate students who were invited to attend the convocation and to provide their perspectives on the proceedings, as well as on their own experiences with research-based courses.

Major Concepts Explored During the Convocation

In a meeting and in continued discussions after the convocation, the committee that oversaw the organization of the convocation and the writing of this report identified major concepts and issues that emerged during the workshop. These major concepts and issues are listed here to provide an overview of the broad range of topics considered during the convocation by those present.

The workshop report has been prepared by the planning committee as a factual summary of what occurred at the workshop. Statements, recommendations, and opinions expressed are those of individual presenters and participants, and are not necessarily endorsed or verified by the National Academy of Sciences, Engineering, and Medicine; they should not be construed as reflecting any group consensus. Thus, these concepts and issues are attributable solely to those speakers and participants who raised them and their statements, especially about individual programs or initiatives, should not be seen as conclusions of the convocation as a whole nor as consensus statements of the convocation participants or the committee. A companion consensus study that is currently underway, supported by the National Science Foundation, will explore some of the issues discussed during this convocation in greater depth and will issue a report with findings, conclusions, and recommendations (see Box 1-4 for more information).

In the interim, this convocation report provides an overview of individual perspectives of relevant topics that could be valuable for those who are considering initiating or expanding course-based research experiences for undergraduate students at their school. Notes in italics indicated specific sections of the report that focus on a given issue.

- Course-based research can provide many benefits both for the students and for the faculty members who are engaged in these programs.
- Many faculty members who could use course-based research to improve student learning and advance their own research are not familiar with this approach or are not aware of the wealth of local and national models that already exist.
- Current models demonstrate that the approach is applicable across the STEM disciplines and is effective with a broad range of students, from first-year students to seniors, as well as engaging students from populations currently underrepresented in STEM fields. (*See case studies*)

Box 1-4
Consensus Report

Even as the convocation was being held, another major activity was getting under way at the National Academies of Sciences, Engineering, and Medicine under the aegis of the Board on Science Education (BOSE) with support from both BOSE and Board on Life Sciences staff. Supported by the National Science Foundation, a separate committee was beginning a more detailed study of undergraduate research experiences, including a deeper examination of the literature on undergraduate research, and its influence on learning.[5] Unlike this report of the convocation, which focuses on course-based research approaches, that committee's report will contain consensus findings and recommendations for future actions on a broad array of undergraduate research experiences.

The two projects are closely coordinated. The chair of the convocation's organizing committee is a member of the consensus report committee. Four additional members of the consensus report committee, including the chair of that committee, participated in and served as presenters or facilitators during the convocation. As part of the convocation project, a year of outreach and discussion at disciplinary and professional society meetings will follow after the release of this report. These discussions also may help inform the work of the consensus committee.

- Well-designed course-based research projects encompass many of the "best practices" identified by pedagogical research, providing instructional support and a collaborative atmosphere but requiring students to make decisions, thereby building project ownership. Providing a schedule that allows for failure and reiteration is a critical aspect. (*See Chapter 3 and case studies*)
- How research is conducted within the context of undergraduate courses, and common measures and methods that should be used to assess the outcomes of course-based research, have not yet been well defined. Indeed, depending on the goals of the course, assessments of learning and efficacy will likely differ in different settings (*See Chapter 3*)
- A database of best practices, model programs, vetted assessment tools, and pedagogical research findings could help resolve questions concerning scaling-up of existing programs and implementing this approach in new locations. (*See Chapters 3-5*)
- Different kinds of institutions have different strengths that can be used to develop and implement course-based research; collaboration across institutions can build on these diverse strengths. (*See Chapter 4*)
- Continued investigation of the cost-effectiveness of course-based research could help make the case for the advantages of this approach. (See *Chapters 4-5*)
- Scaling up course-based research generates a number of challenges, including identifying research topics that can be undertaken in a course setting, shifting course design and implementation to accommodate new directions as dictated by experimental outcomes, and moving students from working primarily at the levels of observation and discovery

[5] A more detailed description of this project and committee membership are available at http://sites.nationalacademies.org/DBASSE/BOSE/CurrentProjects/DBASSE_090473.

based on hypotheses formulated by others to generation and testing of their own hypotheses. (*See Chapter 5*)

- Students have constraints on their time, schedules, and resources, and they may be wary of course-based research if the value of this (often new) experience is not clearly communicated to them. To reach those students who might benefit most (e.g., historically underrepresented, older, first generation students and those who may be well qualified to undertake and benefit greatly from a research experience but who may not have the academic credentials to be accepted into a research program in the labs of individual faculty members), it may be necessary to make research experiences part of the required courses for the major. (*See Chapters 5 and 7*)
- The culture of higher education, including the expectations and reward system for faculty members, can have a major impact on the adoption of course-based research. (*See Chapter 6*)
- Successful course-based research at many institutions has been characterized by strong administrative support, which has created stability and sustainability for these programs. (*See Chapter 6*)

The committee hopes that this report of the convocation will help faculties and administrators around the world consider whether research-based courses could improve STEM education on their campuses and how, by building on the lessons already learned, this approach can help achieve the best possible outcomes for students, faculty members and institutions.

2
Historical Context for Course-Based Research: The Need for Improved Science Education

Important Points Made by the Speaker (Gates)

- During the latter half of the 19th century and most of the 20th century, educational levels in the United States were higher than in other countries, which fueled U.S. prosperity.
- U.S. educational levels have now fallen behind those in most other developed countries, and median household income has fallen.
- Workers will need different sets of skills in the future from those that were required in the past, including the ability to interact with educational institutions to continue learning throughout a career.
- New forms of learning, such as discovery-based research courses, can help meet the expanding need for workers trained in STEM fields.

In his opening keynote presentation, James Gates, John S. Toll Professor of Physics at the University of Maryland, College Park, a member of the National Academy of Sciences and a member of the President's Council of Advisors on Science and Technology (PCAST),[6] placed course-based research into a much broader educational and economic context.

Since World War II, economists have concluded that STEM-related activities are responsible for much of the growth in the U.S. economy. But the link between economic growth and new knowledge in the United States began well before World War II. As Goldin and Katz (2008) observed in their book *The Race Between Education and Technology*, the common school movement in the 19th century, which called for free public schooling of all U.S. children, helped create the best educated workforce in the world by the 1850s. And in 1862, the U.S. Congress passed the Morrill Act, which used federally owned land to support higher education. These investments in people "paid off enormously," said Gates. In 1830 the size of the U.S. economy was less than half that of the United Kingdom's economy, but it surpassed the British economy in the 1880s and was nearly 50 percent larger by 1900.

According to Gates, the high school movement in the early part of the 20th century, which increased the enrollment of 15- to 18-year-olds from 19 percent in 1910 to 73 percent in 1940,

[6] For additional information about PCAST see https://www.whitehouse.gov/administration/eop/ostp/pcast.

further increased the United States' educational advantage compared with all other countries. The G.I. Bill of 1944, which opened up college to many more Americans, and the National Defense Education Act of 1958, which boosted STEM education in response to the space race of the time, greatly augmented direct governmental investments in education. By the year 2000, the U.S. economy was six times the size of the U.K. economy, and U.S. workers shared broadly in this greater prosperity.

The Decoupling of Economic Growth and Income

However, since 1999, growth in the U.S. economy has become decoupled from gains in middle class income, Gates noted. Per capita gross domestic product has continued to climb while median household income has fallen.

Many of the forces behind this decoupling of economic growth and incomes are visible in the recovery from the recession that began in 2008. For example, in North Carolina, textile factories had been closing for many years before the recession hit. Since then, they have been reopening, but they are very different places. Today's textile factories are dominated by robots and computers. Traditional jobs in textile factories have been replaced by jobs that involve controlling electronic devices. "Forty years ago you could graduate from high school, go to work in a factory—if you were a man—have a job for 30 years, raise a family, buy a house, put your children through college, and even have money for retirement and some vacations," said Gates. "You can't do that with a high school degree anymore."

Almost no economic sector is immune from these trends, Gates observed. As an example, he cited ongoing work on not only self-driving cars but self-driving trucks, which could put millions of truck drivers out of work when such trucks are perfected in the future.

The United States has not excelled in creating or filling high-paying, technology-intensive jobs, said Gates. The United States today has the largest fraction of low-paying jobs of any developed country, which "makes it hard to sustain a middle class." According to labor market projections, the three fastest growing job areas in the near future will be in health care, community services and arts, and STEM fields (Carnevale et al., 2013). But will the United States be prepared to fill those STEM positions, Gates asked?

The percentage of adults ages 16 to 34 performing below minimum standards of proficiency on the Organization for Economic Cooperation and Development's (OECD) Program for the International Assessment of Adult Competencies Test of Literacy, Numeracy, and Problem Solving puts the United States at the bottom (Table 2-1). For example, since 2003, the numeracy scores of U.S. millennials (the group of people born after 1980 through the mid-2000s) have declined from 264 to 247, for those whose highest level of education is "high school," and from 296 to 285, for those reporting "above high school," on a 500-point scale. The percentages of U.S. millennials scoring below Level 3 in numeracy—the minimum standard—has increased at all levels of educational attainment since 2003. U.S. millennials with a four-year bachelor's degree were outperformed by all other participating OECD countries except Poland and Spain, and the scores of U.S. millennials whose highest level of educational attainment was high school or less were lower than those of their counterparts in almost every other participating country. Even the "best-educated" millennials—those with a master's or research degree—were

TABLE 2-1 Percentage of adults age 16-34 performing below the minimum standard of proficiency level on PIAAC literacy, numeracy, and problem solving in technology-rich environments (PS-TRE scales, by participate country/region: 2012.

Country/region	Literacy, % below level 3	Numeracy, % below level 3	PS-TRE, % below level 2
OECD average	41*	47*	44*
Australia	38*	51*	43*
Austria	43*	42*	43*
Canada	43*	50*	45*
Czech Republic	39*	40*	42*
Denmark	42*	43*	40*
England and Northern Ireland (UK)	49	58*	50*
Estonia	37*	43*	48*
Finland	23*	32*	32*
Flanders (Belgium)	34*	35*	40*
France	46	54*	—
Germany	42*	44*	43*
Ireland	50	59*	54
Italy	60*	63	—
Japan	19*	33*	33*
Netherlands	28*	36*	38*
Norway	39*	43*	38*
Poland	45*	53*	55
Republic of Korea	30*	42*	40*
Slovak Republic	44*	43*	54
Spain	59*	65	—
Sweden	35*	40*	35*
United States	50	64	56

— Not available.

* Significantly different ($p < .05$) from United States.

SOURCE: Organisation for Economic Co-operation and Development (OECD), Programme for the International Assessment of Adult Competencies (PIAAC), 2012.

outperformed by their peers in all other OECD nations except for Ireland, Poland, and Spain. This performance looks no better when disaggregated along demographic lines. For example, across all levels of parental educational attainment—which was strongly correlated with skills in all countries—there were no countries where millennials scored lower than did those in the United States.

The Skills of the Future

The United States has 92 million millennials, Gates noted, a number exceeding the number of baby boomers (Council of Economic Advisers, 2014). In general, the members of this group avidly use technology to look for information to help them make decisions. According to a variety of surveys that Gates cited, 94 percent use at least one outside source for guidance, 40 percent visit a website review to help them make purchasing decisions, and 50 percent use mobile devices to read user reviews and research while shopping for products. But this familiarity with and use of technology is not necessarily translating into needed job skills, Gates said.

In the future, workers will need different sets of skills than were required in the past, Gates continued (e.g., Goodman et al., 2015). They will need to be able to change careers as the economy evolves. They will need to interact with employers and educational institutions, including colleges and universities, in different ways than they have in the past. The millennials are living in the middle of this shift, but the statistics on educational attainment and test scores cited above do not inspire confidence that they can meet the challenge, he said.

Meeting the Challenge

"So do we just give up?" asked Gates. "I hope not. That's not the country that I have known for 64 years." Gates was one of four co-chairs of a working group under the President's Council of Advisors on Science and Technology that, in 2012, published a report titled *Engage to Excel: Producing One Million Additional College Graduates with Degrees in Science, Technology, Engineering, and Mathematics*. That report pointed out that traditional approaches to STEM education are failing many of the students who come to college wanting to major in these fields. In the first two years of college, more than half switch to other majors, despite having academic credentials that on average are not statistically different from those who remain as STEM majors.

> *"It's just as important that we have an impact on the rest of society in terms of understanding what science is, how we make arguments, how data are collected, and how data are interpreted as it is to attract [future] scientists to the field."*
> *—Jo Handelsman, OSTP*

To reverse this trend, the report made several recommendations that are relevant when considering course-based research. Most pertinent, it advocated replacing standard laboratory courses with discovery-based research courses (Recommendation #2). Recommended actions include funding implementation of research courses for students in their first two years of college, and establishing collaborations between research universities, smaller 4-year colleges, and community colleges, to provide all students with access to research experiences. In part, said Gates, this will require changing the culture of higher education. While challenging, it can be done with appropriate administrative support; faculty members "will figure out how to optimize the reward system that's presented to them," he said.

The *Engage to Excel* report has led to several major new efforts, including additional interest and plans for increased investments in undergraduate STEM education by the National Science Foundation, the Department of Education, and other federal agencies. (Box 2-1 describes President Obama's interest in the issue.) Gates focused on several small-scale initiatives, primarily in physics, during his presentation. For example, he has been involved with a program at Hampton University (Virginia) known as the Hampton University Graduate Students (HUGS) program, in which for 30 years undergraduate and graduate students in physics have worked at the nearby Thomas Jefferson National Accelerator Facility on experimental and theoretical topics of current interest in strong interaction theory. Similarly, at the University of Texas at Brownsville (which has a student body that is about 90 percent Hispanic), physics students work

Box 2-1
Presidential Interest

In her introductory remarks at the convocation, Jo Handelsman, associate director for science at the White House Office of Science and Technology Policy, noted that President Obama has a particularly strong interest in STEM education. Two issues have risen to the fore in the Obama administration: increasing diversity in STEM education, and preparing students for the needs of the future.

An aspirational goal, said Handelsman, is that every student, at all institutions—from community colleges to universities—would have a course-based research experience sometime during his or her first year in college. Not only would such experiences help keep students who are interested in STEM subjects in those fields, but they would also help change the understanding of science for students who do not major in a STEM subject. "It's just as important that we have an impact on the rest of society in terms of understanding what science is, how we make arguments, how data are collected, and how data are interpreted as it is to attract [future] scientists to the field," said Handelsman.

Reaching every first-year student will take time, she acknowledged, but a short-term goal could be to reach "many tens of thousands, even in the first year." Doing so will take commitment from faculty members and administrators, teaching materials or templates that faculty members new to course-based research can easily access and use, and focused efforts to overcome administrative barriers and provide resources for such courses. Continuing research into how best to structure and implement these courses will also be important.

at the Center for Gravitational Wave Astronomy, funded by NASA and NSF. At the University of Texas at El Paso, which also has a high percentage of Hispanic students, undergraduates work in the physics department on medical, applied, and atmospheric research projects. Gates also has been involving undergraduates in research in his own laboratory. At the time of the convocation, he was about to publish a paper in *High Energy Physics-Theory*—his seventeenth with undergraduate co-authors—co-written with one of his daughters and with a student who began college at a nearby community college. "The paper, by the way, is on string theory," he said He emphasized that undergraduate research is possible on topics that many would consider beyond the reach of students at this level, and that students from different types of institutions that are not traditionally thought of as being engaged in research can participate.

3
Promising Practices and Ongoing Challenges

Important Points Made by the Speakers

- Successful examples of research-based courses that rely on multiple indicators of student learning and program efficacy can provide design principles for people who want to start new courses. (Linn)
- The more students can be directly engaged in posing and addressing important research questions, the more likely they are to learn about the nature of science. (Sadler)
- By agreeing to and adopting common program goals, sets of activities, training or professional development for instructors or teaching assistants, and a central support system and site, collaborating organizations can then develop a common set of metrics which can provide unique opportunities for assessing the efficacy of their efforts. (Lopatto)
- Partnerships between state systems of higher education and public and private consortia can foster the institutionalization of research-based courses. (Ambos)

Course-based research remains a relatively new practice when used at scale to reach large numbers of students. But examples of course-based research have existed for many years, and several large-scale projects have been developed recently, each of which have provided valuable lessons from which to derive effective practices. (See the boxes throughout this report for details on a dozen such projects across the spectrum of STEM fields.) Course-based research also can build on a rapidly growing knowledge base in the learning sciences.

In the first panel of the convocation, four presenters examined promising practices in course-based research and some of the challenges that remain in learning about effective approaches. As continued research in the learning sciences reveals the best ways to engage undergraduates, these practices can be incorporated into new and expanding programs. Specific issues discussed included the difficulty of agreeing how to measure student outcomes and getting faculty to undertake assessments that go beyond self-report data (e.g., Dirks et al., 2014), the alignment of undergraduate research experiences with known learning strategies, and the use of consortia to assess the impact and disseminate best practices (see Box 3-1). It was pointed out by several participants that generating more informative evaluations of the benefits of CREs beyond student self-reporting may depend on a change in policy at funding agencies to require such evaluations from the faculty teaching and carrying out research on these courses with agency support.

Box 3-1
The Science Education Alliance—Phage Hunters Advancing Genomics and Evolutionary Science: A Prototype "Parallel" Project

The Science Education Alliance-Phage Hunters Advancing Genomics and Evolutionary Science (SEA-PHAGES) program is a two-term discovery-based research course targeted at beginning college students that is focused on a specific scientific question: mapping and defining the genetic diversity of the viruses which infect bacteria, known as bacteriophages. In the first semester of the year-long course, students use standard microbiology techniques to isolate viruses from the environment that infect a specific host bacterium and isolate and characterize DNA from those viruses. After the DNA is sequenced at an external laboratory facility between the two terms, students use bioinformatics tools to annotate the genome and compare genomes across bacteriophages. Viral "diversity is sufficiently high that there's a very good chance [a sample] will be unlike any other virus that has been isolated before," said Graham Hatfull, professor of biological sciences at the University of Pittsburgh. "You get to name it. You get to study it and dissect its genome. It's a particularly good feat for a first-year undergraduate experience."

Hatfull stressed that the key to involving large numbers of students is to develop a "parallel" project, one in which all students are using (and can be taught) a small suite of investigatory tools but each has responsibility for their piece of the project. "While sacrificing some student-initiated research planning, parallel projects facilitate the involvement of multiple students and are well suited to peer and near-peer mentoring," he pointed out. The phage isolation protocol also has the advantage of moving students from the concrete (the phage) to the representational (its genome), and is technically not too difficult, providing multiple milestones by which students (and faculty) can measure their achievement (Figure 3-1).

More than 70 institutions have implemented the program, including research universities, master's degree-granting institutions, baccalaureate colleges, and community colleges, usually as a replacement for introductory biology labs. In 2014, more than 2,600 students participated in the program, and the numbers of participating institutions and students are continuing to grow. The cost to the institutions is $100 to $200 per student, with centralized administration done through a collaboration of the Howard Hughes Medical Institute, the University of Pittsburgh, and James Madison University.

SEA-PHAGES has added greatly to the generation and annotation of genomic data on bacteriophages. The program has produced more than 20 scientific papers[a] published in the peer-reviewed literature, with thousands of undergraduate and faculty co-authors. Hundreds of bacteriophage genomes have been deposited in GenBank, and thousands of genes have been described, including many with novel features.

A variety of assessment tools have demonstrated substantial learning gains, greater retention in STEM fields beyond the first year, and better academic performance in other classes (see data in Jordan et al., 2014). "Students respond to being part of a community, recognizing that they are doing a research activity that is important to that community," said Hatfull.

More information is available at http://seaphages.org.

[a] A list of publications to date is available at http://seaphages.org/publications/.

Measuring the Outcomes of Course-Based Research

Many courses that incorporate undergraduate research are doing great things, said Marcia Linn, professor of development and cognition in the Graduate School of Education at the

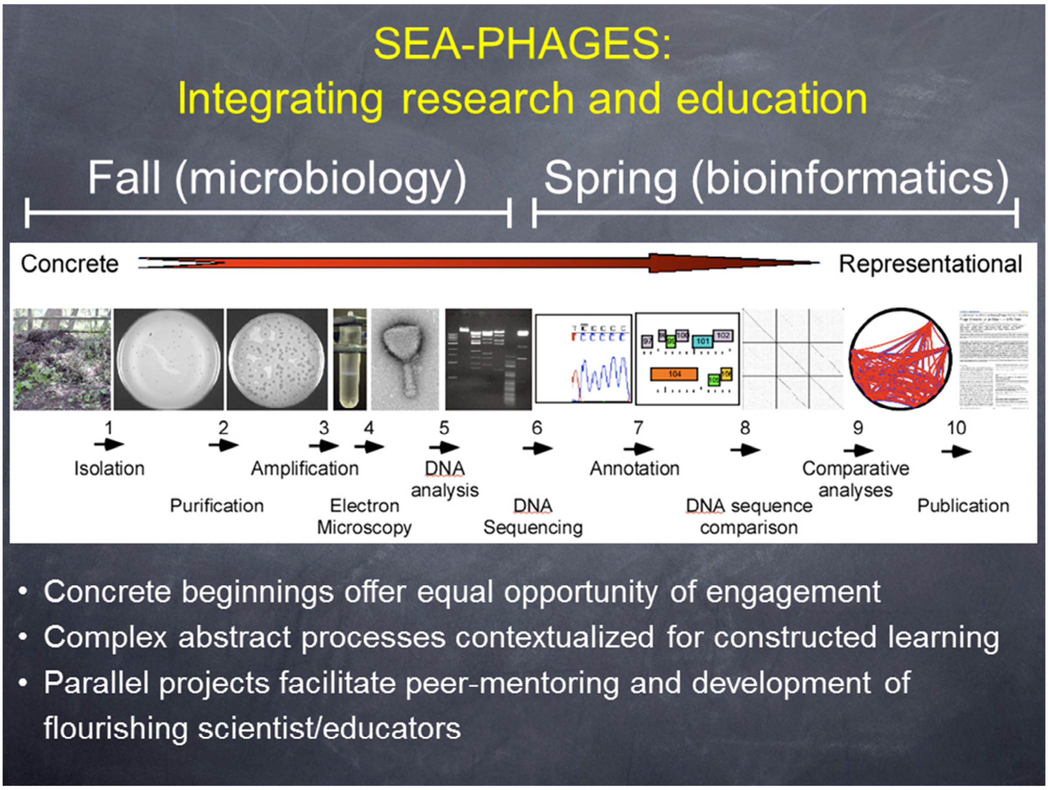

FIGURE 3-1: Milestones for students to measure their progress in SEA-PHAGES. Courtesy of G. Hatfull.

University of California, Berkeley. The question is how to capture best practices so as to offer design principles for people who want to start new courses.

In her own teaching, Linn had computer science students in the 1990s working on big and fundamental problems rather than on simple demonstration programs. Early on, she collaborated with computer science faculty as they implemented a "flipped" classroom, where most of the work of the course was done in a laboratory (Linn and Clancy, 1992). This required figuring out how to give the instructor credit for teaching the course, since at the time only lecturing counted as instruction. "We had to go up to the highest levels to get that changed," she said. Using a case study approach, students were able to deal much more quickly with large and complex programs. "This case study approach is now widely used in introductory computer science," she said. In computer science, offering lab-centric courses is now the accepted norm.

Linn pointed out that many of the outcome measures used to study the impact of research experiences are based on students' self-reports rather than on student testing, research presentations, student notebooks, or other external evidence of effectiveness and impact (Linn et al., 2015). Self-report data are suspect, in part, because students often seek to make themselves look accomplished or to report what they think researchers want to hear. More nuanced and valid evidence of outcomes could help instructors refine courses iteratively so that they provide increased benefits to students, she said.

Course-based research experiences tend to be short—usually one semester or less—which can be a disadvantage. But many current undergraduate research experiences, particularly those using an "apprenticeship" model, serve only a selected audience, and these efforts can be difficult to scale up, Linn pointed out. Linn challenged the field to rethink undergraduate research as a continuous process, saying: "How can we promote lifelong learning of science practices by engaging students in research experiences from their first course through to their final capstone course?"

One way to make research experiences a continuous process, Linn proposed, is to start by introducing research dilemmas as case studies in introductory courses. These cases would illustrate difficulties posed by experimental design problems, and by conflicting results, leading to development of strategies for critiquing experiments, and ways to deal with unanticipated consequences. These science practices could be reinforced in subsequent laboratories and through lectures, discussions, and assessments. For example, students could be asked in laboratory assignments to design or critique an experiment.[7] These experiences could be consolidated in capstone courses, with research projects required for all majors. "Why can't all lab courses have some of these components?" she asked. "Why can't we replace cookbook labs with opportunities to deal with uncertainty?"

In designing research experiences, Linn emphasized the importance of knowledge integration as a process that promotes lifelong learning (Linn and Eylon, 2011). "We want students to keep building on their understanding of experimentation." Students' ideas about scientific research remain fragmented, even when they learn something about the nature of research in high school. "Students get a glimmer of what it means to do science, they get a glimmer of the frustration or the excitement of a discovery, but they need to integrate those ideas and build a coherent understanding of experimentation." For example, she quoted a student saying of course-based research, "I honestly expected it to be like my organic chemistry lab. . . . I'm used to 'here is the procedure, now get to it.'"

Linn suggested looking at a wide range of indicators of learning in courses and projects. This could include challenging students to produce designs for experiments, reviews of primary literature, journal reflections, data collection and analysis, accounts of collaboration practices, and a final poster and/or research presentation. This would allow students to demonstrate their mastery of the scientific approach by asking and responding to questions. Longitudinal indicators of impacts could include determining who succeeds (in terms of both developing identity as a scientist and developing autonomy), tracking engagement in follow-on experiences (such as future courses, internships, or a senior project), and gathering evidence of persistence and success (such as presentations at meetings, publications, graduation, and decisions to attend graduate school or enter a STEM career). Such measures also would be useful to college and university

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[7] Immersing students in analyzing seminal research papers in science has been described by one of the invited participants to the convocation, Sally Hoskins from the City University of New York (e.g., Stevens and Hoskins, 2014; Gottesman and Hoskins, 2013; Hoskins et al., 2011; see also Chapter 5).

administrators who are looking for additional metrics for program efficacy beyond self-reporting by students.

> *"How can we promote lifelong learning of science practices by engaging students in research experiences from their first course through to their final capstone course?"*
> *—Marcia Linn, UC Berkeley*

Linn recently has been working on the development of virtual experiments that use machine learning to score students' responses. As an example, she demonstrated a virtual experiment on atmospheric warming in which students manipulate levels of greenhouse gases to learn more about climate change (Svihla and Linn, 2011).[8] Students might, for example, use evidence from virtual experiments to address the question, "Ozone is causing global climate change. Do you agree or disagree?" The online materials developed in the Web-based Inquiry Science Environment (WISE) are in widespread use in precollege schools and some colleges (see WISE.Berkeley.edu). "WISE is open source and free, and it's very easy to customize," she said.

Linn concluded with suggestions based on what has worked at her institution. The design of research experiences for undergraduates benefits from trial and refinement, she said. New and more nuanced indicators and assessments can help the designers of course-based research identify ways to improve student experiences (e.g., Dirks et al., 2014). And comparison studies where two or more promising alternatives are implemented could yield valuable design principles such as have been established for computer science (Linn and Clancy, 1992).

Learning about the Epistemology of Science

Troy Sadler, professor of science education at the University of Missouri, and his colleagues have been studying the potential for research experiences to teach students about the epistemology of science—how science operates, the nature of scientific knowledge, and the ways in which scientific ideas build, develop, and change over time. A frequently made assumption is that research programs for students or teachers will lead them to develop more sophisticated ideas about how science operates, and research does demonstrate some learning gains of this type, he said. However, Sadler emphasized that gains of this type are only seen if there is explicit attention to teaching the nature of science. Students who engage in research have demonstrated gains in understanding of the complexity of the scientific research process, the uncertainty of research processes, the significance of validity, the role of collaboration, and the nonlinearity of scientific methods (Richmond and Kurth, 1999; Ryder & Leach, 1999; Bell et al., 2003; Schwartz et al., 2004; Varelas et al., 2005; Hunter et al., 2007; Sadler et al., 2010). These are important gains that help them prepare for more demanding research. However, little evidence exists for the learning of more complex themes, including an appreciation for the different kinds of scientific knowledge (such as the distinction between theories and laws), the tentative yet durable nature of scientific knowledge, the social dimensions of science, and the role of creativity in science (Bell et al., 2003).

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[8] The experiment is available at http://wise.berkeley.edu/previewproject.html?projectId=9028.

One interpretation of student learning from research experiences, said Sadler, is that learning gains represent shifts in the "practical epistemologies" of science, that is, students' ideas about their own science experiences and the ways in which they engaged in the practices of science (Sandoval, 2005). In contrast, the ideas resistant to change correspond to students' "formal epistemologies" of science, which correspond to ideas students hold about how science works beyond their own personal experience. In addition, research experiences vary, and learning gains may be related to these variations, Sadler noted. Mediators associated with learning include the duration of the research experiences, the degree to which students focus on various aspects of epistemology, personal interest in the project, collaboration within the laboratory group, mentoring supports, explicit instructional supports and the amount and quality of reflection associated with the experience. For example, students can have very different experiences depending on the extent to which they are able to contribute to the development of research questions and make important decisions around analytic procedures. Laboratory constraints may make such involvement difficult or impossible, but when students have greater involvement with the epistemic dimensions of research, not simply the mechanics of data collection, they are more likely to learn about the epistemology of science, Sadler said. Thus it is important that students are not just doing the monotonous tasks involved in most research, but are directly engaged in posing and addressing important questions (Burgin et al., 2012; Burgin and Sadler, 2013; see also Box 3-2).

Providing students with explicit instructional support is another important variable, Sadler commented. For example, Sadler and his colleagues recently did a quasi-experimental comparison between students engaged in research experiences who were in seminars that focused either on the nature and content of science, or just on the content of science. In the former case, much of the nature of science material was drawn from activities developed for K-12 education, such as discussions of historical cases and knowledge of how students understand scientific processes. The instructors also took a structured approach to eliciting student reflection. For example, they provided students with composition books and had them write out answers to questions designed to help them think about the nature of science, after which the students were given feedback on their reflections. In both cases, students showed gains in their knowledge of how science operates, but the students with the extra instructional support demonstrated more sophisticated ideas, even in areas known to be more resistant to change, such as different forms of scientific knowledge (e.g., distinctions between theories and laws), the diversity of scientific approaches, and the social and cultural dimensions of science (Burgin & Sadler, in press).

The mediators of learning can interact among themselves, Sadler noted. For example, mentorship generally enables students to develop more sophisticated ideas about science, but mentorship can be provided by other students through laboratory collaboration, not just by faculty members. Peers, graduate students, and others can help students think through and reflect on their decisions and actions. Mentors also can help students understand the development of research questions and the use of analytic techniques even in circumstances where students have less involvement in these areas. Similarly, explicit instructional support can help make up for a lack of support in other areas.

Sadler suggested several ways to help students learn as research experiences become a bigger part of undergraduate science education:

- Optimize research contexts, including the connections among student interests, research opportunities, and collaborative environments. This requires that a school develop a 'menu' of several different options for research experiences.
- Help faculty members and graduate students develop effective mentoring practices (e.g., Pfund et al., 2015).
- Encourage students to reflect on their research and its connections to broader themes in science.
- Balance the requirements and realities of undertaking shared research (e.g., the need for standard protocols) with opportunities for students to engage with epistemic practices such as decision-making, so that they can make significant contributions to the research program as they progress.

Box 3-2
Synthetic Biology: Testing Hypotheses of Molecular Function

Synthetic biology, which combines engineering, mathematics, computer science, chemistry, and biology to design and build new biological systems, is an ideal topic for course-based research, according to A. Malcolm Campbell, professor of biology at Davidson College in North Carolina and founding director of the Genome Consortium for Active Teaching (GCAT). As reported by Campbell, synthetic biology is inexpensive, requires minimal preparation time, has a high success rate, requires relatively little faculty training, has results that are easy to disseminate, and is scalable.

As part of GCAT, Campbell and his colleagues have provided synthetic biology workshops for more than 150 faculty from a very wide range of institutions over the course of five years (Campbell et al., 2012). Assuming that every faculty member can reach 100 students per year, more than 45,000 undergraduates have benefited from this training, and an additional 15,000 are added each year. Workshop participants develop their own research and teaching programs. As Campbell said, "GCAT is more decentralized, more do-it-yourself than most national programs. If you have an interest where you can use synthetic biology as a tool, then we encourage you to do whatever it is that you're interested in."

At Davidson, for example, first year students use synthetic biology to characterize novel promoters, driving expression of visible reporter genes. In contrast, sophomores at Missouri Western State University mutate well-known promoters to test their hypotheses about the consequences of the mutations. Results are deposited into publicly available databases, so that anyone working in synthetic biology can make use of the information that students generate. Promoter research with pClone plasmids can be done in as little as three weeks or over a longer period if students are making more of their own decisions, testing alternatives. The cost, using a commercially available kit, is only about $1.25 per student (Campbell et al., 2014, 2015; Eckdahl and Campbell, 2015). Lab times are kept to two and a half hours to avoid conflicts with other demands on students.

Since starting the synthetic biology program, undergraduates at Davidson have published several papers, including two in the *Journal of Biological Engineering* that are the most popular papers in the journal's history.[a]

More information is available at http://www.bio.davidson.edu/113/113labscedule2015.html.

[a] For a list of research, pedagogical, and program description publications from the GCAT initiative see http://www.bio.davidson.edu/gcat/pubs.html.

Box 3-3
The Genomics Education Partnership and Genome Solver: Large Consortia Enabling Research in Science Education

One model for bringing research into undergraduate classrooms is to build a national consortium of faculty with shared interests to tackle large projects as a group. Such projects may have a lead institution with funding for core functions, including establishing common tools, providing training for interested faculty partners, and maintaining a communications hub. Working as a consortium can be cost-effective and beneficial to individual faculty participants, allowing for shared curriculum and joint publications. Use of a common strategy also allows for joint assessment, providing larger numbers of subjects (students) and verifying the approach's generality across different types of institutions, as discussed by Lopatto. The downside is that the individual faculty members sacrifice some autonomy in their choice of a scientific problem for students to investigate. Two examples of such national consortia are the Genomics Education Partnership (GEP) and Genome Solver.

GEP is a collaboration among a growing number of primarily undergraduate institutions and the Department of Biology and McDonnell Genome Center of Washington University in St. Louis that focuses on major questions of *Drosophila* evolution. Its goal is to provide students with opportunities to participate in genomics research. Students work on selected chromosomal regions of particular interest, taking raw sequence data to high-quality finished sequence, then annotating genes and other features (Shaffer et al., 2010). Appropriate analysis of the resulting high-quality genome assemblies has led to research publications with multiple student authors. (For example, Leung et al. 2015, has 940 undergraduate co-authors.)

GEP provides three- to five-day workshops for educators that provide familiarity with the bioinformatics tools being used, discussion of the scientific questions that can be addressed, and planning for implementation. To date, more than 100 faculty have implemented GEP curriculum materials and approaches in their research courses for undergraduates. GEP provides designs for courses that are fully dedicated to genomics, as well as modules that can be incorporated into pre-existing courses. The program is easily accessible, collaborative, exploratory, effective in a short time frame, and practical for a large number of students at once. Currently over 1,000 students participate annually in the program;

- Leverage explicit instructional supports for learning about the nature of science.
- Expand strategies for assessing epistemology-related constructs.

As Sadler pointed out, developing measures of effective learning remains "a huge problem." Self-report may not reveal the level of understanding of difficult concepts, and the assessment models that do exist are not easy to scale up and disseminate. However, some measures developed for K-12 education could work in higher education. Bringing together different communities and devoting resources to the development of appropriate assessment tools could help to develop and disseminate such measures, promoting their use.

Using Quasi-Experiments to Measure the Outcomes of Course-Based Research

In his commissioned paper and video presentation, David Lopatto, professor of psychology at Grinnell College, observed that undergraduates can realize many benefits by participating in course-based research. Based on a survey of undergraduates at four institutions, these benefits generally include the following (Lopatto 2010):

approximately fifteen schools have joined the partnership annually for the past four years.

A spinoff of GEP, Genome Solver aims to create a community of faculty and students interested in studying microbial genomes, specifically examining the rich data sources now available as a result of the NIH's Human Microbiome Project.[a] More than 140 faculty members have received professional development in bioinformatics research through teaching workshops, and an interactive website allows students and faculty to exchange information and develop shared interests. Genome Solver is currently developing a community science project to look at horizontal gene transfer between phages and bacteria. Learning goals for students are to apply comparative analysis to demonstrate that fitness for an environmental niche is determined by an organism's genome, to understand the process of genome annotation as it relates to gene structure and function, to examine the relationship between DNA sequence and predicted protein coding sequence, and to understand how homology to defined protein domains can infer function. While Genome Solver is designed to allow faculty members more latitude in project design, in practice many prefer to join the larger group project because of limitations in available time for curriculum development.

DNA sequencing techniques and other recent technical developments have produced much more data than ever before; computers can store and manage those data, but few people, including few biology faculty members, have been trained to analyze this information. As Anne Rosenwald, associate professor of biology at Georgetown University, said, "Convincing students, colleagues, and administrators that bioinformatics has a place in life science education isn't always easy or straightforward." But students only need a computer and access to the Internet to conduct authentic research projects, and these programs are easy to implement at all colleges and universities, including community colleges. "Group projects like these result in networks of like-minded peers," said Rosenwald. "We feel that this is a win-win for students and faculty."

More information about the Genomics Education Partnership is available at http://gep.wustl.edu. More information about Genome Solver is available at www.genomesolver.org.

[a]Additional information is available at https://commonfund.nih.gov/hmp/index.

- Personal development
- Knowledge synthesis
- Data collection and interpretation skills
- Design and hypothesis testing skills
- Information literacy
- Computer skills
- Interaction and communication skills
- Responsibility
- Professional development

Course-based research is a complex package of treatment variables, Lopatto emphasized. This package may produce positive benefits at one site (college or university), but a major question is whether same package can produce similar benefits at other sites. A program that has common features across several sites can help answer this question (see Box 3-3). This strategy shifts the focus from confounding variables to the robustness of a program's overall effectiveness.

It seeks to determine which treatment variables produce a successful outcome in different environments.

To study the effects of course-based research, Lopatto suggested the use of what Cook and Campbell (1979) identify as quasi-experiments—that is, an experiment that examines "treatments, outcomes measures, and experimental units, but does not use random assignments to create comparisons from which treatment-caused change is inferred. Instead, the comparisons depend on nonequivalent groups that differ from each other in many ways other than the presence of a treatment whose effects are being tested. . . . In a sense, quasi-experiments require making explicit the irrelevant causal forces hidden within the *ceteris paribus* [other things being equal] of random assignment" (Cook and Campbell, 1979, p. 6).

Lopatto also argued against using dispositional variables as outcomes—that is, human traits, motivations, and other characteristics that suggest the occurrence of structural change in the character of students. Instead, he urged focusing on behavior. STEM education is successful when students are able to behave as scientists in those settings where it is appropriate to do so. For example, he pointed to a separate set of statements made by Smith college alumnae when they were five, ten, and fifteen years out of college that show how difficult it is for some people to maintain a scientific identity as they mature:

> "After completing my MS degree, I decided I was tired of working in the sciences and wanted to do something completely different."
>
> "I was at a wonderful PhD program . . . with the path of many, many career options ahead. . . . But I had been away from my husband for years and wanted to be with him and have children. My science education argued for BOTH cases. . . . I know the biological downsides to waiting to have kids, but I also had an appreciation for the stats: if I left, I'd probably never finish my degree."

As another example of the importance of relying on behavior rather than dispositions, Lopatto observed that the best way to know whether an undergraduate science major wants to go to graduate school is to ask him or her. "Her future in graduate school is not affected by content or critical thinking skills if she does not intend to submit an application." As argued by the psychologist Kurt Lewin, behavior depends on what can be termed the psychological field at the time of the behavior, which consists of the influence of the past and the future on the person in the present. Thus, an undergraduate in a course-based research program will respond in a way affected by his or her past experiences, his or her present experiences, and his or her expectations of the future. "If we wish to know what their intentions are and how they will continue in the program, we need to ask," said Lopatto. Discussions of assessment usually revolve around three domains of student learning: cognitive, behavioral, and attitudinal, Lopatto said. The cognitive domain includes content learning, the behavioral domain includes demonstrations of skill acquisition, and the attitudinal domain includes how students feel about their education. How much the three domains overlap or correlate remains unknown, said Lopatto, which makes it difficult to predict how measures might correlate in the field.

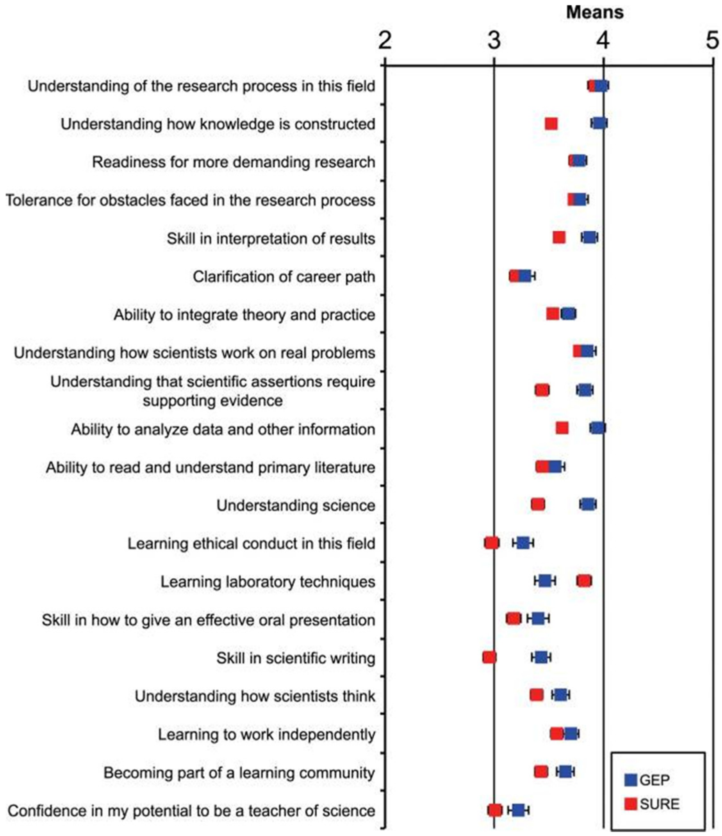
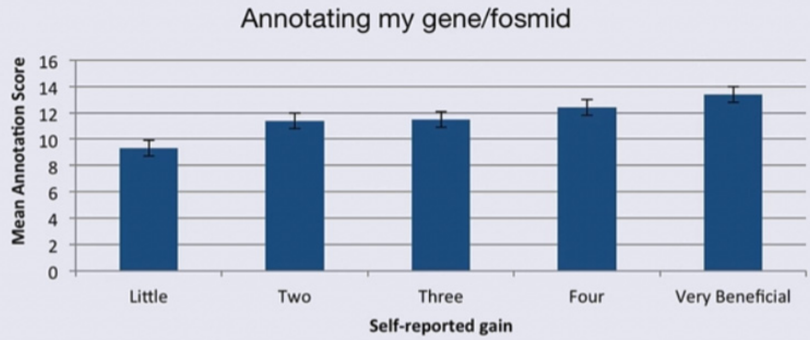


FIGURE 3-2: GEP students report similar gains in understanding of science compared to students in a summer-in-the-lab program. Self-reported student learning gains (on a scale of 1 (none or very small gain) to 5 (very large gain) using the SURE survey. Blue squares indicate the mean for GEP students, while red squares indicate the mean for SURE summer research students, 2009. Error bars represent two SEs below and above the means. From Shaffer et al., 2014, Figure 4, p. 120. (SURE = Survey of Undergraduate Research Experience). Reprinted with permission from Shaffer et al., 2014.

Fortunately, Campbell's work on quasi-experiments sheds light on how to proceed, Lopatto continued. He advocated the concept of multi-operationalism, the use of more than one outcome measure. If multiple measures tap into the same learning domain, they should correlate. However, the correlation should be modest. A high correlation renders the measures redundant. A zero correlation suggests that the measures are tapping into different learning domains. A modest correlation suggests the two measures are tapping into the same domain, but that each has sources of error. What is important is that the two measures have *independent* sources of error. For example, in the assessments Lopatto and his colleagues have done of the Genomics Education Partnership at Washington University, a modest correlation exists between how students assess their experiences and their test scores on relevant material (Shaffer et al., 2010, see also Figs. 3-2 and 3-3).



One example of the relationship between a GEP student self-report question (how beneficial was training on annotating my gene/fosmid) and the mean annotation quiz score for the same student. Self-evaluation items correlated with quiz scores in the range of 0.2 to 0.3, using Pearson's r.

FIGURE 3-3: The quiz scores (knowledge acquisition test on genes and genomes) of GEP students correlate with their self-reported learning gain scores on items shown in Figure 3-2 (from presentation of David Lopatto, modified from Figure 7 of Shaffer et al., 2010 and reprinted with permission).

Consortia afford many advantages for doing these kinds of experiments, Lopatto said. A group of sites can be in agreement about program goals, offer a common set of activities, provide common training for instructors or teaching assistants, have a central support site, and use a common set of assessment measures. This approach permits the detection of a successful treatment despite multiple sources of noise, enables the generation of relatively large data sets, tolerates departures from experimental control, and allows for subsequent replication, assuming that new members can join an ongoing consortium.

A Systems Perspective on Best Practices

The mission of the Council on Undergraduate Research, which is a national organization of more than 10,000 individual and 700 institutional members, is to support and promote high-quality undergraduate research and scholarship (e.g., Karukstis and Elgren, 2007; Boyd and Wesemann, 2011) .[9] It has ten discipline-based divisions—arts and humanities, biology, chemistry, geosciences, health sciences, mathematics and computer science, physics and

[9] Additional scholarly papers on course-based research experiences for undergraduates can also be found in the CUR Quarterly, available at http://www.cur.org/publications/curquarterly/.

astronomy, psychology, social sciences, and engineering—and two multidisciplinary, administration-based divisions—at-large and undergraduate research program directors. It has grown 40 percent over the last four years, said its executive officer Elizabeth Ambos, and growth has been particularly strong in non-STEM areas.

"I'm not sure we can engender deep change in the faculty reward system for STEM faculty without having it be an all-university partnership between STEM and non-STEM faculty."
—Elizabeth Ambos, Council on Undergraduate Research

Ambos described a recent publication, based on work supported by the Council and the National Science Foundation, which explores the prospects for enhancing and expanding undergraduate research from a systems perspective (Malachowski et al., 2015). This study focused on the potential for partnerships within state systems of higher education and public and private consortia to foster the institutionalization of undergraduate research at individual member institutions and across the systems or consortia as a whole. Most campuses in all of the systems and consortia studied had expanded and enhanced their undergraduate research programs. Even more important, all planned to incorporate more undergraduate research directly into the curriculum and at earlier stages.

Major strategies were to establish centralized undergraduate research offices and to create inventories of available opportunities for research, address faculty reward structures, and use the power of convening and messaging among participants. Faculty members were encouraged to align course-based research with their own research, as appropriate. The project also identified roadblocks to increasing undergraduate research, including leadership transitions that resulted in lost momentum, the fact that academic cultures are slow to change, and recent decreases in state funding. For example, Ambos noted, academic leaders tend to turn over much faster than do tenured faculty members, which has "a huge impact on the change process."

The results of this project have led to several recommendations, noted Ambos. One is to recommend sustained institutional investment in such programs for at least a decade, not just for the more common three- to five-year planning horizon. Another is to invest in teams and use a nested leadership model, where leaders come from different parts of an institution's instructional and administrative structure, thus helping to align strategic thinking and reward structures. Undergraduate research can be linked with institutional change, said Ambos, which can help avoid the trap of such research becoming an isolated goal. Finally, change can be leveraged through systems and consortia convening, messaging, assessing, building infrastructure, and redistributing resources.

Ambos also said that the value of the nested leadership model extends beyond STEM subjects. "I'm not sure we can engender deep change in the faculty reward system for STEM faculty without having it be an all-university partnership between STEM and non-STEM faculty. Except in the very largest research universities, where reward structures can often be determined within a college basis, almost all other institutions' reward structures are determined at the institutional level." The institutions that are moving fastest to incorporate research into undergraduate courses are those where STEM and non-STEM faculty are moving more quickly to rewrite tenure and promotion strategies, are providing more opportunities for adjunct faculty to be engaged, and are aligning hiring practices with milestones for the engagement of students in research.

The Value of Student Reflection

> *"The learning is not directly from the feedback but from the revision process to their reflection. [The benefits from] having students reflect is one of the most important findings that we have in the literature in the learning sciences."*
> *—Marcia Linn, UC Berkeley*

A prominent topic in the discussion following the panel presentations was the value of student reflection when incorporated into course-based research. (Chapter 7 provides a synthesis of the discussions that occurred throughout the convocation.) Sadler noted that in his studies, student reflection is set up to be both multifaceted and structured. For example, when students have an opportunity to talk through what they are doing with their mentors, they can connect their activities to broader themes, he said. Also, instructors can provide students with composition books in which they answer targeted questions geared toward getting them to think about how their work relates to the nature of science. "They put down their ideas, and we'd provide feedback on their reflection," Sadler said. "For some students in rich laboratory contexts maybe that kind of structured experience wasn't necessary. . . . [But] we find those journals to be helpful."

Linn added that her group has found "the value of reflection in student journals or in activities that include specific prompts for reflection to be extremely beneficial." When students are asked to explain what they have been observing, their learning tends to be more durable, she said. "It's difficult to have to write a reflection," she added. "But courses with this type of difficulty, which is hard work, often result in student errors during learning but more durable understanding on subsequent assessments" (Bjork and Linn, 2006). Reading and evaluating students' reflections can be time-consuming for the instructors of a course, especially for those courses with large enrollments. Using natural language processing and machine learning takes advantage of computers to evaluate student responses—a reasonable strategy especially when these evaluations are used not for grades but to guide further student thinking (Gerard et al., 2015). "The learning is not directly from the feedback but from the revision process to their reflection. [The benefits from] having students reflect is one of the most important findings that we have in the literature in the learning sciences."

Ryan Kelsey from the Helmsley Charitable Trust noted that his organization has been working with a consortium of engineering schools to incorporate reflection into engineering practices. "It's everything from the right kinds of prompts all the way up to e-portfolio kinds of approaches. We have schools attempting an entire continuum of different types of approaches." Such efforts should lead to a more nuanced appreciation of best practices in this area.

4
Leveraging Available Resources to Create Greater Access to Research Opportunities

Important Points Made by the Speakers

- Local resources, including campus priorities for research and development, and even the physical resources of campuses themselves, can provide abundant and rich opportunities for course-based research. (McDonald)
- The remote use of analytical instruments is another avenue to providing large numbers of undergraduates with access to research experiences. (Ryan)
- DNA barcoding using inexpensive DNA extraction, amplification, and sequencing technologies demonstrates how students can engage in forefront research of local interest, while drawing on publically available bioinformatics databases and tools. (Micklos)
- Virtual internships can enable many more students to take action, reflect on that action, and develop ways of thinking about real-world practice than would be possible through real internships. (Shaffer)

Course-based research can bring research experiences to larger numbers of students in cost-effective ways, but this approach requires a robust infrastructure to be successful and sustainable. In the second panel of the convocation, four speakers provided examples of courses that incorporate research, while also describing the availability of the infrastructure required to make those courses work. In each example—ranging from on-site sustainability research, to remote access to shared instrumentation, to accessing on-line databases, to "virtual internships"—students engage in activities available only in the context of research, but they do so through regular courses using available resources, demonstrating the widespread applicability of course-based research.

Using the Campus as the Lab

One way to make course-based research cost effective is to take advantage of the local resources that already exist. For example, the California State University system has created a partnership between faculty members and facilities management staff at its institutions to use the state university campuses as forums to explore sustainability concepts and theories (see also Box4-1). Known as *The Campus as a Living Lab* course,[10] it involves students in design,

[10] Additional information is available at http://www.calstate.edu/cpdc/sustainability/liv-lab-grant/.

Box 4-1
Place-Based Research at UW-Madison

A college or university campus offers opportunities for undergraduate student research in places that instructors may not expect. Energy use, food supply chains, and waste are common elements of every campus environment. As a result, any campus can serve as a "living-learning laboratory" in which research findings can be used to improve campus operations.

At the University of Wisconsin-Madison, students enrolled in an introductory environmental science course are carrying out campus research projects that connect to the work of the university's Office of Sustainability (http://sustainability.wisc.edu). By participating in place-based projects on campus that also have applications in the broader community, students explore questions that connect to a larger research agenda in sustainability.

"Every number has a story," said Cathy Middlecamp, a chemist and professor of environmental studies at the university. "It is important to tell that story." Consider, for example, the number 25 percent. In a recent semester, this was the percentage of the trash that students discarded in one of their residence halls that could have been recycled, based on data collected by the class. "Don't stop with a number," said Middlecamp. "Real people living in a real dorm tossed real recyclable bottles into the regular trash bins. What is the story?" Part of any research experience is for students to ask questions about their findings. The answers to their questions help to tell a story.

Instructors can find many opportunities for undergraduate research on their own campuses. At first, the projects may not appear to be "real" research. A trash audit, however, gives students the opportunity to follow a protocol, collect data, and ask research questions of their own. For example, an unexpected finding in the study described above was that this trash also included 20 pounds of cups, dishes, silverware, and even a tray from a campus dining hall. This finding in turn catalyzed a future research agenda for the undergraduate students.

engineering, research, documentation, and public relations. It is a "holistic approach," said Margot McDonald, architecture department head at Cal Poly-San Luis Obispo.[11]

As an example, she described a second-year architecture course at Cal Poly that serves about 120 students. The course was redesigned to create a focus on real world issues associated with design and building occupancy. Learning goals for students were to:

- Interpret a complex construction document set
- Perform on-site field measurements and direct observations of building performance
- Conduct a climate analysis
- Compare design intent to actual building performance
- Discuss findings with stakeholders

For example, students analyzed shading devices and day-lighting design in a new campus science building completed in 2013. Students worked with building drawings, performed field

[11] A similar effort aimed at community colleges is detailed in Cohen and Lovell, 2011.

This type of research has many stakeholders, said Middlecamp, including not only students but also campus administrators who work in facilities planning and management, and the institutional staff responsible for budgets. For example, some of the projects she has done with her students have resulted in data that can be used to improve the efficiency of campus operations, yielding cost savings that can support ongoing research. The same observation can be made of many place-based and local projects on campuses where people live and learn, she said.

More information is available at http://nelson.wisc.edu/undergraduate/sustainability-certificate/syllabi/env_st_126-spring_2015_syllabus.pdf.

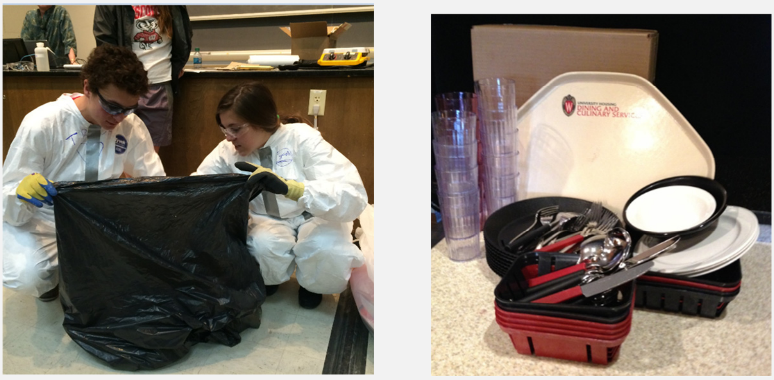


FIGURE A: (Left) Students investigating the composition of trash collected from a dormitory at the University of Wisconsin, Madison. Courtesy, Cathy Middlecamp. (Right) Eating utensils, plates, cups, and a tray found by undergraduate students in "Principles of Environmental Science" in the six-day trash audit carried out at a university residence hall. Courtesy, Cathy Middlecamp.

measurements, and did a climate analysis. Pacific Gas and Electric lent students data loggers, light meters, and other measurement equipment, and much of the software used to do the computer analyses was free. Students developed a hypothesis to test, discussed findings among themselves, and presented their conclusions to the architects.

McDonald emphasized the availability of building designs, utility data, and other records for data mining. LEED (Leadership in Energy and Environmental Design) buildings are designed to collect data on building function. An extension of the Living Lab course has been a data repository from which students can download any non-proprietary data. The course organizers are now reaching out to other schools, software companies, other STEM educators, industry, and other disciplines to enhance outreach and engagement.

McDonald drew several lessons from the experience:

- The campus context provides an abundant and rich laboratory setting for data collection, analysis, and synthesis.
- The Living Lab course relates to students' everyday experiences of occupied indoor and outdoor space to sharpen their observation skills.
- Even "bad" buildings provide great learning opportunities for students and professionals.
- Campus resources provide good access to data and documents for students to use.

In surveys, students commented positively on their experiences. For example, one student wrote, "Just being aware of these strategies should allow us to create a more suitable environment for future generations, and allow us to soften the impact of previously very wasteful practices in our field. I feel as though incorporating these practices into our projects is not only a great start to our introduction into the field, but also a start of finally realizing that these practices shouldn't be supplemental to the overall process, but rather already incorporated into the design process."

Sharing Instruments to Support Discovery-Based Research

The use of sophisticated analytical instruments in classes can have a major impact on students and is a common subject of proposals to government agencies like the National Science Foundation (NSF), noted Jeffrey Ryan, professor of geology and chair of the School of Geosciences at the University of South Florida. However, large analytical instruments typically are not in the classroom: they make specialized demands on such resources as space, they are expensive to maintain, and learning how to use them takes time, which is always in short supply in the undergraduate curriculum.

After a period as a geosciences program officer at NSF, Ryan began to look into ways to get the benefits of accessing and operating sophisticated instrumentation without having to own the equipment. Advances in technology already had been making remote instrumentation the norm in some fields, such as astronomy, and it was becoming more common in the geosciences. Some of the early adopters of remote access technologies in the geosciences used microbeam instruments, so Ryan requested grant support from NSF for a pilot study to use remotely operable electron probe micro-analyzers and scanning electron microscopes in two of his courses, one for majors and the other for introductory honors students (Figure 4-1).

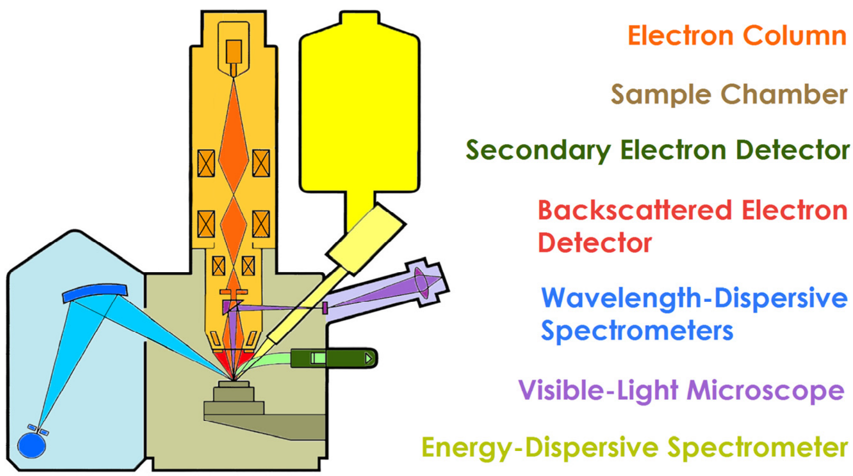


FIGURE 4-1: Remote operation capability is now standard on many geoscience research instrumentation systems (Modified from the presentation by Jeffrey Ryan. Original figure is available at http://serc.carleton.edu/download/images/8435/probe_schematic.jpg).

The questions he wanted to answer were:

- Does in-class instrument use improve student confidence and interest in geoscience courses/content?
- Do these activities improve student learning of core course content?
- Do these activities foster interest and participation in undergraduate research?
- Do such activities contribute to student persistence, retention, and interest in graduate education?

In this case the instruments are at the Florida Center for Analytical Electron Microscopy on the campus of Florida International University in Miami. From Tampa, Ryan and his students used the probes to do traditional thin section petrography followed by microprobe study and electron microscopy. The courses were modified, in what Ryan called a "Full Monty intervention," to support student projects using the instruments. Getting students up to speed on the machines was done in whole-class exercises via remote operation. Imagery could be downloaded to the web server in real time, and the machines could be operated as if they were in the same room as the operators. Students in the majors' course did "serious discovery-based research," said Ryan. The introductory course was more forensic in nature, in that students were expected to learn the origins of a sample.

Students had strong positive feelings about the new courses, saying that they felt empowered by the approach (Ryan, 2013). Learning gains were hard to measure because students were working at a higher level than the assessment tools available in the discipline, but at the very least, said Ryan, the new approach did no harm. Persistence and retention were excellent in the major's course but not much different in the introductory course. "Most freshmen and sophomores come to USF as premed students, and nothing was going to make them not be doctors." One outstanding question, said Ryan, is the "dosage" of such experiences that are needed for a beneficial impact.

The course for majors definitely facilitated subsequent involvement in research by students, Ryan observed. A quarter of the students in the course took follow-on courses. They also have requested that other courses be taught this way, and Ryan has personally taught three other such courses. Seven students expanded their in-course projects into research efforts presented at professional meetings, and six, so far, are pursuing graduate degrees.

Funding for the pilot program ended in 2010. Since then, the courses have had laboratory fees of about $30 per student to buy an hour of time on the microprobe or scanning electron microscope.

The program has been expanded to three other institutions: Florida International University, Florida Gulf Coast University, and Valencia College, which is a two-year college. The intervention now has different scales, including term projects, sets of related laboratory activities, single-laboratory demonstrations, and in-class demonstrations. Dissemination and expansion strategies include live interactive demonstrations of the project's instructional strategies and the offer of a free day of instrument time with project staff if faculty members commit to conducting a live remote exercise in their classroom. Similar programs could be envisioned with a wide variety of instruments across the other STEM disciplines.[12]

> *"Typically, when they can't figure something out, students blame themselves and feel that their knowledge is short. But in DNA barcoding, they can very easily see that it is not their fault but that in fact they are at the edge of scientific knowledge."*
> *—David Micklos, Cold Spring Harbor Laboratory*

Learning from Big Data in Biology

The ability to generate large data sets often exceeds the ability to "mine" the data, and policies making many such data sets publicly available have opened up new opportunities for students. For example, between 2007 and 2013, the cost of sequencing DNA dropped 10,000-fold. This radical technological innovation has created tremendous opportunities to bring research-based courses to both college and high school classrooms, said David Micklos, founder of the DNA Learning Center at Cold Spring Harbor Laboratory.[13]

Many other sources of big data have become available in biology in addition to DNA sequences, ranging from other sources of molecular data to phenotypic descriptions to remote sensing of plants from drones. However, each form of data traditionally has had its own database, and converting them to a common platform has been difficult or impossible, Micklos noted. A recently developed tool called DNA Subway (Figure 4-2)[14] offers a way to deal with many such data-handling issues in bioinformatics. It bundles several high-powered tools into an easy graphical user interface to assemble gene models, investigate genomes, work with phylogenetic trees, and analyze DNA barcodes.

DNA barcoding is a simple laboratory procedure that Micklos called the "do everything" research tool. Just as the unique pattern of bars in the universal product code identifies each consumer product, a short "DNA barcode" (about 600 nucleotides in length) is a unique DNA sequence that can potentially identify each species. Barcoding provides a single infrastructure that supports a very wide range of distributed projects—such as determining the species in a given ecosystem, or checking the labeling in a favorite sushi restaurant—and many of these projects can reach a satisfying endpoint in a single semester. Barcoding subsumes many important biological concepts and can integrate genetics, ecology, and conservation biology. It combines lab experimentation (extracting DNA, doing a PCR amplification of the appropriate region for sequencing) with bioinformatics (using that sequence to determine the species in a BLAST

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[12] Many of the U.S. National Laboratories offer remote access to their instrumentation for scientists and students. For additional information see https://www.nomachine.com/node/2496. A Registry of Analytical Geochemistry Equipment is at http://serc.carleton.edu/NAGTWorkshops/petrology/instruments.html. The Southeastern North Carolina Regional Microanalytcal and Imaging Consortium (http://sencr-mic.info/index.htm) is available for research and educational usage.
[13] Additional information is available at https://www.dnalc.org/.
[14] Additional information is available at http://dnasubway.iplantcollaborative.org/.

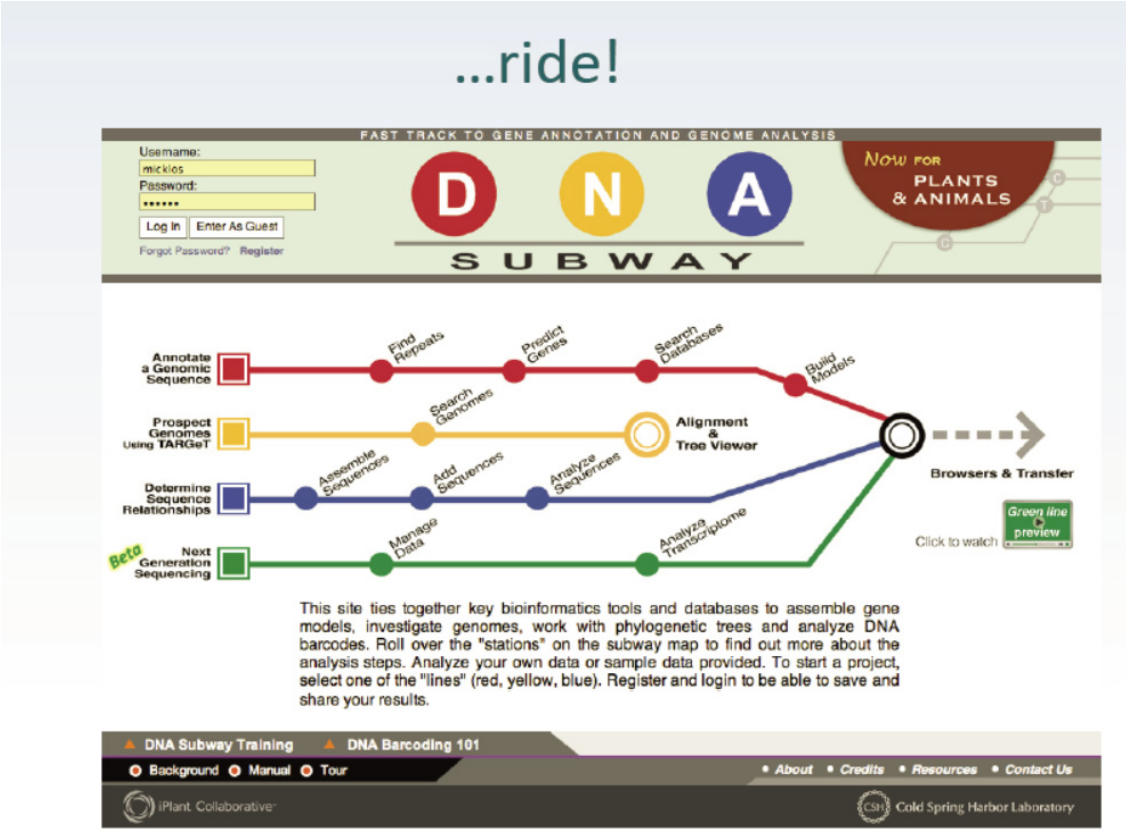

FIGURE 4-2: The DNA “Subway.” From presentation by David Micklos.

search, for example) and provides opportunities for student discovery and publication of novel findings.

The most exciting thing about DNA barcoding, said Micklos, is that it quickly brings students to the frontiers of scientific knowledge. “Are these two things the same species or different species? How do mutations alter DNA sequence? How can DNA or protein sequences be used to show relationships between different organisms? Typically, when they can’t figure something out, students blame themselves and feel that their knowledge is short. But in DNA barcoding, they can very easily see that it is not their fault but that in fact they are at the edge of scientific knowledge.” That realization can be very exciting for students!

An integrated biochemical/bioinformatics workflow can bring together all the materials needed to do barcoding as PDFs or online. DNA can be extracted easily and cheaply from almost everything that is or once was alive, and the required sequence can be amplified by PCR.[15] Students can get DNA sequences back from commercial sequencing labs in 24 to 48 hours, after which they can start to analyze and manipulate those sequences using DNA Subway. They can import sequences from elsewhere into DNA Subway, search for sequence matches, and build phylogenetic trees. In the end, they often can submit their own data to such databases as GenBank. [16]

> *"Many of us who are mainly educators in primarily undergraduate institutions are doing research that's every bit as good as the research in Research One institutions, and coming along are lots of students."*
> *—David Micklos, Cold Spring Harbor Laboratory*

In one project, students from around New York City, including high school and college students, high school teachers, and college faculty members, looked at organisms in the urban environment, including plants, animals, and fungi. In another example, students discovered that "shark fin soup" from restaurants often contains winter skate rather than shark, and they discovered a novel sequence that was submitted to GenBank. Another project found that gingko products sold as traditional Chinese medicine often do not contain any gingko. Students used DNA barcoding to look at the diversity of ants in a Bronx park, identifying seven different species, and developed a phylogenetic tree for one case.

The other example Micklos cited, called Barcode Long Island,[17] took place at summer camps from 2012 to 2014. This project supported 600 student projects engaging 1,800 students, trained 240 students as peer mentors, and studied Long Island biodiversity along with the impact of this approach to discovery-based research on students and teachers. This project utilized a supercomputer at the Texas Advanced Computing Center (the seventh largest computer in the world) to analyze the data. Projects of this sort, which help to provide information to the local community, or tackle specific local needs, can be especially engaging to students (Box 4-2).

DNA barcoding, and other genomics projects, now offer biology students opportunities to work with the same data at the same time and with the same tools as research scientists, said Micklos. "[With this access] many of us who are mainly educators in primarily undergraduate institutions are doing research that's every bit as good as the research in Research One institutions, and coming along are lots of students." However, taking advantage of this capability means living with several paradigm shifts, he said, including the transition from limited data to unlimited data, the transition from a world where hypotheses are underdetermined by data to a

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[15] The need for PCR technology may present a barrier for some high school teachers to adopt this approach although a number of loaner programs exist. For a list of many such programs, see https://www.google.com/search?q=PCR+loaner+programs+for+high+schools.

[16] Sponsored by the National Institutes of Health, GenBank is an annotated collection of all publicly available DNA sequences that is updated daily and with new releases every two months. GenBank provides and encourages access within the scientific community to the most up to date and comprehensive DNA sequence information. It places no restrictions on the use or distribution of the data contained within it. Additional information is available at http://www.ncbi.nlm.nih.gov/genbank/.

[17] Additional information is available at http://www.barcodeli.org/.

world where data are underdetermined by hypotheses, and the move from reductive biology to constructive biology. Students and faculty members will need to be retrained to think about how to utilize high-performance computing. “There is plenty of capacity to do biology on supercomputers, on things called cluster computers, and in the cloud, like the Amazon cloud, but

Box 4-2
SENCER: Community-Centered Research

The Science Education for New Civic Engagements and Responsibilities (SENCER) program was designed to help faculty design, implement, and assess learning through projects that attract and hold student interest in undergraduate STEM courses. Though the program did not originally anticipate discovery-based learning as an outcome, program leaders found that conscientious engagement with real world issues generated a research approach, as well as helping to meet several of SENCER’s goals for students, including:

- Experiencing both the limits and the power of disciplinary approaches;
- Becoming aware of the local and global implications of a problem;
- Developing a desire to learn and understand more;
- Investigating ways to maintain or change a given set of conditions and outcomes;
- Becoming engaged in learning to be conscientious citizens in a democracy.

SENCER is a “faculty and student empowerment project,” said David Burns, executive director and principal investigator at the National Center for Science and Civic Engagement, headquartered in Washington, DC. Typical undergraduate introductory courses can seem to have nothing to do with real world questions, whereas these questions are central to SENCER pedagogy. Assessment is focused on student interests and motives. “The study of student motives and attitudes—best known, however imperfectly, through direct reporting by the student—will be crucial to understanding the impact of any undergraduate pedagogy,” Burns said.

SENCER supports a community of practice by offering faculty development programs through regional symposia and annual summer institutes. It supplements those interactions with a collection of resources, including field-tested and emerging course models, background papers, and bi-weekly e-mailed updates. It also encourages and participates in the development of assessment strategies and tools that help educators better evaluate and promote student learning and engagement.

Supported by the National Science Foundation, SENCER has established a number of formal projects designed to lead to development and implementation of SENCER courses; teams have included more than 2,800 educators, administrators, and students from more than 500 two- and four-year colleges and universities, non-governmental organizations, government agencies, educational associations, informal education venues, and community-based organizations. SENCER also has shared its ideals, programs, and materials with thousands more STEM faculty and academic leaders at symposia, poster sessions, disciplinary society meetings, and other venues. Understanding the study of complex civic issues, said Burns—which involve what June Osborn called “multidisciplinary troubles”—requires a broad, open, and inclusive notion of what constitutes research, basically seeking the widespread application of discovery-based methods in undergraduate education.

General information about SENCER is available at http://sencer.net. Links to examples of community-based research efforts through Regional Centers for Innovation using the SENCER approach are available at http://www.sencer.net/RegionalCenters/aboutthecenters.cfm. Links to examples of SENCER model courses can be found at http://www.sencer.net/Resources/models.cfm.

most biology faculty don't know where it is or how to use it." Biology as a whole also will need to train and incorporate data scientists in research teams to cope with the era of big data, Micklos said (see also National Research Council, 2009). While challenging, successfully making this transition can provide valuable access to freely available data and tools, making it relatively inexpensive to provide research experiences for students.

Virtual Internships to Support Learning

The learning sciences have revealed that "authentic learning" makes a difference in the lives of learners, said David Shaffer, professor in the Department of Educational Psychology at the University of Wisconsin, Madison. Authentic learning combines acquisition of skills, knowledge, identity, values, and epistemology into what he called an "epistemic frame" that can guide practice. Scientists and other people who solve complex problems in communities of practice know how to link their ways of knowing with their ways of doing. And one way they learn how to do this is through practice during their education, whether through residencies, internships, moot courts, design studios, capstone courses, or research experiences. These experiences allow learners to have discussions with their peers and mentors and then reflect on what they have learned and what they have done. "It's this cycle of action and reflection on actions that, progressively through the practicum, builds the "reflection in action" of a mature practitioner." (See also Box 4-3)

Shaffer and his colleagues have used these ideas from the learning sciences to create virtual internships—simulated experiences that give students the opportunity to take action, reflect on that action, and develop ways of thinking about real-world practice. One simulation, for example, lets students play the role of intern at an engineering company that manufactures membranes for dialysis machines. The students conduct research on a material used for filtration membranes given the specifications requested by consultants with the company. They create simulated devices to test the materials and develop a final prototype. In teams, they determine which attributes of the material are most important and prepare a presentation that justifies their design choices. They also can communicate with live design advisers, who model how professional engineers work, help the students when they get stuck, and push them to reflect on their work. The program has been used by students ages 16 to 18 in high school classes and by first-year college engineering students (Shaffer, 2007; Chesler et al., 2013; Arastoopour et al., 2014; Chesler et al., 2015).

Real internships or real research experiences have some obvious advantages, Shaffer acknowledged, including real-world experience and work on immediate problems. But virtual internships offer realistic experiences with tractable problems. Further, in real internships, practice may be compromised and mentoring may be inconsistent, which is not the case in virtual internships. In real internships, Shaffer observed, "you could spend most of your internship doing the conceptual equivalent of washing beakers or test tubes. In the virtual internship, we know that the practice is authentic because we have designed it that way." And, because students are under the supervision of faculty connected with the program, consistency of mentoring experiences are likely less variable. Real internships are also difficult to scale, whereas virtual internships are easy to scale, being available online.

Box 4-3
Vertically Integrated Projects Program: Engaging Innovation Teams

The goal of the Vertically Integrated Projects (VIP) program is to enable undergraduates to participate in and contribute to innovation activities in ways that benefit them and faculty members. The VIP Consortium currently includes 15 colleges and universities with a focus on long-term, large-scale teams of undergraduates working together with graduate students and faculty on a broad array of topics and disciplines. "It's a mechanism that anyone could use to improve your research and education activities," said Ed Coyle, John B. Peatman Distinguished Professor at the Georgia Institute of Technology "Our goal, really, is systemic reform of STEM education."

VIP is free, self-renewing, and constantly evolving with each passing semester. Every undergraduate student has the opportunity to participate in the program for up to three years. Teams are composed of ten to twenty students, with the potential for sophomores, juniors, seniors, graduate students, and postdoctoral fellows all to be involved in a single team. A single faculty member or a group of faculty members leads each team, allowing the faculty to support the students and vice versa. When seniors on a team graduate, the rising students fill their places, and new students are brought onto the team. Returning students train incoming students, offering a mentoring program that is both free and effective (Figure 4-3). Students earn academic credit and are graded each semester, with a credit incentive to participate for multiple years. Teams can persist for years and even decades, increasing the opportunity to develop skills and participate in in-depth interdisciplinary research.

A model VIP course schedule includes a 1.5-hour team meeting each week where reports, plans, and ideas are discussed. Sub-team meetings are scheduled as needed. In the first two weeks of a VIP course, new students are introduced to the concepts of the program and receive additional information about their participation. In weeks three through seven they focus on course modules, and In weeks eight through fifteen concentrate on special projects (Figure 4.5).

Both faculty and students have incentives to participate in VIP programs. Faculty can achieve research goals that they could not achieve without the contributions of students, and they can lead teams that contribute multiple years of research to a single project. The hierarchical structure allows for knowledge, expertise, and function to build and develop with each semester. Faculty members also have the chance to interact with students across disciplines and to identify potential graduate students in their fields.

Students are able to work collaboratively on innovative projects; they learn and master different roles and skills, and they exchange knowledge and ideas with other students across disciplines. While they have an incentive to be on campus, they are preparing for jobs and graduate school work, and they begin to understand the research process. In addition, the consortium provides the chance to work across institutions and share resources, tools, and ideas.

More information is available at http://www.vip.gatech.edu.

"Of course, no one is arguing that we should just do virtual internships," Shaffer said. "Obviously, the best of both worlds is to have both of these experiences. The point is that virtual internships can be a useful tool." Virtual internships can be written for many different contexts, can interface with real instruments and data to provide more real-world experience, and can lead to real-world extensions of the internship that build on a student's new knowledge and skills.

Shaffer provided data on more than 1,250 students who have done virtual internships in engineering and ecology at five universities (Shaffer, 2007; Chesler et al., 2013; Arastoopour et al., 2014; Chesler et al., 2015). Not only did the students tend to learn basic engineering concepts

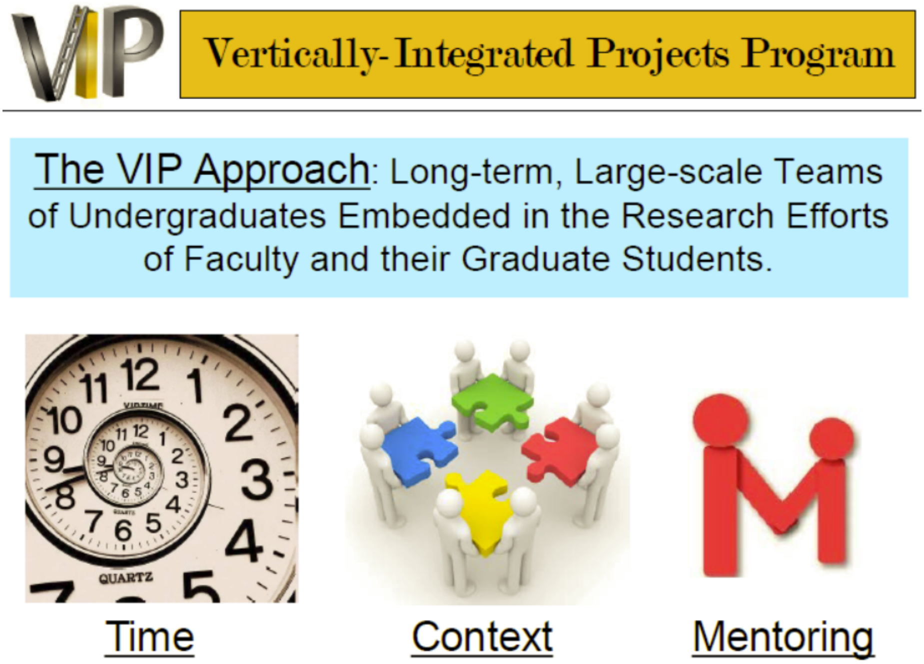

FIGURE 4.3: The VIP model for engaging undergraduates in research (from presentation by Ed Coyle).

better, they also maintained greater commitment and confidence in engineering, especially among the women, than a control group. Students reported positive responses to virtual internships, and the positive responses increased from the first internship to the second.

Because the computer programs used in virtual internships can record every keystroke and every decision made in navigating through the application, they also produce a wealth of data about the actions students take and the connections they make among the skills, knowledge, identity, values, and epistemology of their fields. For example, these data demonstrate that more experienced engineers rely more heavily on data and think more deeply about design considerations compared to novices (Shaffer, 2007; Chesler et al., 2013; Arastoopour et al., 2014; Chesler et al., 2015) The data also are available in real time as students work their way through an internship, allowing for ongoing modifications of the experience.

Finally, Shaffer noted that the development and use of virtual internships can boost collaborations among faculty members, disciplines, and institutions, which in turn can transform the education of students.

Educational Challenges To Leveraging Available Resources

A topic that arose during the discussion session (see Chapter 7 for a full summary of the discussions) centered on whether students should be put to work on a specific research problem or have more open-ended choices about which options to pursue. Speaking of virtual internships, Shaffer pointed to the advantages of having a defined range of options, along with the resources, people, tools, and expectations needed to explore one or more of those options. Typically, such options converge on a specific kind of outcome, he said, though not necessarily a specific answer. The availability of big data sets also creates options for students to pursue, Ryan noted. They can either explore a data set or develop new data to analyze within the context of the larger data set.

Finally, an interesting conversation following this panel centered on Institutional Review Boards (IRBs), which can impose restrictions on education research that make it difficult to gather data from students and therefore assess and develop effective educational interventions. Shaffer pointed out that IRBs can sometimes be overzealous in finding potential dangers in educational research; this is particularly true at universities that conduct medical research. However, exemptions exist for research that takes place as part of an ordinary educational experience. One solution is to educate IRB members about the nature of educational research so that they do not perceive dangers where none exist. A National Research Council committee has studied this problem and has issued recommendations designed to balance respect for the individuals whose consent to participate makes research possible, with respect for the social benefits that productive research communities make possible (NRC, 2014a).

5
Rewards and Challenges of Scaling Up

Important Points Made by the Speakers

- Required research-based courses can help a broad range of students decide whether they would like to pursue further research. (Brownell)
- One-on-one guidance can help faculty members turn their ongoing research projects into research modules for the classroom. (Wink)
- Research-based courses can become powerful recruiting and retention tools for the departments or colleges that offer them. (Wright)
- Universities are facing a variety of economic pressures that can impact the resources available to undertake and scale-up research-based courses, though such courses also can reduce costs by improving retention and graduation rates. (Langford)

A major advantage of course-based research is that it can be scaled up to include most or all of the undergraduates in a department, college, or institution, as well as being disseminated from one institution and adapted by others. But scaling up inevitably generates challenging issues, including student acceptance, faculty buy-in, administrative recognition and support, infrastructural capacity, and funding for the latter. Four presenters in a panel on scaling up course-based research looked at these challenges and demonstrated, through examples and analysis, ways in which they can be overcome. In particular, they focused on opportunities for beginning students, the question of whether research-based courses should be optional or generally required, how to maintain mentorship in a large program, using course-based research to help freshmen adapt to active learning, and the question of scale-up in the context of college's or university's objectives as a whole.

Increasing Diversity and Access through Scale-Up

"When students show up at college, some students know that research exists, some students don't; some students know how to get into research, some students don't: some students have confidence to apply, some students don't; some students have the time in a semester or two to volunteer before they can get access to these experiences, some students don't," said Sara Brownell, assistant professor in the School of Life Sciences at Arizona State University. Faculty members also tend to be selective about the research positions available in their lab, choosing undergraduates who have high grades, prior research experiences, or plans to attend graduate school as selection criteria. When combined with the implicit biases that people tend to have toward the members of certain groups, and the natural hesitation of freshmen to take on additional new things, many undergraduates choose not to participate, or find it very difficult to become

Box 5-1
Preserving the Past: A Research Project for the Community

Tens of thousands of Native American rock art sites in the western United States are at risk of erosion and damage, yet very few have been thoroughly examined or documented. The Rock Art Stability Index (RASI) was created to help preserve these unique cultural and creative records by classifying their condition on a numerical scale with a replicable system. RASI is an easy to learn and cost effective research tool. It can allow crucial pieces of human history to be documented before they are lost forever.

Through a program at Mesa Community College in Arizona, students are using RASI to help answer a fundamental question: which rock art panels are in greatest danger of being eroded away? After a two-day training session, students can assess the severity of damage and the dangers present at a site based on analytical categories that include geological factors, site weaknesses, large and small erosion events, and rock coatings. Conservation is controversial and often underfunded, but RASI provides an inexpensive way to pinpoint and prioritize the specific areas that need the most financial support.

"It's very much within the ability of a first- or second-year college student to learn about rock decay and erosion," said Niccole Villa Cerveny, professor of geography at Mesa Community College. "By presenting geosciences competencies through a cultural context, all students are engaged more deeply . . . [and] minority and female students even more so."

Students have been working with the national parks to analyze cultural resources and score them between 0 and 100, with corresponding colors and verbal descriptions that range from excellent condition to severe danger. The index distinguishes between objective and subjective assessments of a site so that an evaluator can adequately express his or her concerns or observations without affecting the hard numerical data. After an individual site has been assessed, the data are entered into a GIS database to enable a broad and comparative analysis. Students synthesize information from multiple disciplines, including biology, paleontology, meteorology, anthropology, and geomorphology. Students' research enhances the National Park Service's documentation and decision making while introducing the students to field-based science (Figure A).

involved in research. In some cases, a community-oriented research project can overcome this hesitation.

In general, course-based research eliminates these barriers, said Brownell. When students enroll in a course that includes research as part of the normal curriculum, they can engage in research without being selected. In this way, course-based research experiences, either in a small number of high-enrollment courses or in a larger number of lower enrollment courses, can greatly increase both access and equity in research opportunities for undergraduates (Bangera and Brownell, 2014).

As emphasized by many speakers at the convocation, course-based research has a number of benefits that can be widely distributed by scaling up this activity, said Brownell. Course-based research can increase collaboration among students, which can have a multiplier effect on the benefits they receive from the actual conduct of research. In addition, students gain experience with the procedures, data, and outcomes of research. Students may eventually be co-authors on papers generated as part of their course-based research experiences. In this respect, an even more important outcome, argued Brownell, is the increased potential for faculty members to publish papers with student input. In this way, faculty members can be rewarded for their involvement in

FIGURE A: Students and faculty undertaking anthropological research (from presentation by Niccole Cerveny).

As of the convocation (in May 2015), more than 100 undergraduates had participated in the program. Four continued on to graduate school, and four changed their major to geoscience after working in the field. Students were able to work with five graduate students, an Arizona state climatologist, and seven park rangers in their research. Five of the students co-published articles, and two presented their findings nationally. This interdisciplinary field-based research is clearly an effective pedagogical tool for engaging introductory level students.

More information is available at http://alliance.la.asu.edu/rockart/stabilityindex/RASI_Overview.html.

course-based research through traditional mechanisms, as publications improve prospects for tenure and promotion.

As an example of how course-based research can be scaled up to include large numbers of students, Brownell described the redesign of introductory biology courses at Stanford University. Today, every biology major or pre-medical student at Stanford takes two courses that feature research. In one of these courses, students use yeast as a model system to explore functional defects in the p53 protein, which is mutated in more than half of human tumors. Students are assigned a mutant version of p53 that has a single point mutation, and they work with a partner to characterize this mutant over the course of ten weeks. Students who are working on the same mutant come together in discussion groups to share their data and talk

> *"When students show up at college, some students know that research exists, some students don't; some students know how to get into research, some students don't: some students have confidence to apply, some students don't; some students have the time in a semester or two to volunteer before they can get access to these experiences, some students don't."*
> *Sara Brownell, Arizona State University*

about what they are finding, so that their individual sets of data contribute to a common pool of data that everyone uses. They talk about outliers, troubleshooting, lab procedures, and other aspects of their work. This course is now being studied, Brownell said, to determine how it affects "cooperative scientific thinking" in students (Brownell et al, 2015). The fact that all students in the major participate means that all have some experience as a basis for deciding whether they would like to pursue further research, and some knowledge of how to access further opportunities.

Scaling Up in Beginning Chemistry Courses

Scaling up has also been a major concern of the Center for Authentic Science Practice in Education (CASPiE), which has been supported through the Chemistry Division of the National Science Foundation.[18] To involve much larger numbers of first- and second-year students in research, CASPiE has experimented with the idea of undergraduate research centers. Five such centers have been funded so far, said Don Wink, director of graduate studies and professor and director of undergraduate studies in chemistry at the University of Illinois, Chicago: one at his institution and four others at Ohio State University, a group of colleges in the northern plains, the University of Texas, Austin, and a group of community colleges in the Chicago area.

> *"There is a human element that is important and time consuming. It has to be paid attention to, because you won't succeed at implementing these [research modules] without all of those people being on the same page." —Don Wink, University of Illinois, Chicago*

The overall goal of CASPiE has been to develop, implement, and evaluate a course-based model of undergraduate chemistry research for first- and second-year students. It has pursued this goal by developing laboratory experiments using discovery-based research modules, providing access to research-level instrumentation networks, and creating a community environment for research groups. Modules have been authored by researchers in the program based on their current research interests and reviewed by faculty members involved in their implementation. The experimental design has been improved through an iterative cycle, and the resulting research lab was implemented within existing programs, with support for remote instrumentation if needed.

To develop their capacity to undertake the required work while they are being introduced to the research, students participate in a three-week skill-building curriculum that covers the materials, equipment, and procedures they will be using. They do three to four weeks of research while learning what is known and not known on the problem under study from the scientific literature. They also receive suggestions for research directions, which often incorporate findings from previous courses.

Research modules that have been developed include investigations of the following topics:

- Ion sensors using surface protection/deprotection
- Antioxidants in foods

[18] More information about CASPiE is available at http://www.purdue.edu/discoverypark/caspie/.

Box 5-2
A Scaffolding Approach for Undergraduate Biology Using Yeast

North Carolina Central University, which is located in Durham, North Carolina, near Research Triangle Park, is one of the 16 state-supported institutions in North Carolina. A master's degree-granting institution known for its strength in biomedical, biotechnical, and pharmacological research, the university has about 6,400 undergraduates, 29 percent of whom are first generation college students, 65 percent of whom are eligible for Pell Grants, and 78 percent of whom are African American. The biology department is the largest of the five science departments, with 400 majors.

In 2010 the department began a curriculum revision designed to expose students underrepresented in STEM fields to authentic research experiences as part of an effort to improve STEM retention rates. It revised its three introductory biology courses to provide a research experience for all biology majors, and enhanced faculty members' teaching to ensure effective implementation of this innovative curriculum. In all three courses, students are introduced to basic research methods, including the application of the scientific method, measurements, micropipetting, and practical lab skills. When students are proficient with standard research methods, they apply their skills in investigations focused on yeast. In the first introductory course, they engage in genomic comparisons and assessment of phylogeny; in the second they work on fermentation and metabolism; and in the third they examine gene expression and the molecular biology of the cell. At the end of their research, students are expected to submit lab notebooks for evaluation and deliver oral presentations.

Students were "more engaged, more inquisitive, actually talking about science outside of the lab," said Gayle Hallowell, associate professor at the university. "There is a sense of ownership that our students have about taking pride in their work."

Including research experiences in the classroom has increased the number of students who have continued onward in the biology track. Student performance, as measured by grade point averages, has gone up, and self-reported learning gains have increased. Future goals are to use the program as a gateway to independent research experiences and to expand course-based research in upper-level biology courses and other introductory science courses.

More information is available at http://www.phdavid.com/documents/McDonaldCUREnet2014.pdf.

- Solid-phase organic synthesis
- Band-gap tuning of ZnO_x films for solar cells
- The enzyme system in dairy products
- Lipids and fatty acids
- Biodiesel from waste fats
- Small-molecule antiviral drug discovery
- Analysis of NO_x from bio-derived diesel

As Wink pointed out, these modules fit within a typical chemistry curriculum in the first two years of college.

Several of these modules have resulted in scientific publications based on work done by students. For example, a paper on biodiesel catalysis done at Northeastern Illinois University in Chicago represented work that could not have been done without student involvement, which in turn becomes a major benefit for the faculty who are involved with this project (Curtis-Palmer et al., 2009). Similarly, research on on-bead reduction of carbon double and triple bonds resulted in a publication (Dickson et al., 2009), as did research on solid-phase biosensors (Jaganathan et al., 2010; Richards et al., 2010) and adhesion (Valentin-Rodriguez et al., 2011).

Wink described several challenges in scaling up this approach. The first involves creating a sense of collaboration among undergraduate students, graduate students, and faculty members. CASPiE has used peer-led team learning (PLTL, e.g., Gosser et al., 2001) to introduce students to keeping good laboratory records, reading the literature, research ethics, interpreting data, and making presentations. The peer leader facilitates two three-student teams simultaneously, moving back and forth and sometimes bringing the groups together. Peer leaders are not involved in grading, but can help guide the research. They have not always been familiar with the research topic, which has created challenges, said Wink, but they have provided the sense of having an expert nearby with whom to consult.

The CASPiE model has required one-on-one guidance to help faculty turn their ongoing research projects into researchable modules for the classroom. In addition, faculty members and teaching assistants have needed professional development sessions to help them understand the different roles they are expected to play with students. Their role in the grading process has also shifted, because they are now looking for different kinds of evidence of learning and providing different kinds of feedback. "There is a human element that is important and time consuming," said Wink. "It has to be paid attention to, because you won't succeed at implementing these [research modules] without all of those people being on the same page."

Another challenge has been generating enough data for publications. If first- or second-year students do research three hours a week over the course of eight weeks, they will put in 24 hours. But a third- or fourth-year student doing research might devote 320 hours to a summer project or 150 hours to a 30-week academic year project. By the time a first- or second-year student is up to speed and doing experiments, it can seem as if the semester is almost over. However, the many students involved can increase the amount of data generated.

A third challenge involves scale-up in the larger community. CASPiE has been scaled up through partnerships with two-year colleges, predominantly undergraduate institutions, research universities, and international institutions; it has now been implemented at 19 institutions and has involved more than 6,000 students. The research modules have been used for projects for high school science fairs, for professional development for high school teachers, and as an introduction to university science for promising high school students. The organizational strategy has also has been extended to other disciplines, such as the atmospheric sciences and biology. Each of these extensions of the program involves training K-12 and undergraduate faculty members, providing equipment, and managing the new program.

"It was the simplicity of the idea followed by the depth of the development work we did that made people say, 'Oh, that's what I should do.'"
—Don Wink, University of Illinois, Chicago

As Wink pointed out in response to a question, CASPiE was designed to be adaptable, which is one reason why so many other institutions have adopted the model. "It was the simplicity of the idea followed by the depth of the development work we did that made people say, 'Oh, that's what I should do.'" The resulting program may look different from the original, but the model is the same.

Finally, just as the program needs to be scaled up to have a widespread effect, it needs to be scaled down when a research project is over. A hallmark of research is that it comes to an end as questions are answered and the research heads in new directions as new hypotheses are developed, said Wink. Three of the original modules have ended as sources of original research results. The ZnO_x and biodiesel modules are now available as traditional inquiry laboratories. The solid-phase synthesis and acid-catalyzed biodiesel synthesis projects ended after results were published. Thus a sustainable model requires constant generation of new research problems.

Transitioning Into Early Course-Based Research in the Biological Sciences

The Nature of Life project[19] is essentially a course-based research experience in the College of Biological Sciences at the University of Minnesota, said Robin Wright, professor of genetics, cell biology, and development at the University of Minnesota, Twin Cities. It is a required, two-year, two-credit course that starts in the summer before the students' first year at the university. Because it is required, it supports equity of opportunity for all incoming first-year students. An analogous Nature of Science and Research course is available for transfer students. Together, the courses and their associated follow-on research experiences demonstrate how large numbers of students at an institution can be involved in these kinds of discovery-based activities. (For another approach to introducing students to research early in the academic careers, see the description of the Freshman Research Initiative in Box 5-3.)

For first-year students, the course begins at the Itasca field station near the headwaters of the Mississippi River. A course fee covers transportation, room and board, and supplies, while tuition fees cover staff time and small honoraria for participating faculty members, which makes the course sustainable. At the field station, students work through active learning modules, interact with peer mentors, learn university traditions, and engage in research. Goals of the course include developing students' identity as scientists, building a peer and student-faculty community, and learning about opportunities in the College of Biological Sciences and elsewhere in the university. "Before they even walk onto campus, we're talking to them as if they are emerging professional biologists, and we treat them as colleagues," said Wright.

During their first year, students work collectively on a project called Biology Saves the World. They also develop time management skills and graduation plans, meet with professors during office hours, and choose a major. During their second year, they take workshops on such subjects as career plans and work in "engagement labs"—small group research projects. Academic advisers are involved throughout the two years, and peer mentoring is critical, Wright said. In particular, putting at-risk students into

> *"Before they even walk onto campus, we're talking to them as if they are emerging professional biologists, and we treat them as colleagues"*
> *—Robin Wright, University of Minnesota, Twin Cities*

[19] Additional information is available at https://www.cbs.umn.edu/explore/departments/btl/academics/nol-series.

Box 5-3
The Freshman Research Initiative at the University of Texas at Austin

The Freshman Research Initiative (FRI) at the University of Texas at 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. The goals of the program are to:

- Engage large numbers of students in authentic and publishable research
- Engage students in research early to attract and retain them in science
- Improve undergraduate academic success, scientific literacy, and critical thinking skills
- Create an environment in which the effects of research training can be assessed
- Bridge the gap between education and research by using research as a vehicle for teaching
- Drive curriculum reform at the college and university levels
- Enhance collaborations that promote education through undergraduate research

The three-semester program provides integrated coursework and laboratory research in newly renovated, dedicated research labs. After training in research methods and lab techniques, students choose one of many research streams, each if which draws from a faculty member's body of work. Students work in a team of 30 to 40 undergraduate researchers per faculty-led group under the supervision of a research educator, who is a Ph.D. scientist occupying a non-tenure-track position, a hybrid between a research appointment and a teaching position. The research educator meets regularly with the research team of undergraduates to provide mentoring and research momentum and manages each lab on a daily basis, focusing on both the education of the students and the quality of the science. Students learn techniques as a team but have their own independent projects that can lead to publishable contributions to science. At the time of the convocation, more than 150-peer-reviewed publications with student co-authors had emerged from the initiative.

"The philosophy behind this program is that we are taking down the brick wall that existed between teaching and research, where there were often the same people on each side of the wall wearing different hats, and merging those roles, so that the PI and the professor are the same person, the postdoc and the research educator are the same person, and the student is a research assistant," said Sarah Simmons, who is now a senior program officer at the Howard Hughes Medical Institute and was the former director and co-founder of the program. "This freshman-year experience allows students to have a jump start and engage [with biology] in ways that they couldn't otherwise."

From 45 students in 2005, the program expanded steadily to more than 800 in 2014 (out of approximately 2,000 incoming freshmen). Assessments of the program have shown that 35 percent more students graduate with a science or mathematics degree from the pool that participated in FRI (Figure A). A

leadership positions is extremely useful, she added. "We're trying to create a fabric in which every student is embedded, and if there's anything bad that happens or anything good that happens, people will know."

The required Nature of Life program unexpectedly has become a powerful recruiting tool for the College of Biological Sciences. "It has turned into a signature program for our college that sets us apart from any other place that [students] could be thinking about." In 2003 the college had 1,326 applicants and matriculated 350. In 2014, the college had 8,100 applicants and matriculated 550 students. First-year retention in the college has increased from 90 percent to 98 percent. Over the same period, the four-year graduation rate for the students who have participated has gone from 50 percent to 75 percent. These outcomes are thought to derive in part quarter of the students entering the program are Hispanic, and participation in FRI more than doubles the graduation rate for Hispanic students. The program improves performance in mathematics and science, as measured by third-year grade point averages. Among the students who entered FRI in 2006, 32 percent went to graduate school, compared with 9 percent of students college-wide.[a]

More information is available at https://cns.utexas.edu/fri.

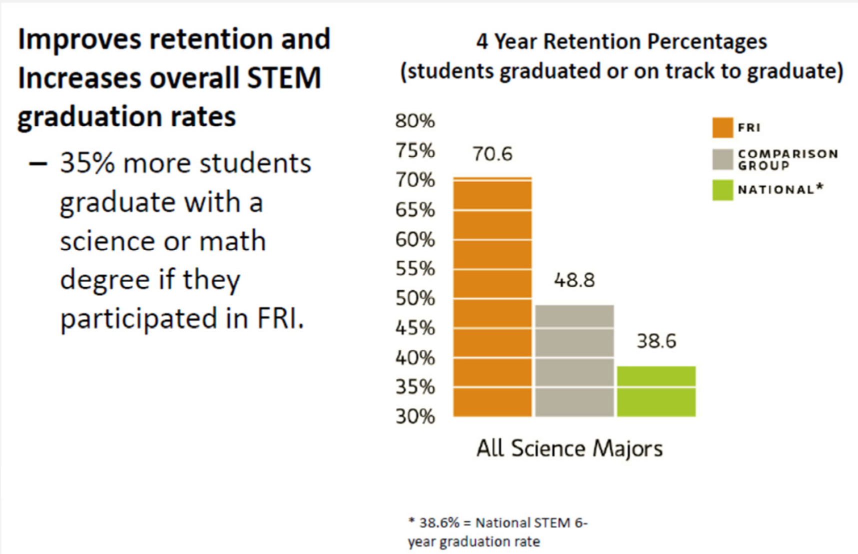

FIGURE A: A comparison of retention among students who were enrolled in the Freshman Research Initiative at the University of Texas, Austin, vs. a comparison group at that university and national statistics. The data shown here are from the 2007 cohort. The 35% increase in retention rates is from the program averaged over all cohorts through 2015. From presentation by Sarah Simmons.

[a] In personal communication with Dr. Simmons, she indicated that the FRI has attempted to measure gains in academic success, scientific literacy, and critical thinking skills, but has not been able to develop assessments to do so successfully to date. However, additional efforts are underway and assessing these aspects of student learning remains an important goal of this initiative.

from the positive impact of the program features, but also to reflect increased recruitment of interested students.

Faculty participation also has increased dramatically over time. Faculty can bring their children to the field station, which enables new students to see them as more than professors. “[Getting] faculty buy-in has been easy,” said Wright.

This program for the first two years is a lead-up to the college’s year-long Foundations of Biology discovery research experience. Research projects take place in eight-student teams. The projects are under the direction of a team leader, a research mentor, and a faculty research

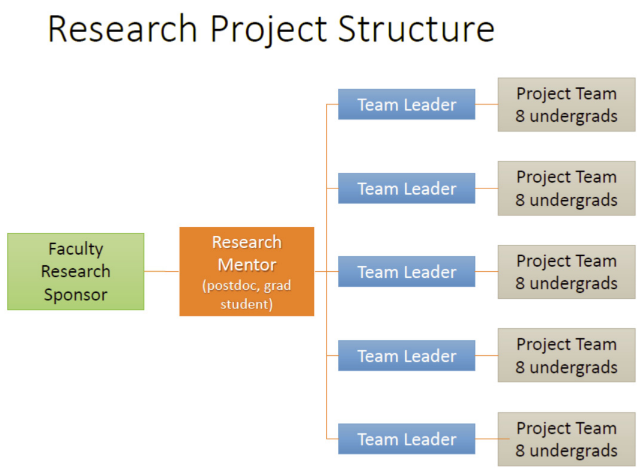

FIGURE 5-1: Organizational structure for the research projects within the Two-Year Program in Biological Sciences at the University of Minnesota, Twin Cities. From presentation by Robin Wright.

sponsor, and research topics range widely across the biological sciences (Figure 5-1). In this way, said Wright, biological sciences majors start confident and end confident. She also said that surveys have revealed just one predictor of students leaving the college: not feeling that they are valuable members of the college. For students identified to be at risk, the college provides extra supports. The student experiences change the relationship the students have with learning and pay dividends not only for the students but for faculty members as well.

> *"Universities are having to operate with an income that is less than what it actually costs to run the institution, and that's true for both state and for private institutions."*
> *—George Langford, Syracuse University*

Economic Pressures on New Models

Universities are facing a variety of economic pressures that inevitably influence the resources available to undertake and scale up new initiatives, including course-based research, observed George Langford, Distinguished Professor of Neuroscience and Professor of Biology and former Dean of Arts and Sciences at Syracuse University. At the top of the list of concerns is the affordability of college for students. Average tuitions have been increasing faster than the rate of inflation, which has exerted pressures on universities to cut costs or find other sources of revenue. At private universities, the average annual total for tuition, fees, and room and board now exceeds $42,000, and the average in-state total for public universities is approaching $20,000 per year. "There's real sticker shock when you see these numbers," said Langford.

Yet tuition represents the primary source of income at many colleges and universities, and it is virtually the only source of income at institutions that lack large endowments or other sources of support. Furthermore, the average annual percentage increase in inflation-adjusted published tuition and fees for colleges has been falling in recent decades—from 4.0 percent in the decade centered on 1990 to 2.2 percent in the decade centered on 2010 for private nonprofit four-year

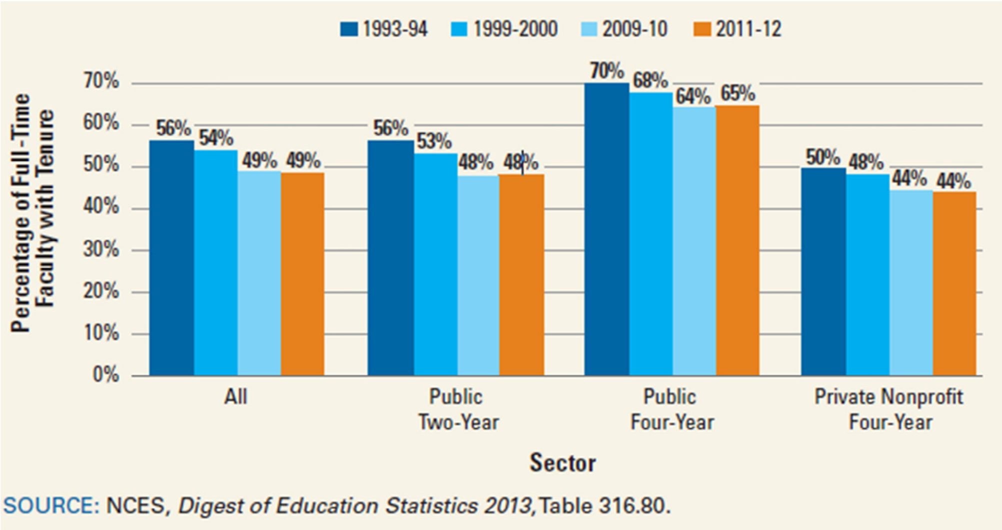

FIGURE 5-2: Percentage of Full-Time Faculty with Tenure at Institutions with a Tenure System, 1993-94, 1999-2000, 2009-10, and 2011-12 (College Board, 2014, p. 40)

colleges, from 4.4 percent to 3.5 percent over the same time period for public four-year colleges, and from 4.6 percent to 2.5 percent for public two-year colleges. This annual increase in tuition is less than the increase in the cost of higher education today, said Langford. "Universities are having to operate with an income that is less than what it actually costs to run the institution, and that's true for both state and for private institutions."

In addition, the net revenues to colleges and universities from tuition and fees have grown much less than the published amounts because of the increasing levels of financial aid that institutions are making available to students, with a substantial decline in net revenues following the recession that started in 2008. "This has put a lot of pressure on institutions to figure out how to continue to run their educational programs," Langford said.

Meanwhile, enrollments have increased at all types of institutions since 1995, with slight declines only at two-year public colleges and for-profit colleges following the recession. Furthermore, colleges are becoming increasingly diverse, with more underrepresented minorities and international students enrolling. The increases in enrollments, as well as increasing interest among all groups in taking STEM courses are putting strains on these courses in a number of disciplines, said Langford.

At the same time, the number of tenure track faculty positions has been stagnant or has slightly declined. The percentage of full-time faculty with tenure at institutions with a tenure system fell from 56 percent in 1993-94 to 49 percent in 2011-12 when averaged for all institutions (Figure 5-2). This reflects the fact that institutions have relied more heavily on non-tenure-track and part-time or adjunct instructors to increase instructional capacity. Governing boards and legislators also have been asking institutions to look for efficiencies by using a variety of mechanisms such as online learning activities or virtual labs, or by sharing prominent faculty members across campuses through electronic means.

Box 5-4
The Community College Undergraduate Research Initiative

The Community College Undergraduate Research Initiative (CCURI) aims to expose students to real world science through hands-on research experiences. Using an inquiry-based teaching model, students take an introductory course where they are taught basic scientific procedures while investigating a specific case study. Mathematics is fully integrated into the course work, and students are encouraged to explore their questions with faculty members and peers. Students then work together to investigate questions developed from the case study, either as a CURE (course-based undergraduate research experience), a SURE (summer undergraduate research experience), or a PURE (program undergraduate research experience, stretching over a longer time period). Students have an opportunity to pursue their research work into the summer or for a second year, and in their second year they also have the chance to continue their research independently.

CCURI emphasizes the development of faculty skills and networks. "Community colleges are often very isolated, and [faculty members] don't have networks of professionals to work with on a regular basis," said James Hewlett, professor of biology at Finger Lakes Community College in New York. "They have heavy teaching loads, committee work, and so many duties that they're overburdened. They don't have time to meet. Their need is professional networks." Networks help community college faculty connect to other professionals at research institutions, allowing them to bring novel research questions to their students. Students also are able to connect to undergraduates at other institutions, creating avenues for transfer to four-year institutions. "A quarter of the research that's ongoing at our partners came from some other partner, so there's a lot of sharing going on," Hewlett observed.

CCURI represents about 50 two-year schools across the country. Many of the partners have modified previously existing CURES, a third have created a novel course, a third have implemented a PURE, and 22 percent have implemented a SURE. From an initial investment of $24,000, the economic impact of the initiative has been estimated at $1.2 million.

Graduation rates for students who participate in CCURI courses have risen by 13 percentage points,

Course-based research experiences entail start-up, operating, and scale-up costs, Langford observed. One-time costs include things like space renovation, equipment, faculty release time to design the new courses, and faculty professional development to assist in the process. Ongoing costs include supplies and personnel, whether instructors, staff, or teaching assistants. The cost of course-based research experiences compared with a standard laboratory course is difficult to determine, Langford said. Per student, they tend to cost less than internship-style undergraduate research experiences in the laboratories of individual faculty members. Also, the added benefits of higher persistence and improved student outcomes may offset any additional costs, he said.

A key question for course-based research is whether it can be started and scaled-up without adding to the costs of a college education at the current level. The convocation has provided many examples of cost-effective research-based courses, Langford observed. Also, other options for funding may be possible. Some costs may be appropriately allocated from the research grants supporting faculty members' research programs. Funding agencies may be

> *"The added benefits of higher persistence and improved student outcomes may offset any additional costs."*
> *—George Langford, Syracuse University*

from 24 percent to 37 percent, which is more than 10 percentage points higher than the national average. Students participating in research had a completion time of 3.9 years to obtain a degree versus 5.3 years for students who did not participate in research. Students also reported (in surveys) a variety of additional benefits from CCURI participation, including increased confidence in laboratory skills, increased job opportunities, increased scholarship support, an increased desire to take more science courses, an increased desire to transfer to a science program at a four-year college, and an increased interest in pursuing science after college (Figure A).

More information on the CCURI is available at http://www.ccuri.org/content/home.

Benefits of UR?

Metric	Result (Nat avg ~ 26%)	
Graduation Rate (pre/post research experience)	Before	24%
	After	37%
Graduation Rate (research vs. non-research students)	No research	35%
	Research	47%
Completion time	No research	5.3 yrs to degree
	Research	3.9 yrs to degree

I enrolled in additional science courses *because* of my research experience	40.9%
I plan to transfer to a science program at a 4-year college *because* of my research experience	36.4%
I am much more confident in my laboratory skills	81.8%
Research gave me an internship or employment opportunity that would not be available without it.	36.4%
My research experience helped me obtain scholarship support	22.1%
I have plans to continue my education in science beyond a four-year degree *because* of my research experience	13.1%

FIGURE A: Data on potential benefits of undergraduate research for students enrolled in community colleges. Data on the right represents all students surveyed in a pre-post design from 6 partner CCURI institutions (pre-post experience in a CURE). From presentation by James Hewlett.

willing to support student research projects. Institutions could rely more on philanthropy and use their development offices to direct more funding to these kinds of programs. Corporations also could play a larger role in funding these activities though such mechanisms as outsourced open innovation funding for research and development.

Another potential source of support can come from the generation of additional cost savings as a result of course-based research projects. For example, McDonald stressed during her presentation (summarized in Chapter 3) that the “Campus as a Living Lab” initiative began when budgets for support of higher education were shrinking rapidly in that state. The projects that McDonald described in her presentation have generated results that save the campus physical plant money.

Similarly, Cathy Middlecamp, University of Wisconsin, Madison, noted that her interactions with the physical plant and dining services on her campus are also resulting in lowered costs based on outcomes such as reduced food wastage. The university, in turn, has agreed to devote part of those savings to supporting and expanding these course-based research initiatives.

Thus, while costs are involved, particularly during ramp-up, creative solutions are possible, not only using conventional revenue streams but also by recognizing the value of the research accomplished. If this results in more effective accomplishment of an institution's overarching goals such as recruitment, retention, and graduation, undergraduate course-based research can be very cost-effective, Middlecamp noted.

Required Versus Optional Courses

During the discussion period, the panelists turned their attention in part to the advantages and disadvantages of requiring research-based courses, as opposed to offering them as optional classes. Sarah Elgin pointed to research results suggesting that research-based courses have greater impact on students when they are optional rather than required (Brownell et al., 2013). In response, Brownell observed that this research relied on students' self-reports and that students who choose to do course-based research are likely to be more motivated on average than a more broadly based sample of students. Required courses also can have a widespread impact, but self-reports may not be the best measure of that impact. Brownell also noted that essentially everyone who wants to have an independent research experience [in their "apprentice-style" program] at Stanford can do so. About 80 percent of the undergraduates take advantage of this opportunity. Thus, the only lab courses offered by the Department of Biology are the two required introductory labs, in which students are introduced to research; upper-level students have many opportunities to work directly in research labs.

The issue also hinges on the expectations an institution holds for faculty members, several panel members said. Faculty members oriented more toward teaching (including faculty members at two-year colleges) may not have incentives to publish the research they do with their students. However, research-based courses that are straightforward to implement can spark the interest of faculty members and other instructors in doing more research. Community colleges also tend to have closer ties to nearby companies than do most other colleges, and these connections can lead to opportunities for research.

6
Institutional Strategies and Funding Structures

Important Points Made by the Speakers

- Department chairs, deans, and other administrators can advance research-based courses through such actions as support for faculty development, promotion of equity in salaries and workloads, clarification of tenure and promotion guidelines, and efforts toward the establishment of endowments and special funds. (Byrd)
- Major curricular reforms provide opportunities to rethink the integration of research into undergraduate education and to retool the reward system for faculty. (Ellis)
- The construction of new instructional spaces also offers opportunities to change the culture of teaching and learning. (Jungck)
- A diversity of programs can involve students with different needs and expectations in research experiences. (Beise)

In addition to faculty members and students, STEM departments and institutions are critical determinants of success in course-based research. Institutional commitments can take many forms, and the durability of these commitments, despite administrative turnover, helps determine the sustainability of programs to bring research to much larger numbers of students. A final panel at the convocation looked at the role of institutions in fostering change. Issues the speakers covered included the faculty reward system, learning goals for students, design of the learning environment, and institutional commitment to involving students in research at scale.

Changing the Culture of an Institution

The College of Arts and Sciences within North Carolina Agricultural and Technical State University, which is a historically black university located in Greensboro, North Carolina, has an undergraduate enrollment of more than 3,000 undergraduate students and 250 graduate students, with more than 10,000 students in the university as a whole. By involving many more of the students in the College of Arts and Sciences in course-based research, said Goldie Byrd, professor of biology and dean for the College of Arts and Sciences at the university, institutions like North Carolina A&T can help diversify both STEM education and the STEM professions.

As at other colleges and universities, the faculty at North Carolina A&T are rewarded on the basis of their teaching, research, and service. To change the paradigm for undergraduate research, this reward structure has to be addressed, said Byrd. In particular, faculty members will ask whether involvement with course-based research will distract from their research productivity. At the same time, many colleges and universities are dealing with lower instructional expenditures per student, reduced research funding, lower salaries, and heavier teaching, advising, and service responsibilities.

Administrative concerns are another potential barrier, said Byrd. All administrators may not recognize the importance of national imperatives such as those laid out in the PCAST report (see Chapter 2). Many upper level administrators, including deans of arts and sciences, have not been trained in STEM disciplines. As a result, they may be less willing to consider changes in the STEM curriculum than faculty members in those areas, Byrd said.

There are a variety of ways to educate administrators about the significance of undergraduate research, including providing case studies, publicizing the results of pilot projects, holding campus symposia, and initiating frank discussions. Faculty achievements can be emphasized to administrators, such as national awards or other recognition, the products of sabbaticals, or participation in national convenings. "If we want to make a cultural or paradigm shift in this area, then we have to get buy-in all the way from the bottom to the top," Byrd said.

The actions of departmental chairpersons can be particularly influential. They can lead important conversations and initiatives; be effective advocates for faculty; assure equity in salaries, workloads, and opportunities for leadership; clarify tenure and promotion guidelines; write mentoring letters; and engage in and lead collaborative writing.

The restructuring of a department's courses allows faculty to create initiatives that they care about, Byrd observed. For example, restructuring can allow for campus convocations where faculty members discuss course-based research initiatives of interest. Short summer sabbaticals for faculty to visit institutions where course-based research programs are underway can create opportunities for course design and the creation of materials, modules, and assessments. At North Carolina A&T, "success faculty" who are hired to support students' matriculation, research, and overall academic achievement have been hired in biology, chemistry, physics, mathematics, and English. Grants personnel assist faculty members with pre-award and post-award responsibilities. A director of assessment helps evaluate course-based research and how these programs integrate with other undergraduate experiences.

Deans can help by making faculty development a priority. They can put in place strategic plans that emphasize diversity and equity, develop proposals that include faculty development, help establish endowments and special funds, and support special awards and opportunities for international travel. North Carolina A&T, for example, has created an alumni-based endowment to support faculty development. In addition, deans can create opportunities for faculty to develop leadership skills and make available assistance for chairs, formal mentoring programs, targeted hiring practices, and clear policies for evaluation, promotion, and tenure. In that respect, North Carolina A&T looks for faculty members who will engage in scholarship on teaching and learning, not just in laboratory or bench work.

North Carolina A&T has created two new positions: an associate dean for faculty and student success, and a director of assessment (see above). It also has created an innovation fund at the college level. To date, 13 collaborative projects have been funded that aim to enhance student success, including course-based research. In addition, the college has received a $2 million gift from the GlaxoSmithKline Foundation to create a STEM Center of Excellence for Active Learning, which is engaged in course redesign, community building, faculty development, and organizes an annual symposia.

Byrd concluded with several take-home points derived from her experiences. Faculty buy-in is critical, she said, as is administrative awareness and support. Targeted hiring and awards along with faculty and student development can create an environment for success. Tools and teams that work best for a given institution's culture need to be developed, she said, with a repository of best practices and readily available tools. Centers and institutes allow for collective thought, and a culture of assessment and evaluation can spur progress. Funding can support broadening participation among diverse groups, with key partnerships across campus contributing to this goal. Finally, national debates and conversations should be inclusive, Byrd said.

Utilizing a Discovery-Enriched Curriculum for All Majors

> *"What we decided to do with the DEC was to say, very simply, that we want every student—and there are on the order of 11,000 undergraduates at the university—to have the opportunity to make original discoveries."*
> *—Arthur Ellis, City University of Hong Kong*

In 2012, all of the publicly funded universities in Hong Kong were planning to transition from a three-year curriculum to a four-year curriculum. Arthur Ellis, who was formerly with the University of Wisconsin at Madison; University of California at San Diego, and the National Science Foundation, moved to City University of Hong Kong as provost to help lead the change. "It was almost a blank slate, [allowing us] to think about a completely different kind of curriculum and a completely different kind of accountability system," he said.

The centerpiece of the change accomplished was the development of the Discovery-Enriched Curriculum (DEC),[20] which Ellis said addresses a pair of grand challenges in higher education. It helps motivate students by integrating research and education on a large scale, and it helps motivate faculty by aligning rewards with performance. It aims toward the highest levels of Bloom's taxonomy,[21] which involve creating something that an expert in a field would validate as an original and valued contribution to that field. "What we decided to do with the DEC was to say, very simply, that we want every student—and there are on the order of 11,000 undergraduates at the university—to have the opportunity to make original discoveries." Such experiences will help students prepare for the unscripted circumstances they will face for the rest

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[20] Additional information is available at http://www.cityu.edu.hk/provost/dec. Selected awards and examples of intellectual property that have been generated by this initiative are described at http://www.cityu.edu.hk/provost/dec/DEC_awards.htm.

[21] Bloom's taxonomy sets out cognitive, affective, and psychomotor learning objectives that instructors have for students. In the cognitive domain, these objectives include knowledge, comprehension, application, analysis, synthesis, evaluation, and creation of new knowledge.

> *"The best knowledge and experts available today can be found online. But what you can't find on the web is the next knowledge, the knowledge that hasn't been created yet. Higher education is uniquely positioned to fill that [need] as we prepare our students."*
> *—Arthur Ellis, City University of Hong Kong*

of their lives, said Ellis. Students both master existing knowledge and skills, and understand what it takes to create new knowledge, communicate it, curate it, and cultivate it to benefit society.

The DEC was designed as much for the faculty as students, Ellis said. The initiative was intended to energize faculty members and to spur innovation. The year before the transition, for example, faculty members went through every major and every course and listed the attitudes, abilities, and accomplishments they wanted that major or course to inculcate.

Students are told when they first came to the college that they are expected to create intellectual property. They each receive a brochure describing their rights and responsibilities related to intellectual property and academic honesty. Then, in their first years, students identify a research question to explore. They have access to discovery labs with 3D scanners and printers, interactive tabletops, robotics, and other tools. The faculty also have a free hand in providing them with opportunities for discovery.

One group of students designed equipment for fruit fly research and applied for a registered design in Hong Kong and a patent in the United States. Another designed a pointing device for interacting with touch-sensitive devices, received venture capital from the government, and formed a start-up company. "We're seeing all kinds of interesting opportunities," said Ellis.

The initiative emphasizes interdisciplinary work, with an emphasis on the arts as well as STEM fields. Students have created cross-disciplinary teams via social media, resulting in about a hundred proposals for interdisciplinary projects. As an example, Ellis cited a project involving about two dozen students who traveled as part of interdisciplinary teams to Antarctica to collect data and then, in the following semester, created artwork from their data to illustrate sustainability issues in the region.

To align the faculty reward system with individual and collective performance, the university created an annual performance-based pay review for determining salary increments. In addition, allocations to departments reflect their collective contributions in education, research, and management. Departments get a kind of report card with data on where they are doing well and where they need to improve. Individual salary increments for faculty members reflect contributions to education, research, and service determined through bottom-up and transparent processes. If faculty members contribute to the desired changes, their salaries go up more than if they do not. "This has created a culture of accountability at the university, and it has helped to support the DEC," Ellis said. [22]

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[22] In a personal communication, Dr. Ellis indicated that the most effective tool for change has been a reward system that provides tangible rewards for both individuals and departments that help to advance the DEC. Positive outcomes have also helped to overcome initial skepticism on the part of many faculty.

Ellis concluded by observing that higher education is at a tipping point. The best knowledge and experts available today can be found online. "But what you can't find on the web is the *next* knowledge, the knowledge that hasn't been created yet," said Ellis. "Higher education is uniquely positioned to fill that [need] as we prepare our students." (See also Box 6-1.)

Learning Environments that Support Sustainable Student Success

> *"If we really believe that students are researchers, we have to mean that more seriously—that they are not just our research assistants but the creators and leaders of tomorrow." —John Jungck, University of Delaware*

In 2012, John Jungck, who is now the director of the Interdisciplinary Science Learning Laboratories for the University of Delaware, was invited to the university to help create an environment that would support sustainable student success. A three-building complex, with two buildings devoted to education, was designed to support the integration of biology, chemistry, and physics while institutionalizing problem-based learning.[23] Previously, faculty members were accustomed to teaching in lecture halls, the graduate students were used to teaching in labs and basements, and peer-led instruction occurred elsewhere. The construction of a new building complex provided an opportunity to bring these activities together, rethink them, and begin to change the culture of teaching and learning.

The Interdisciplinary Science Learning Laboratories can be "home" for students for a significant part of their first year. Professors, graduate teaching assistants, and undergraduate peer leaders are all in one place. Students participate in multiple learning activities there, including lectures, discussions, problem-solving sessions, wet laboratories, and public presentations. They can take advantage of graduate teaching assistants' office hours, visit a drop-in informal learning center with free tutoring, or check out supplies for informal group learning in lounges spread throughout the building.

The new labs are set up to it make it easier to do investigation, analysis, presentation, and peer review than to do "cookbook" procedures, lectures, and recitation. In a high-tech, high-touch approach, the furniture, technology, and space all support student engagement. Labs have mobile chairs that support laptops and can be clustered together, writeable walls, digital video microscopy, and real-time data acquisition to wall monitors. The rooms do not have fronts and backs, and the transitions to labs are seamless. The cyber environment includes high-speed networks, social collaboration tools, Apple iPads and carts, file sharing support, analysis and visualization tools, and presentation tools. Informal learning areas are popular and always crowded. In addition, Jungck hired what are called preceptors, who are with students in the lab but do no grading. "Professors, graduates, undergraduates, PLTL leaders come and go, but the preceptor is the safe role model that students can reach out to."

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[23] Additional information is available at http://www.udel.edu/iselab.

Box 6-1
The Center for Interdisciplinary Biological Inspiration in Education And Research: Letting Nature Point to Discovery

The Center for Interdisciplinary Biological Inspiration in Education and Research (CIBER) at the University of California, Berkeley, encourages undergraduates to formulate and execute novel designs in engineering that are informed and inspired by biological principles and phenomena (Figure A). The goal of the center is to create a community of next-generation scientists and engineers who can work together to conceive and execute innovative multidisciplinary work.

"We run a discovery-based learning laboratory where biologists and engineers work side by side to make authentic discoveries in a teaching lab in one semester," said Robert Full, Chancellor's and Goldman Professor of Integrative Biology and Electrical Engineering and Computer Science at the university. Students in the program become experts in one subject but also learn a variety of approaches and techniques from multiple disciplines. Through a program called Shared Discoveries, students learn to engage in research and critical thinking while making novel discoveries.

Shared Discoveries offers six different types of courses:

- Research-based teaching using a project format
- Research-based teaching using a symposium format
- Project-based teaching
- A lecture course on comparative biomechanics
- A hands-on, research-based teaching laboratory with the possibility of migrating open-ended projects into the Common Biomechanics Research Laboratory for completion
- An honors course for undergraduate research

FIGURE A: Students design robots based upon biomechanical principles. From the presentation by Robert Full.

Eight to nine laboratories are run each semester, with four weeks for an independent project. The laboratories are equipped with bioinstrumentation, biomaterials, and nanotechnology materials, enabling students to pursue cell and tissue engineering, computational biology, and systems and synthetic biology. Students are held accountable for their work through direct feedback, oral presentations, projects, publications, and lab reports, and a diverse group of mentors is available to guide their learning.

More information is available at http://ciber.berkeley.edu.

Under current rules, faculty members at the University of Delaware only received one-third of the credit for teaching a lab or seminar as for delivering a lecture, so the labs and classroom activities are all scheduled together, with no distinction in terms of the load calculus for the faculty members involved. Out-of-class support is designed to create a pro-success environment by building self-efficacy and perseverance. Informal spaces and drop-in tutoring centers, with support for all students (including attention to students who are trying to achieve at the highest level as well as students afraid to seek help) are all part of a diverse and coordinated set of student support services. Research has demonstrated, said Jungck, that students who study more than one course together in their collaborative learning group persevere and succeed more often; thus creating such groups is one approach taken at the University of Delaware. Independent student work is showcased, with the intent of moving beyond research that serves primarily the faculty members. Students work on causes that matter to the students themselves. Student posters are displayed in areas where other students will see the work regularly. Students are engaged as peer reviewers, editors, and reporters of research. In addition, the university has adopted many proven models from elsewhere, such as Sally Hoskins's C.R.E.A.T.E. approach to introducing primary research literature to beginning students (Hoskins et al., 2007) and David Micklos's urban barcoding project to introduce bioinformatics (see Chapter 4).

For students to be fully engaged, they have to be involved in the full cycle of research, Jungck said. They need to propose research, solve problems, present their research, and go through peer review.[24] They also can become involved in citizen science, not just as distributed sensors or basic interpreters, but as collaborators in problem definition, data collection, analysis, and use.

"There are numerous opportunities for students to be researchers in any way that they want," Jungck concluded. "If we really believe that students are researchers, we have to mean that more seriously—that they are not just our research assistants but the creators and leaders of tomorrow." (For a related model, see also Box 6-2.)

University-Wide Institutional Support at a Large Public University

The University of Maryland is a large public research university with 27,000 undergraduates and nearly 10,000 graduate students. It has a diverse student population that is 42 percent minority and a large transfer population from a strong community college system in that state. Its second-year retention rate is 95 percent, and its six-year graduation rate is 85 percent. Like other colleges and universities, it has gone through a period of severely constrained funding. At the same time, it is rethinking curriculum delivery to develop a culture of research at scale. The college offers many opportunities for high-achieving incoming first-year students through a suite of living-learning programs with strong experiential learning, said Betsy Beise, professor of

[24] Jungck's comments here reinforce and extend Sadler's descriptions of epistemic involvement, as described in Chapter 3.

Box 6-2
The Dynamic Genome Project: A Prototype for Multiple Research Modules

The Dynamic Genome Program aims to provide undergraduates with the same types of experimental activities as graduate students while they learn fundamental concepts in genomics and molecular biology. The program was initially developed by Susan Wessler, now Distinguished Professor of Genetics at the University of California, Riverside, when she was at the University of Georgia. Currently, the course is offered as Biology 20 at UC Riverside in the fall and spring quarters to first-year life science students. "Students are satisfying a core requirement for their biology curriculum," said James Burnette, who teaches the course at the university. "That was key."

Biology 20 features a lab-intensive curriculum where students learn computational and experimental approaches to investigating the genomes of plants and animals. Students are encouraged to think creatively and independently, with a focus on problem-solving. Students meet in the newly renovated Neil A. Campbell Science Learning Laboratory, which features a bioinformatics lab, two wet labs, and state-of-the-art equipment. The wet labs have all the equipment necessary to conduct molecular biology experiments, including pipetters, gel electrophoresis rigs, thermocyclers, and gel imagers. The building also includes lecture halls and office space.

The course starts with a four-week introductory period where students are taught molecular and computational skills and engage in a week-long transitional experiment. In the second half of the course, a faculty member "plugs" in with a module related to ongoing research while the staff handle routine administration. The plug and play model decreases the time required to develop and offer an authentic research experience and increases faculty buy-in. Over the past three years, seven professors and postdoctoral fellows have participated. The current facility can handle up to eight sections per quarter. "That means that we're serving close to a third of our undergraduates, and if we get more space there will be more," said Burnette. Outreach is also a vital part of the Dynamic Genome Project, including faculty training; high school workshops on molecular biology, PCR, and DNA barcoding; community events on science education; and K-12 visits with informational and research-oriented aspects.

The Biology 20 course includes near-peer mentoring by undergraduate laboratory assistants, who assist

physics and associate provost for academic planning and programs at the University of Maryland, College Park. Examples include honors programs, special communities, travel programs, and two NSF-funded living-learning engineering communities for underrepresented populations. It also has many support programs for students who need extra help early in their studies. The group that falls between the gaps, said Beise, consists of the middle students—and here is where course-based research can be especially valuable.

The First-Year Innovation and Research Experience[25] (FIRE) program provides first-year students with authentic research experiences, broad mentorship, and institutional connections that affect academic success, personal resilience, and professional development. It is modeled after the Freshman Research Initiative at the University of Texas[26], but with an expansion to

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[25] Additional information is available at http://fire.umd.edu.
[26] Additional information is available at https://cns.utexas.edu/fri.

students with laboratory work and offer advice on college life and academics. They are also role models who have completed the lower division requirements for the major and have continued in STEM in their junior year. Finally Biology 20 students receive information on STEM careers during class so that they know there are multiple options. These interventions are central to helping students stay in STEM degree programs and careers (see Figure A).

More information is available at http://dynamicgenome.ucr.edu.

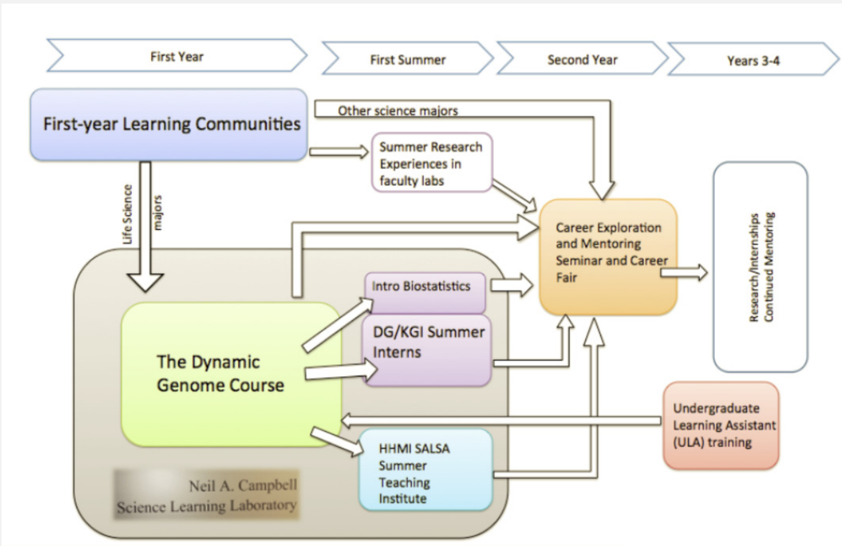

FIGURE A: Overview of the organization and connections with other university components in the Dynamic Genome Authentic Research Experiences Courses for first year students at UC Riverside. From the presentation by James Burnette.

disciplines beyond the STEM fields. For the institution, FIRE provides opportunities to help students find majors they might otherwise not identify, easing pressure on high demand areas. It also leverages collaboration with other initiatives across the campus, including initiatives focused on student research.

As an example of a project-based course at the University of Maryland, Beise mentioned the Partnership for Action Learning in Sustainability (PALS)[27], which is a campus-wide initiative that harnesses the expertise of faculty members and the energy and ingenuity of students to help Maryland communities become more environmentally,

> *"The group that falls between the gaps consists of the middle students—and here is where course-based research can be especially valuable."*
> *—Betsy Beise, University of Maryland, College Park*

[27] Additional information is available at http://smartgrowth.umd.edu/PALS.

economically, and socially sustainable. Such courses are "a way to spread the goal of student engagement beyond STEM disciplines and basic research."

As issues that still need to be addressed, Beise mentioned the tension between funding this kind of research and traditional graduate student teaching and research assistantships, the need to achieve broad faculty buy-in, the challenge of adapting general approaches in varying circumstances, and how best to support transfer students. But a foothold has been established, she said.

The Costs of Course-Based Research

During the discussion session, the panelists turned their attention to the costs of course-based research compared with other types of research experiences. The costs per student are generally much less than those of independent research experiences; research-based courses need not cost much more than other kinds of lab courses. For example, Ellis observed that the changes at City University of Hong Kong were essentially cost neutral. The budget did not change substantially over the five-year period in which the program was instituted. "It's not money. It's the will to do something," he said.

The benefits from such courses are also factors for institutions. For example, these courses can increase retention in STEM fields,[28] said Byrd, which can benefit both students and the institutions. Such benefits can be difficult to monetize but are nevertheless real. "What does it mean to be a STEM graduate who is underrepresented?" Byrd asked.

Elizabeth Ambos, executive officer of the Council for Undergraduate Research, pointed to statistics from the Pennsylvania State System of Higher Education demonstrating the benefits of retention to increasing institutional revenues. As Moran et al. (2015) write in an overview of that research, "With an average cost of attendance of $18,500 per year, we recognized that an annual investment of nearly $500,000 dollars would pay for itself through the retention of just 28 students annually across institutions—an average of two students per university."

Jungck added that considerations of costs for course-based research must take into account the full benefits of that research for students, institutions, and society at large. Colleges and universities can benefit from improved recruiting, alumni donations, and support from the local community and the state. (Value to the community is particularly visible in SENCER-style projects; see Case Studies #s 4-1, 4-2, and 5-1.) The costs to students of not achieving their ambitions and to parents if their children drop out of college should be reckoned against the costs of change, he said. A college or university "has a public responsibility to serve its community," he said. "That should not be an add-on. That is a primary responsibility."

For additional discussion perspectives related to the rewards and challenges of scaling up such efforts, see Chapter 5.

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[28] See reports by Locks & Gregerman 2008 and Jordan et al 2014, and data above from Simmons (Figures 5-3) and Hewlett (Figure 5-5).

7
Observations from Convocation Participants

Summary of Points Made by Workshop Participants

- Students confront many issues in choosing to enroll in research-based courses, including scheduling, the expense of lab fees for STEM courses, and concerns over grading and workload.
- Faculty members and university administrators may have to make special efforts to make students aware of the value of research experiences.
- Non-majors can benefit as much as majors by learning about the nature and practices of science, and the content of a discipline.
- Successful course-based research programs have been characterized by strong administrative support.
- Different types of institutions can learn much from each other about course-based research by sharing lessons learned, participating in discussions, and engaging in collaborations and partnerships.
- If faculty are evaluated and rewarded based only on traditional teaching approaches (as tends to be the case when there is primary or exclusive reliance on student evaluations to measure teaching effectiveness), they will lack incentives to change. Professional development opportunities can be important.
- Assessments that reveal more clearly how students benefit from course-based research could help refine programs and build support.
- A repository for resources, best practices, and results could have widespread benefits. Some web resources of this type are currently available.

Discussion of the many issues that arise in providing undergraduates with course-based research experiences took place throughout the convocation. This final chapter of the convocation report synthesizes these discussions thematically to revisit and elaborate on the recurring issues that emerged during the meeting. Individuals are not cited by name in this chapter since many people contributed to the examination of each topic at different points in the convocation in a free-flowing discussion.

Also in this chapter is a summary of the remarks of four college students from the metropolitan Washington, DC, area. These students had all participated in undergraduate research experiences, had listened to the presentations described above, and were invited to offer their reactions to the idea of a major expansion of course-based research.

As with the list of overarching concepts in Chapter 1, the ideas and comments presented in this chapter should not be seen as the conclusions or findings of the convocation as a whole. Instead, they provide an inventory of issues that may warrant further examination and discussion.

Observations from Undergraduate Student Participants

The four college students who provided perspectives on course-based research were Vincent Cordrey and Nathan Gaul from Northern Virginia Community College, John-Hanson Machado from George Washington University, and Jillian Pailin from Howard University. Though each expressed some concerns about course-based research, they were generally enthusiastic about its potential. They pointed out that it is a way for undergraduates to participate in research without having to seek out and be selected for an independent research experience. It also provides opportunities for interdisciplinary work that they would not have otherwise. The courses can allow for extended research experiences if students can take them for more than one semester or year. And the opportunity to interact with peer mentors is appealing, they said, since peers can act as role models and guides for overcoming both academic and social barriers. One of the students noted that STEM classes traditionally have sought to "weed out" students whom instructors deemed not capable of STEM careers, while course-based research classes sought instead to build students' confidence and ability to collaborate with others in doing science. This difference was greatly appreciated!

One important point made by the students is that using lab fees to pay for research courses creates a significant disincentive. Many undergraduates already have great difficulty paying for college. A number of presenters had pointed out that their projects are supported at least in part by collecting modest additional laboratory or participant fees. One student emphasized that these additional lab fees can add to student financial difficulties, particularly for those with limited financial support, including many non-traditional students. Each individual fee may not seem like much, the student noted, but they add up over time, especially if multiple courses rely on fees to pay for lab or research experiences. He noted that many students can only pay these fees by taking out loans, and they must pay interest on their loans, thereby increasing the actual additional costs significantly.

Students, especially those with families or jobs outside college, also have very limited time. Students with family responsibilities or off-campus jobs need to fit courses into complicated schedules, and course-based research can be more difficult to arrange than regular classes.[29] These complications may make students less eager to take such courses, even if they see potential benefits in doing so—and many do not (see below).

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[29] Erin Dolan (personal communication) noted that students also have commented that these kinds of experiences fit students' schedules more easily than other kinds of research experiences, such as internships..

Many undergraduates are worried about their grade point averages, one of the students pointed out. They need to maintain high grades to achieve their academic and professional ambitions, and many students are likely to be concerned about classes that demand large amounts of work but have unpredictable outcomes. Research projects inherently have the potential to fail; indeed, a number of presenters pointed out that failure is an important and necessary component of scientific research. Fear that such an outcome could lead to a low grade in the course itself may cause some students to be wary of enrolling in a research course, especially if it is voluntary. Students aiming to achieve high grades are not used to taking risks, and they may perceive course-based research as a risky endeavor.

The students expressed a concern that course-based research will generally not be cumulative in the way that independent research is. If each offering of a course covers the same introductory material, and course-based research is not designed to span more than a semester, the experiences may be inherently limiting to students who want to progress as researchers. In that case, they may end up wasting time that they could have spent more profitably doing an independent research project, assuming that that option is available.

Because of these and other concerns, the students pointed out that acceptance of these courses has sometimes been an issue, with relatively few students enrolling in courses that feature research. A number of faculty participants confirmed this point, saying that it is often difficult to persuade students to enroll in these kinds of opportunities. In contrast, the Freshman Research Initiative at the University of Texas, Austin (Box 5-3), has a waiting list to register for these experiences (Erin Dolan, personal communication).

Recruitment of Students to Course-Based Research

As noted above in the reflections of the college students at the convocation, students have limited time and resources, and it can be difficult to recruit them to research-based courses. But, as pointed out by several participants, existing models demonstrate that such courses can attract the interest of students, especially if such projects are presented in appealing ways. These programs aim to benefit students by helping them develop into engaged and knowledgeable researchers, critical thinkers, and the creators of new knowledge, a participant pointed out. Students benefit when they are informed about the value of the work they are doing, both for the research community and for their own futures. They may be able to use the experience to successfully apply for a job, transfer from a two-year to a four-year institution, gain a scholarship or summer fellowship, or apply to graduate or professional school after college. They can benefit from the experience throughout their lives because of what they have learned about how to do research, evaluate evidence, and think critically about data. However, the potential for such gains, and the associated benefits, are not always apparent to students, particularly those who are first in their family to attend college. Thus some extra effort is needed on the part of the faculty to make students aware of the value of a research experience. Students need to feel that doing course-based research matters, not just for the research projects on which they are working, but also for their own futures.

One option is to offer research-based courses as alternatives to existing required courses, a strategy used in the Freshman Research Initiative (FRI) at the University of Texas, Austin (Box

5-3). An ancillary benefit of this approach is that students enrolled in the regular course offering provide a comparison group for assessments. A powerful recruitment strategy can be to use upper class undergraduates, students who previously participated in the research class and enjoyed it, as teaching assistants in these classes, providing stipends or course credits for the teaching assistants (TAs).[30] Assuming that they are not involved in grading, TAs can act as peer mentors, which can attract students to a class. Such students are also the best possible recruiters, as students may trust the judgment of their peers over other sources of advice. Several models use a regular system of hierarchical progression, with more senior students in a team taking responsibility for guiding beginning students. See for example the VIP program (Box 4-3).

Another recruiting tool is to focus research on local communities so that students can more easily make the connection between new knowledge and the benefits to individuals and the broader society. Particularly for minority students who want to return to and work in their communities, such community-focused research can reveal the possible benefits that they could realize by remaining in a STEM field. Examples include projects to maintain a community resource (see Box 5-1), to improve the campus (Box 4-1), or to tackle a local problem (Box 4-2) However, as pointed out by Bangera and others, the most effective way to reach all students, particularly those underrepresented in the STEM professions, is to require such courses as part of the curriculum (see for example Box 5-2). This strategy removes both cultural barriers and faculty bias in selecting students for participation in research. Given the reported ability of research experiences to retain underrepresented minorities in STEM fields (Bangera and Brownell, 2014) and the pressing need to diversity STEM occupations, it would seem most efficacious to offer research courses to all students.

As emphasized by James Gates in his keynote address (see Chapter 2), attrition from STEM fields is especially high during the first two years of college. For many students, an introductory course in a scientific field is also their terminal course in that field. Many students come to college with a passion to major in a STEM field, yet many of them lose that passion. Studies of why students leave these fields have revealed many reasons for their decisions (Seymour and Hewitt, 1997). But as one convocation participant observed, these reasons may have changed in recent years as the college experience has changed. Systematic and rigorous study of why students switch out of STEM fields could shed some light on their decisions, and determine whether (and how) course-based research might change these outcomes.[31] As observed earlier by

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[30] According to Erin Dolan (personal communication), students who serve as peer mentors in the FRI at the University of Texas at Austin are paid, although FRI-like programs at other institutions (e.g., UT El Paso, University of Maryland) offer credit rather than pay for mentoring.

[31] The National Science Foundation is supporting a project that is updating the Seymour and Hewitt (1997) study. Additional information about Talking About Leaving, Revisited is available at http://www.wcer.wisc.edu/projects/projects.php?project_num=956 and http://talr.wceruw.org/. For example, the study is already revealing that there appear to be gender, race, and class-based disparities in patterns of switching majors that are particular to STEM fields (Ferrare and Lee, 2014—http://talr.wceruw.org/publications.html)

Wright (see Chapter 5), a sense of belonging in the field may be key, and being part of a research group can help generate that self-image.

Admittedly, students can have bad research experiences, whether inside or outside of courses. Some convocation participants also expressed the concern that students could be used only to further a faculty member's research interests, rather than being given a rich and full learning experience.

An important point made several times during the convocation is that course-based research should not be just for STEM majors. Non-majors can benefit as much as majors by learning the procedures of research and the associated habits of mind, as well as the content of a research field. However, one might argue that in all cases students will benefit most from participating in research or other creative activities in their major field. Both STEM and non-STEM students may be going directly into employment, and research/practice skills can be valuable for both groups. Thus the most ambitious program described at the convocation, the "Discovery-Enriched Curriculum" of the City University of Hong Kong, is designed for all students in all majors (see Chapter 6). Given the benefits of research to students, one question that must be asked, participants observed, is whether research should be seen as a right rather than a privilege for undergraduates, as was suggested in the PCAST (2012) report.

Institutional Support for Course-Based Research

A point made by many convocation participants during the discussion sessions is that successful course-based research programs at many institutions have been characterized by strong administrative support, which has created stability and sustainability for these programs. In addition, several participants reiterated and reinforced comments from presenters that academic departments are the fundamental unit of change. Without a department's support, course-based research is likely to fade away once an individual champion is no longer running a project. For interdisciplinary research, multiple departments need to be involved in contributing to and supporting course-based research, they observed. However, "pioneers" at a given institution can flourish if they are supported by a national project, such as SEA-PHAGES (Box 3-1), the Genomics Education Partnership (Box 3-3) or Genome Solver (Box 3-3). These national groups can provide both intellectual and pedagogical support, as well as access to well-established protocols and materials as needed.

As noted in Chapter 6 and elsewhere, administrators tend to turn over more quickly than do faculty members, which can detract from the continuity of a program or change process. Long-term support for a new program and for the evaluation of that program can help overcome the difficulties of administrative transitions. Building systems that transcend support from individual leaders is critical to the sustainability of an academic initiative, several commenters observed.

Greater communication among faculty members, administrators, and other institution officials can help build administrative support. For example, inviting the provost or members of the university's board of trustees or regents to student poster sessions and research conferences can show these important community members the value of course-based research. Enthusiastic and knowledgeable students are always the best ambassadors for undergraduate research programs!

As emphasized during several presentations, faculty members respond to the reward system of an institution, as several participants noted during the discussion sessions. If faculty are evaluated and rewarded based on traditional teaching approaches, they will lack incentives to change. Student evaluations, while they have limitations, have a role in the assessment of faculty teaching (e.g., Berk, 2005; Calkins and Micari, 2010; McCabe and Layne, 2012), and especially in the evaluation of course-based research (e.g., Silverthorn, 2006). But students can also be resistant to change, and as noted above, may need to be convinced of the value of the research experience.

Participants noted that uniform and accepted ways to measure teaching based on multiple modes of evaluation can move instruction in positive directions. Transparency and accountability can help faculty members know where an institution stands on undergraduate research so that they can make informed decisions about how to spend their time. (See for example the program described by Ellis, Chapter 6.) In addition, greater synergy among research, education, and service to the institution could reduce the demands on faculty, and course-based research offers unique opportunities for such synergy. When combined with improved assessments of student learning (discussed later in this chapter), methods for evaluating teaching that align with current research on teaching and learning, including effectively engaging students in research, could be a powerful impetus for course-based research.

One issue that came up during the discussion sessions is the time needed for the instructors of course-based research experiences to convert data into papers, time that can be especially difficult to find if their primary responsibilities are in teaching. A research course may not be focused directly on a faculty member's research interests; and/or the faculty member may not be provided with any of the resources required for research, or rewarded for the production of a publication that includes student work (many four-year institutions) or any publications at all (community colleges). Since communication is an essential part of the research process, schools will need to consider whether student communication of the results (at an on-campus symposium, for example) is sufficient, or whether their goal is to see the student work contribute to the scientific literature, and to plan accordingly.

Another perspective on this issue is that course-based research may make it possible for faculty members who want to engage in publishable scientific research to do so, even when they do not have ready access to a research lab or graduate students. This can extend to faculty who are not expected to nor supported for undertaking research, such as adjuncts or faculty at community colleges. For such faculty members, these courses may offer a way to extend and maintain their scholarly interests. Certain types of research, particularly research involving multiple observations, tests, and data analysis which might not be economically feasible with hired assistants, can be accomplished by working with engaged undergraduates. Properly managed, this is a win-win situation for both the researcher and for the students.

The costs of course-based research vary by program and institution. Sometimes the cost is no more than for traditional laboratory courses and, as some presenters emphasized, the cost is often less per student. In other cases, investments are needed to begin, maintain, or scale up course-based research. Use of local resources (field stations, LEED buildings) and of shared instrumentation can further hold down costs (see Chapter 4 and National Research Council, 2014b).

Several workshop participants pointed out that there are many different sources of funding available for undergraduate research. Several federal agencies have multiple programs that can be used to support curriculum innovation and undergraduate research. Institutions could use funds available from these programs for curriculum redesign, teaching support, or other costs; however, the current funding vehicles are more often designed for summer apprenticeship programs than for academic year course-based programs. A focus on innovation and entrepreneurship could attract philanthropic and private sector support. One suggestion was for an independent organization supported by government, philanthropy, and industry that could provide the resources that colleges and universities need to adopt and scale up course-based research until these programs become widespread and institutionalized.

The National Science Foundation and the National Institutes of Health have significant differences in the ways they fund education. For example, NIH tends to fund longer-term training projects with a primary emphasis on training graduate students and on increasing minority participation. NSF appears to concentrate on funding innovative programs that will contribute to the science education knowledge base. Many private institutions are also looking for ways to stimulate improvement in STEM education in the United States. If the leaders of those agencies came together to better align their support mechanisms with the needs of course-based research, many programs and large numbers of students could benefit.

Collaboration among Different Types of Institutions

Different types of institutions have both common and distinct strengths, issues, and cultures, convocation participants observed. As such, they can learn much from each other by sharing lessons learned, participating in discussions, and engaging in collaborations and partnerships. As a specific example, majority-serving institutions can learn much more about attracting and retaining students who are underrepresented in STEM fields by talking with minority-serving institutions, one participant pointed out. Another pointed to the potential for partnerships between small liberal arts colleges or community colleges and local universities that have more research infrastructure. Many research institutions have used the NSF mandate for broader impacts to create opportunities for local high school and college faculty and students to participate in their research programs.

Different kinds of expertise also are needed in securing support for course-based research. For example, science faculty are typically skilled at writing protocols for student laboratory exercises, but know less about the role of assessment in educational innovation. Collaborations among faculty in the natural and social/behavioral sciences or between schools or departments of education and science departments can be synergistic in preparing successful funding proposals and the resulting programs. In addition, some professional societies have expertise at writing proposals, assessing science education programs, etc. that they can share with faculty members through webinars or workshops at their national meetings.

A related issue is the collaboration necessary to do interdisciplinary course-based research, which can be different from a research project based completely within a single discipline. For example, interdisciplinary research can be particularly difficult to scale up because of the challenge of coordinating contributions from multiple departments. However, successful projects in bioinformatics draw both on biologists and computer scientists (see Box 3-3 and Micklos report in Chapter 4). There is a similar need for communication between science education faculty members engaged in discipline-based education research (for example, NRC 2012), and other STEM faculty members. Achieving good communication can be challenging but can benefit both groups.

A major topic of discussion during the convocation was the benefits to be gained through collaboration between two-year and four-year colleges and universities. Many STEM majors start their education in two-year schools, and some students at four-year schools take some of their STEM classes at two-year schools because of lower costs and greater convenience. By working together to develop course-based research classes, these institutions could ease movement back and forth and provide a more cohesive educational experience for students. Community college instructors may be surprised and concerned when asked to do research, a participant pointed out, given their many other responsibilities and the current absence of any research support in most cases. (This participant also observed that some community colleges do not have ready access to scientific journals; partnerships with research institutions can help address this.) But if these faculty members can be shown a relatively easy way to incorporate research into their courses, their "activation energy" will be lowered and, with experience, they could realize the benefits to their students from research participation, as reported by Hewlett (Box 5-4) and Cerveny (Box 5-1). Similar comments were offered regarding opportunities for non-tenure track and adjunct faculty at four-year institutions, a rapidly growing component of the faculty workforce on many campuses.

Some colleges and universities have created offices on campus to facilitate discussions and partnerships among two-year and four-year institutions, one participant pointed out. Some funding agencies also provide grant competitions for programs focused on the transition of students from two-year to four-year schools, particularly in the STEM disciplines. Another participant pointed out that a significant student group at many community colleges is veterans, who bring with them particular skills that can be useful in research, along with particular, specialized needs.

Professional Development of Faculty Members, Other Instructors and Mentors

Many faculty members, teaching assistants, and peer mentors need initial professional development and ongoing assistance to teach research-based courses, participants observed. Faculty may want to institute course-based research, but not know how to get started. In some cases, joining a "national experiment" is a solution [see case studies for SEA-PHAGES (Hatfull, Box 3-1), the Genomics Education Partnership, and Genome Solver (Rosenwald, Box 3-3)]. Alternatively, "translators" could help faculty structure and organize courses based on their own research and provide assistance; ideally the translators will have experience both with the specific discipline and with course-based research. Organizations such as the CCURI (Hewlett, Box 5-4) and REIL-Biology[32] provide such assistance. A part of an existing teaching and learning center on campus could be repurposed to provide such assistance, or a teaching laboratory facility can be structured to provide assistance [see comments by Jungck (Chapter 6) and Wessler (Box 6-2).

Faculty members also need a safe space to try new things and possibly fail, it was observed. To encourage innovation, assessment of faculty efforts would have to count the learning involved in a failed course as an asset. Instructors also have to realize that at least initially their student evaluations could go down when they switch to course-based research, especially if students perceive the course as requiring more work or if the course pushes them outside of their comfort zone (see discussion above). Engaging in course-based research requires restructuring time, incentives, rewards, and responsibilities for faculty. It also can require different roles and relationships for graduate students and postdoctoral fellows, who may be asked to help design and run research-based courses.

Professional development can help instructors recognize and offer help to students who may not be totally engaged or are otherwise having problems in a research-based course. For example, first-generation college students may not want to admit that they are having problems or to stand out in any way. Many students can suffer from the "imposter syndrome"—the feeling that they do not belong. One participant suggested that a group discussion in which everyone is asked, "What is your greatest fear?" can help reveal that students are not alone in suffering from this syndrome. But such an approach may not be effective in all situations or with all groups of students. Peer mentors also can help students build their confidence and overcome the fear of trying something that they have not done before or that requires them to assume unfamiliar responsibilities. In research, it is not just a question of memorizing material or learning to solve a certain type of problem. Students are asked to generate novel information and to do their best to ensure that their conclusions can be defended—and some undergraduates feel that it is inappropriate to ask them to take up this challenge. Participants have responsibilities to the group as a whole. Doing this first in an academic year class, supported by teammates and peer mentors, can be very helpful to students, getting them past their initial fright and leading to real growth.

Several representatives of professional societies present at the convocation noted that their organizations can provide help with faculty mentoring and have supportive resources that can be accessed. In addition, one participant pointed to the National Research Mentoring Network headquartered at Boston College and directed by David Burgess as a valuable resource.[33]

Two committee members (Gita Bangera and Mary Smith), both of whom are PULSE Fellows, noted the work of PULSE (Partnership for Undergraduate Life Science Education). PULSE Fellows are current or former department chairs and who are working together across the nation and across institution types to improve undergraduate biology education.[34] They have

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[32] More information is available at http://www.rcn.ableweb.org.
[33] More information is available at http://nrmnet.com.
[34] PULSE was established with funding from the Howard Hughes Medical Institute, Nation Institute for General Medical Sciences (NIH), and the National Science Foundation. Additional information is available at http://www.pulsecommunity.org/.

developed a rubric for evaluating the efficacy of departmental efforts in improving undergraduate education, which can serve as a useful guide for asking appropriate questions about the roles of undergraduate research in biology education.[35]

Assessment of Learning from Course-Based Research

Several convocation participants pointed to the need for assessments to dig more deeply in order to understand how students benefit from course-based research. Benefits from undergraduate research generally are well established (see Chapter 1), and initial reports indicate that similar benefits can be achieved by participation in course-based research experiences (Jordan et al, 2014; Shaffer et al., 2014). New approaches to assessment could help reveal what the research experience is for the student, what it means for research to "work" in an undergraduate setting, for whom it works best, and in what contexts. Specifying the desired outcomes of course-based research, which can include the more traditional dimensions such as learning gains, increased interest in STEM, or persistence, can clarify the benefits of that research experience and the kinds of activities needed to realize those benefits. But assessment also can encompass dimensions such as critical thinking, gains in understanding the nature of science, or gains in experimental design ability. Also, assessment is generally needed to publish on innovative programs, and published data, especially if those data are from local activities, can be powerful spurs to action for faculty members, administrators, policy makers, and other stakeholders, encouraging adoption and support of course-based research. Currently available assessment tools are discussed in Chapter 3 above.

To aid in assessment, general instruments might be developed for evaluation that could be adapted to specific circumstances, one participant suggested. On-campus teaching centers could reach out to faculty members to help, or might refer education specialists in the discipline to collaborate with faculty in this work. Eventually faculty members could have a "menu of measures," instruments, and assessments that they could use to evaluate their own courses and programs. In this way, faculty members could evaluate the outcomes of their classes and programs even if they are not experts in assessment.

It was pointed out that the results of specific assessments depend not only on the measures used, such as the questions on a survey, but on the characteristics of the students who are being measured. For example, much more research is needed to determine whether students who actively seek out or are chosen for such experiences realize different outcomes when compared to a broader group of students who are required to take such courses.

Convocation participants discussed the creation of a "matrix of success" that would define and make possible the measurement of desired outcomes. A multi-scale system operating at different levels would seem to be necessary to capture the many aspects of success sought in course-based research. For example, measures of success could include enhanced student use of

[35] Additional information about the PULSE rubrics is available at http://www.pulsecommunity.org/page/v-c-certification.

scientific practices, self-efficacy, and metacognition;[36] the number of faculty and students involved in course-based research and their reactions to that research; the number of institutions participating in course-based research and the outcomes of that research; and even the international spread of these practices.

Course-based research will require different grading mechanisms that have not yet been well developed in many instances, one participant said. Faculty members will need the tools and support to make such a transition—for example, to grade students' lab notebooks or progress reports on research using appropriate rubrics, rather than assessment using exams or standard lab reports, added another participant.

Several existing tools from the social sciences could be applied to assessments of course-based research (e.g., National Research Council, 2000, 2001, 2012, 2015). Ways of categorizing problem types from simple to complex and from ill-structured to well-structured could be useful in studying course-based research. Variables of interest at the level of students, courses, programs, and institutions need to be better defined to drive observations and analyses.

However, "plug and play" assessments will not be possible in many cases, several participants cautioned. Faculty members and departments will need to learn how to adapt instruments and interpret data according to their own contexts. But, as one convocation participant noted, developing valid indicators can be as difficult as designing instruction. Taking advantage of existing resources for assessment (e.g., Dirks et al, 2014) and simultaneously co-designing the course and its assessment(s) can ensure that outcomes measures align with course goals and minimize the need to create new indicators or assessment instruments.

An issue that arose several times is the longstanding "controversy" about breadth vs. depth of coverage of subject matter. Some participants asked whether providing opportunities for students to learn fundamental concepts in depth through research experiences will result in less breadth of coverage in the curriculum; other participants acknowledged this as a pressure that many faculty continue to face, especially those who are involved with introductory courses, where breadth is often viewed as paramount. However, as noted in Chapter 1, research on human learning has emphasized the importance of the ability to both *acquire* and *use* content in novel ways, making connections between what might at first appear to be disparate concepts, and applying that knowledge in novel situations (National Research Council, 2000).

Instructional and learning time in classes and laboratories during a fixed length semester are limited commodities. Perspectives among convocation participants on the importance of breadth of coverage differed, since some educators hold that students today can more easily access knowledge that they may not have absorbed from a class than was true in the past. One

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[36] According to the authors of *How People Learn* (NRC, 2000), "metacognition" is defined as acquiring the abilities to predict one's performances on various tasks (e.g., how well one will be able to remember various stimuli) and to monitor current levels of mastery and understanding. Metacognition can help students develop personally relevant pedagogical content knowledge, analogous to the pedagogical content knowledge available to effective teachers. Metacognition also can be defined along many other dimensions (for more perspective see papers in Hartman, 2001).

possibility, for example, is that students will use resources such as online courses or modules to fill in the gaps in their knowledge while building more depth of understanding through course-based research. Colleges and universities already offer many survey courses, one participant pointed out, but they offer fewer opportunity for transformative experiences that take learners into a given topic in depth for both content and analytical understanding.

Many basic questions remain unanswered. For example, faculty members' and administrators' understandings of the distinctions between course-based research, inquiry courses, or independent research experiences may differ. For these activities, student autonomy and epistemic involvement are important considerations. Each could be assessed in different ways or with different components of a more comprehensive assessment tool. As one participant pointed out, in many ways innovations in assessment are as important as innovations in course design, which opens up an area ripe for future research and subsequent implementation of new tools.

Dissemination of Models of Course-Based Research

Many more models for course-based research exist than could be featured at the workshop or highlighted in the breakout sessions and posters displayed by participants.[37] If information about these models could be made more readily available, faculty members at institutions would have more resources to emulate or adapt than is typically the case today. In general, said several participants, a repository for resources, best practices, and results could have widespread benefits.

Such resources are being developed. For example, CUREnet offers a website that "is a network of people and programs that are creating course-based undergraduate research experiences (CUREs) in biology as a means of helping students understand core concepts in biology, develop core scientific competencies, and become active, contributing members of the scientific community" (from the home page).[38] Bio-Link, an Advanced Technological Education Center that is supported by the NSF, provides resources for identifying community college partners in Biology and Biotechnology who are doing or would be interested in undergraduate research.[39]

However, as one participant noted, a program has to work at the institution where it is being implemented, not just at the institution where it was originally developed. Adaptation is not a trivial process, but can be facilitated by workshops created by a central core institution (see Boxes 3-1 and 3-3). There are distinct advantages and disadvantages to national course-based research consortia vs. locally developed experiences, and which will work best in a given instance often turns on local resources and the interests of the faculty members. (For a case study of GEP members' experiences in implementation see Lopatto et al. 2014.)

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[37] Posters are available at https://www.dropbox.com/sh/lhxz8fokljbwe7i/AAAiwXqUmbshQurCxzCzIehga?dl=0.
[38] Available at http://curenet.cns.utexas.edu/.
[39] Additional information is available at http://www.bio-link.org/home/.

Publishing about course-based research increasingly requires that such courses be evaluated, which generally means that authors with expertise in the STEM disciplines find it advantageous to work with assessment experts (see above). Professional societies could help provide this expertise while also offering guidance on publication, one participant volunteered. Several of the scientific societies sponsor journals that regularly publish papers on course-based research and other pedagogical innovations, and many of these journals are freely available on the web.

Many innovations in classroom-based research may not become known or available because many faculty do not have the time or incentive to undertake the formal assessments and writing needed to publish them. This is likely to be particularly true for work at community colleges. A participant noted that professional societies also might help disseminate information about course-based research informally, for example through blogs and newsletters and through sessions devoted to this topic at regional and national meetings.

An issue related to dissemination involves the publication of the research accomplished by undergraduates in these courses. As noted above, faculty members may not have the time or funding to move research results from the classroom to publication. Organizing publication of papers with large numbers of student co-authors can be challenging, but several recent examples illustrate the feasibility, given modern communication networks. See Leung et al., 2015, which has 940 student co-authors, and Pope et al., 2015, which has 2,853 collaborators, mostly undergraduates. There has been some controversy around publications with large numbers of undergraduate co-authors. As with other kinds of research papers with large numbers of authors, careful documentation of student contributions, including manuscript review, critique, and approval, must be maintained by the corresponding authors who submit these papers.

A Broader Transformation

Course-based research is still a young and growing movement, but it has major potential to impact STEM education. Several participants recalled Jo Handelsman's admonition at the beginning of the convocation (see Box 2-1), that such research experiences should be available to all students and become routine in all colleges and universities, with the ultimate goal of providing every student with such an experience during the first year of college. Several parallels can be drawn between the mediators of student learning described earlier (Sadler, Chapter 3) and the parameters of successful undergraduate research programs. While a campus program can start with just one or two courses, ultimately one would like to have a "smorgasbord" of courses available so that *a student can select a project in which they have personal interest* (see UT Austin case study, Box 5-3). Well-developed courses have *explicit instructional supports*—a defined goal, starting protocols that all students in the course learn—but are structured so that each student has individual responsibilities and *must make reasoned decisions* on the progression of their research. Collaboration within the lab provides *peer support*, increasing students' comfort level; *mentoring* can come both from peers and from faculty. What is commonly missing is time for *reflection.* A concern is that most course-based research experiences are designed to be only one semester or quarter, while it is clear that the *duration of the research experience* is important (see Chapter 3; Sadler, Linn). Thus, achieving maximal benefit will require many courses to change, across the department and across the institution, as pointed out by Bangera.

Several forces are converging that could help make this goal a reality, participants pointed out. The *Next Generation Science Standards* at the K-12 level represent the culmination of decades of reform in science education, which potentially will generate cohorts of high school graduates who are much better prepared and eager to do research in college. New findings from discipline based education research are showing how best to structure research-based courses to help students realize desired outcomes (National Research Council, 2012; Corwin et al., 2014; Brownell and Kloser, 2015; Corwin et al., 2015). Colleges and universities are under intense pressure to change traditional practices to meet the needs of the workplace and society. Some students are now completing their entire degrees online, and both Shaffer and Linn pointed to online mentoring systems and virtual internships as possible mechanisms for reaching more students (Chapter 3). However, as emphasized by Ellis, who has ushered in a "Discovery Enriched Curriculum" at the City University of Hong Kong, research experiences are one area where in-person interactions are most important (Chapter 6). "Higher education is at a tipping point," said Ellis; "Knowledge is on the web, but the next knowledge is not yet on the web."

Consideration of a major expansion in course-based research led to a discussion of the kinds of skills that students need to take advantage of such experiences. Given the growing importance of big data sets in science, skills in statistics can be important in research. Some speakers pointed to computer science as a fundamental skill for students, though they added that computer science departments do not always offer the kinds of courses students need. In those cases, computer science needs to be built into STEM departmental offerings to enable students to learn fundamental computing concepts in the context of their discipline.

A related point involves the need to align course-based research with independent undergraduate research experiences. Emphasis on the former can help the latter to thrive, one participant said. In some schools (such as UCLA and UT-Austin), a course-based research experience has become almost a prerequisite for entry into an individually mentored research experience. Ironically, funding mechanisms are much better established for summer research experiences than for research courses; some realignment may be needed to get optimal returns from the funding available (see Chapter 6, Byrd).

The Potential of Course-Based Research

In closing remarks Susan Wessler, one of the leaders in implementing research-based courses as Distinguished Professor of Genetics at the University of California, Riverside, a member of the National Academy of Sciences, and a member of the convocation organizing committee, provided a fitting overview of the broader issues raised by the convocation. Course-based research is a way to show legislators and other funders that the tasks of research and education are intertwined and can produce benefits simultaneously, she said. "Trillions of dollars of our gross national product comes from scientific discovery, and our congressmen and senators realize this." Course-based research also does not have to be expensive," she continued. "Many of these [needed] dollars exist in universities. We just need to be creative about it." As described by Gates in the opening session of the convocation, the nation's future prosperity depends on doing a better job in educating all students; emerging evidence suggests that course-based research may be one way to generate deeper student learning, but more evidence is still needed (see in particular Chapter 3).

Finally, Wessler pointed out that all faculty, regardless of rank or institution type, have many reasons to join in this work. The students in their universities “are our future,” she said. “We are importing scientific talent into this country. . . . It’s a real opportunity to talk to your colleagues, to talk to the assistant professors, and to talk to your deans and department heads. . . . There’s huge potential here.”

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Appendix A
Convocation Agenda

Monday, May 11

6:00 PM **Registration and Opening Reception**

7:00 **Welcoming remarks and overview of the convocation**
Jay Labov, Project Director, National Research Council
Sarah C.R. Elgin, Organizing Committee Chair, Washington University
Elizabeth Boylan, Sloan Foundation (Sponsor)
Ryan Kelsey, Harry and Leona Helmsley Charitable Trust (Sponsor)
David Asai, Howard Hughes Medical Institute (Sponsor)
Jo Handelsman (Office of Science and Technology Policy)
James Gentile, Chair of the BOSE Consensus Study Committee

7:30 **Keynote Address and Discussion: Think Different: Allowing STEM Precociousness To Bloom**
James Gates (University of Maryland, College Park; Member, NAS; President's Council of Advisors on Science and Technology; Co-Chair of Authoring Committee for PCAST report, Engage to Excel).

Tuesday, May 12

7:30 AM **Registration continues and Full Breakfast**

8:30 **Contrasts in Current Models, Set #1: Brief Overview of 6 of 12 Programs**
Note: these brief overviews will describe programs and issues that will be discussed in much greater depth in the one-hour breakout session that begins at 9:15. They are designed to help participants decide which breakout session to attend.
1. Programs for first year students drawing on local resources and those based on a national organization: First Year Research Experiences at the University of Texas: **Sarah Simmons**, formerly at University of Texas, Austin SEA-PHAGES: Graham Hatfull, University of Pittsburgh
2. Programs designed for community colleges and those aimed at four year institutions:

Community Colleges Undergraduate Research Initiative: **James Hewlett,** Finger Lakes Community College Dynamic Genome Program: **James Burnette,** University of California, Riverside
3. Programs focusing on on-campus research projects vs. community oriented programs
The Campus as a Living-Learning Lab for Sustainability: **Cathy Middlecamp**, University of Wisconsin Madison Civic Engagement: **David Burns**, SENCER

9:00 **Move to First Breakout Sessions**

9:15 Breakout Sessions I:
Using these programs as examples, the 6 presenters in the preceding overview session will facilitate discussion about these models during the breakout session as a way to stimulate discussion about the following general issues:
- Opportunities (both planned and unplanned),
- Challenges (both anticipated and unanticipated)
- Available evidence for the efficacy of the program, and
- Potential for dissemination and scalability.

Each participant will attend one breakout session. Each session will be interactive. Presenters will have ~ 10 minutes to describe their experience before opening up for discussion.

10:15 **Break and Networking**

10:45 **Showcase of Current Models, Set #2: Brief Overview of 6 of 12 Programs**

Note: these brief overviews will describe programs and issues that will be discussed in much greater depth in the one-hour breakout session that begins at 11:30. They are designed to help participants decide which breakout session to attend.
1. National initiatives, Developer's and User's Perspectives:
Synthetic Biology: **Malcolm Campbell,** Davidson College GEP and Genome Solver: **Anne Rosenwald,** Georgetown University
2. Initiatives focusing on challenges and opportunities for underrepresented students
Preserving the Past and Promoting the Future: **Niccole Cerveny,** Mesa Community College CUREs for Introductory Biology: A Scaffolding Approach with Yeast: **Gail Hollowell,** North Carolina Central University
3. Challenges and opportunities in engineering VIP, EPICS: Edward Coyle, Georgia Institute of Technology Bioengineering: **Robert Full,** University of California, Berkeley

11:15	**Move to Second Breakout Sessions:**
11:30	**Breakout Sessions II:** Using these programs as examples, the 6 presenters in the preceding overview session will facilitate discussion about these models during the breakout session as a way to stimulate discussion about the following general issues: - Opportunities (both planned and unplanned), - Challenges (both anticipated and unanticipated) - Available evidence for the efficacy of the program, and - Potential for dissemination and scalability. Each participant will attend one breakout session. Each session will be interactive. Presenters will have ~ 10 minutes to describe their experience before opening up for discussion.
12:30	**Buffet Lunch and Small Groups**
1:45	**Bringing Research into the Undergraduate Curriculum: Evidence of Best Practices and On-going Challenges—What Do We Know, What Remains to be Known, and What's Next?** **Erin Dolan**, Presiding (University of Texas, Austin, Committee Member) Speakers/Panelists - **David Lopatto,** Grinnell College [summary of his commissioned paper to be presented by Sarah Elgin (committee chair] - **Troy Sadler**, University of Missouri - **Marcia Linn,** University of California, Berkeley - **Elizabeth Ambos,** Council on Undergraduate Research
3:00	**Break and Networking**
3:15	**How can we be cost-effective? Infrastructural Opportunities and Challenges to Making Discovery-Based Research Available to Larger Numbers of Students** **Sean Decatur,** Presiding (Kenyon College, Committee Member) Presenters/Panelists: **- Margot McDonald**, California Polytechnic State University San Luis Obispo: The Campus as a Living Laboratory **- Jeff Ryan**, University of South Florida: Remote instrumentation - **David Micklos,** Cold Spring Harbor Laboratory: DNA Learning Center **- David Shaffer,** University of Wisconsin, Madison: Virtual Internships

4:30 **Challenge questions: small group work (1 hr.) and reporting (30 min.)**

(Each group led by a member of the organizing committee)
1. There are many different kinds of CURES; key features for success?
2. How do we take what evidence indicates are the most effective approaches, and bring them to scale? What does "scale" mean in this context?
3. Challenges and solutions: What resources would help to overcome the challenges?
4. How can we determine best strategies, how to improve assessment? What tools are missing?
5. Are there special needs of beginning students, community college students, under- represented students?
6. Is research for everyone, or are we becoming over-zealous?

6:00 **3-2-1 Exercise**
Jay Labov, Presiding (National Research Council, PI)
List 3 "aha" moments from the convocation thus far
List 2 questions that you feel still need to be addressed

List 1 action that you will take when you return home as a result of what has been discussed thus far. The organizing committee will meet after dinner to consider the responses from the 3-2-1 exercise to make any necessary modifications to the schedule for the next day.

6:15 **Dinner and Networking**

Wednesday, May 13

7:30 **Full Breakfast**

8:15 **Results from 3-2-1 Exercise and Challenge Questions**
Reporting out on findings from first day. Changes to agenda, if any, as a result of this feedback.
Sarah Elgin, Presiding

8:45 **What are the Rewards and Challenges in Scaling Up?**
Gabriela Weaver, Presiding (University of Massachusetts, Amherst, Committee Member)
Speakers and Panelists:
- **Sara Brownell,** Arizona State University: Issues of Scale-Up

	- **Don Wink,** University of Illinois, Chicago: Center for Authentic Science Practice in Education (CASPiE) - **Robin Wright,** University of Minnesota, Twin Cities: Use of University Field Stations - **George Langford**, Syracuse University: Economic Pressures for New Models
10:00	**Break and Networking**
10:15	Panel discussion: **Elvyra San Juan,** Presiding (California State University System, Committee Member) **What are the institutional and funding structures needed to promote and support these kinds of changes in pedagogical strategy? Best strategies for dissemination?** - **Goldie Byrd,** North Carolina A&T State University - **Arthur Ellis,** City University of Hong Kong - **John Jungck,** University of Delaware - **Elizabeth Beise,** University of Maryland
11:30	**The SLAM:** All participants who wish to do so may make up to a 2 minute statement about what they have observed and learned. This session will serve to stimulate commentary after lunch from a panel of invited undergraduate students, members of the organizing committee, and participants. **Kerry Brenner,** Presiding
12:45	**Buffet Lunch and Brainstorming via working groups:** Small groups will reflect on what has been discussed thus far in the Convocation and consider what is needed in a future research agenda to further explore the features of discovery-based science experiences for undergraduates. Exploratory questions include: 1. How do we account for individuality and uniqueness of different institutions? 2. How can course-based research experiences best be sustained locally and disseminated more broadly? 3. How can faculty who engage in such efforts be supported? How can they most effectively mentor all students who are involved? 4. How might administrative structures be restructured to best support these efforts? 5. How might external funding opportunities be structured to most effectively support these efforts? 6. What should define “success” in such initiatives and what are the most effective ways to measure success?

1:45	**Lessons Learned, Gaps Remaining** **James Gentile**, Presiding - Brief reports from morning working groups - Comments from invited local undergraduate students - Comments from organizing committee members - Comments from sponsors - Comments from convocation participants (open microphone)
2:45	**Next Steps** **Sarah Elgin,** Presiding - Timeline for production of report - Plans for year of communication activities—suggestions for venues solicited - Issues that the consensus study might consider, urgent questions
3:00	**Convocation Adjourns**

Appendix B
Commissioned Paper:
The Consortium as Experiment

David Lopatto

Grinnell College

The Consortium as Experiment

Introduction

The 2012 PCAST report to the president reported the "need to increase the number of students who receive undergraduate STEM degrees by about 34% annually over current rates" (PCAST, 2012). The report asserts that the principal mechanism by which these additional STEM graduates could be achieved is by reducing the attrition from undergraduate science programs, and that this reduction in attrition may be achieved by a number of reforms, including replacing standard science laboratory courses with discovery-based research courses. The latter assertion leads naturally to the theme of the current convocation on integrating discovery-based research into the undergraduate curriculum. My intended contribution to this discussion is a result of my work in the assessment of student learning in undergraduate science and in particular my familiarity with a successful discovery-based program, the Genomics Education Partnership. I hope to offer some observations regarding the research agenda that might be formulated to assess the impact of course-based undergraduate research programs.

A CURE as a "complex package"

The hypothesis that a course-based undergraduate research experience (CURE) is a vehicle for retaining science students is based on the observation that an undergraduate research experience (URE) is the model for a successful science educational experience (Lopatto, 2003, 2004; Seymour, et al., 2004). Thus, the simplest definition of a CURE is a URE-like experience occurring within a scheduled science course. This definition requires us to say something about UREs in general, and about how the CURE outcomes might be shown to resemble URE outcomes.

My research concerning student learning outcomes from undergraduate research experiences began about 15 years ago when my college won an NSF award for the integration of science research and education. The history of how this initial award propelled a research program on student learning is described in Lopatto (2010). The brief version is that I was privileged to collaborate with Dr. Elaine Seymour and her colleagues to conduct a mixed-methodology study of the benefits of the URE experience at four colleges. Seymour (see Seymour, et al., 2004) took a qualitative, interview approach to gathering data, while I arranged quantitative surveys for

TABLE B-1. A summary of the categories of benefits following from a URE found by Seymour, et al. (2004, left) and by Lopatto (2010, right). The categories on the left emerged from a coding of statements made by students during interviews. The categories on the right emerged from an exploratory factor analysis of numerical survey data.

Based on Seymour et al. (2004)	**Based on Lopatto (2010)**
Personal/professional	Personal development
Thinking and working like a scientist	Knowledge synthesis
Skills	Interaction and communication skills Data collection and interpretation skills Design and hypothesis testing skills Information literacy Computer skills
Clarification, confirmation and refinement of career/education paths	Professional development
Enhanced career/graduate school preparation	Professional advancement
Changes in attitudes toward learning and working as a researcher	Interaction and communication skills Responsibility
Other benefits	

students (for example, Lopatto, 2003). Our results triangulated well (Table B-1). It seemed that a successful URE provided a wide range of skill learning, professional preparation, and personal development. This knowledge informed the development of a new survey, the Survey of Undergraduate Research Experiences (SURE) (supported by the Howard Hughes Medical Institute), which became widely used as an assessment tool for UREs. The heart of the SURE is a list of 21 learning benefits, which students evaluate for gain on a scale of 1 to 5. The benchmark data, drawn from over 100 institutions and programs, replicates very well from year to year (Lopatto, 2004; 2007), providing a credible baseline against which classroom undergraduate research outcomes may be measured. When demand grew for a similar instrument to assess student learning in CUREs, a new survey evolved from the SURE called the Classroom Undergraduate Research Experience (CURE) survey. The CURE survey retained the evaluation of learning benefits used in the SURE, permitting a comparison of the CURE and URE benefits.

The CURE survey was not based on an a priori definition of a CURE. Instead, course instructors were asked to fill out a brief form to indicate what course activities they stressed. Some of the activities were classic—reading a textbook, taking a test—while others reflected discovery-based learning. Analyzing the instructor data, I found that a combination of 5 items constituted a rough scale for indexing a CURE:

- The course has a lab or project where no one knows the outcome.

- The course has a project in which the students have some input into the research process.
- The course has a project entirely of student design.
- The students become responsible for a part of the project.
- The students critique the work of other students.

Using the numerical ratings of the instructor as a grouping variable, I performed a "median split" of the courses. The median split identified a group of high-scoring "high research-like" courses (in other words, CUREs) and a group of low-scoring "low research-like" courses (in other words, traditional "cookbook" science lab courses). Later, on the CURE survey, students evaluated their learning gains from the above course elements. The results are shown in Figure B-1. The student data reflects the observation that students learn based on what teachers teach. Beyond that observation, however, the students who participated in CUREs also evaluated the 20 learning gain items in a pattern similar to students in UREs (Figure B-2). The simplest conclusion that the CURE is successful is that the outcomes of the program are comparable to the outcomes observed following the URE experience. Lopatto (2008), for example, presented comparative results from the Genomics Education Partnership program and a group of summer undergraduate researchers. The self-reported gains from the experiences were similar. But while a CURE may resemble a URE in outcomes, the CURE may not resemble a URE as a process. The CURE may have many more local constraints imposed by the nature of the institution, its undergraduate science program, and the characteristics of the student body. These constraints limit the generalizability of any reported success of a CURE program at a particular college or university. The question remains as to how to establish a more generalized model of a successful CURE.

The methodologist Donald Campbell wrote extensively on the issue of generalizability, or external validity (Campbell, 1969, 1982, 1986). He observed that a successful program at one institution expresses "local molar causal validity" (Campbell, 1986). Local molar causal validity is "a first crucial issue and starting point for other validity questions." This sort of validity has to do with the question, "did this complex treatment package make a real difference in this unique application at this particular place and time?" In other words, before we get down to the work of parsing the components of a successful CURE, do we have evidence that the "complex package" is successful in effecting desirable outcomes? I believe the answer is clearly "yes", and I refer readers to the extensive body of evidence (see, for example, Auchincloss, et al., 2014; Linn, et al., 2015; Trosset el al., 2008; as well as issues of the CUR Quarterly or any teaching journal in your preferred discipline). Once we become convinced that the complex package leads to desired outcomes, then research questions become more precise (Beckman and Hensel, 2009). Researchers strive to measure the relative contribution of independent variables, the interactions among these variables, and the nature of mediating and moderating variables that influence outcomes. This research, in turn, leads to attempts to model the CURE experience (e.g., Corwin et al., 2015). Concurrently, researchers create and improve instruments that may measure the components of the CURE experience (e.g., Hanauer and Dolan, 2014; Laursen, 2015).

Research objective: efficacy versus effectiveness

As research on CURE experiences proceeds, however, we might pause to consider the strategic goal of a research agenda dedicated to understanding the CURE. There is a distinction to be made between analyzing components of a CURE that might affect its success and components

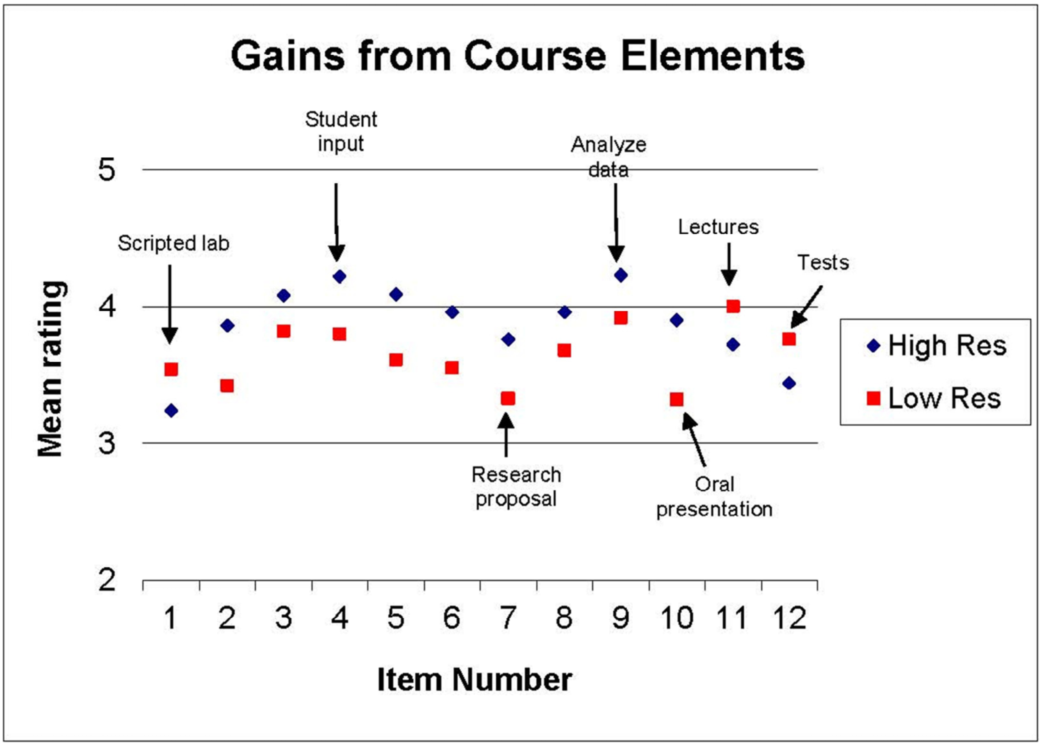

FIGURE B-1. After an initial round of data collection in 2005-2006, CURE survey items reflecting the student's gains from different course elements were compared. Two groups were formed based on the course instructor's use of CURE components. Courses from instructors emphasizing CURE elements form the "high research-like", or High Res group. Courses from instructors not emphasizing CURE components form the "low research-like", or Low Res group. The student ratings of gains from course elements reflected the instructors' intent. Elements that are common in traditional courses (Low Res) included using a scripted lab, listening to lectures, and taking tests in class. Elements that are common in CUREs (High Res) included a lab or project where no one knows the outcome (Item 2), a project with some student input (Item 4), a project entirely of student design (Item 5) as well as writing a research proposal (Item 7) and making an oral presentation (Item 10). The overall N = 397 student surveys.

that do affect its success. The first case, demonstrating what might, all things being equal, affect a CURE, typically results from laboratory studies that isolate a variable as much as possible to establish the internal validity of the relationship between the independent variable and the target outcome (Mook, 1983). The second case, demonstrating what does affect a CURE, typically results from field research (Cook and Campbell, 1979). The distinction is found in psychology, where, for example, researchers attempt to study the success of psychotherapy and the comparative success of particular therapies. Therapy, like education, is an applied field aimed at changing human behavior. As research on therapy advanced, a distinction grew between two methodological approaches, called "efficacy" and "effectiveness." Efficacy refers to the outcome of randomized clinical trials of therapies—controlled experiments. Effectiveness refers to the success of a therapy in actual clinical practice (Chambliss and Hollon, 1998). Efficacy studies emphasize internal validity, i.e., the effect of treatments in controlled settings to minimize

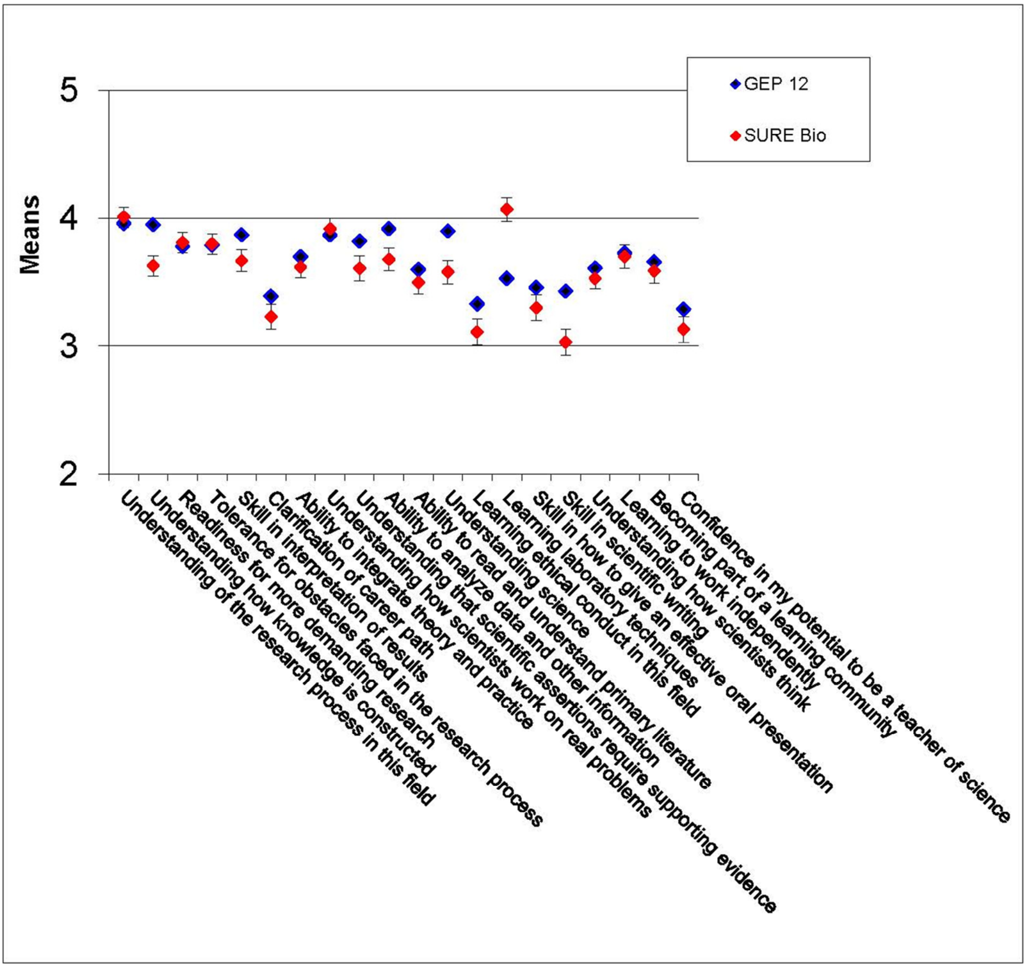

FIGURE B-2. Genomics Education Partnership students (N = 397) evaluated their genomics experience (in a CURE) on 20 learning gain items that also appear on the SURE survey, evaluated by biology research students (in a URE; N = 555). The results indicate that GEP students report learning gains comparable to URE students. (Note that the GEP is a bioinformatics project that emphasizes computer skills, and in any given participating class may not involve any wet-bench work; this may account for the low score on "learning laboratory techniques.")

confounding variables, while effectiveness studies emphasize ecological validity, i.e., the effect of treatments in a genuine, relatively uncontrolled, applied setting. The lesson for CURE research is that these two research paths do not always converge. While the tough-minded scientist may feel that only efficacious practices should be employed, practitioners argue for "what works," even if the approach does not fare well in controlled experiments. Treatments that show promise in controlled experiments may not have an effect in the open environment of the undergraduate program, while effective components of the CURE may evaporate in the laboratory. As a result, researchers may become frustrated on finding that standard experimental methods may produce an inconsistent, probabilistic picture of those variables that contribute to the success of a CURE.

The problem may go deeper than the fallibility of research design or statistical analysis. Our attempts to understand the nature of the CURE experience may yield only probabilistic outcomes because the nature of the CURE experience is such that it yields only probabilistic outcomes (Brunswik, 1943, 1952). There may be no single package of components in a CURE that guarantees success for the target outcome, no one best way.

We can further illustrate the possible frustration that may occur if CURE researchers insist on following a path toward efficacy rather than effectiveness. Recalling again the analogy to psychology's attempt to understand the nature of psychotherapy, it should be noted that therapy studies are routinely confounded by the influence of "nonspecifics," confounds that are difficult to measure. In a therapy setting, the chief candidate for a nonspecific is the therapist. Therapists may impress a client as warm or cold, experienced or inexperienced. They may inspire confidence that therapy will be productive and so produce placebo effects. Experienced and charismatic therapists may help their clients regardless of the therapy type they employ. The parallel case of the nonspecific in CURE research is the course instructor. If CUREs are to be employed across institutions to help produce the 1 million additional STEM graduates that PCAST recommends, then course instructors will loom as a major nonspecific in any model of the CURE. Some models of the URE and CURE explicitly include the influence of research supervisors and course instructors under the concept of "mentor" (Linn, et al., 2015; Lopatto, 2010). I have no doubt that effective mentoring is a strong determinant of student success in undergraduate research experiences (Figure B-3). Despite a plethora of training opportunities and

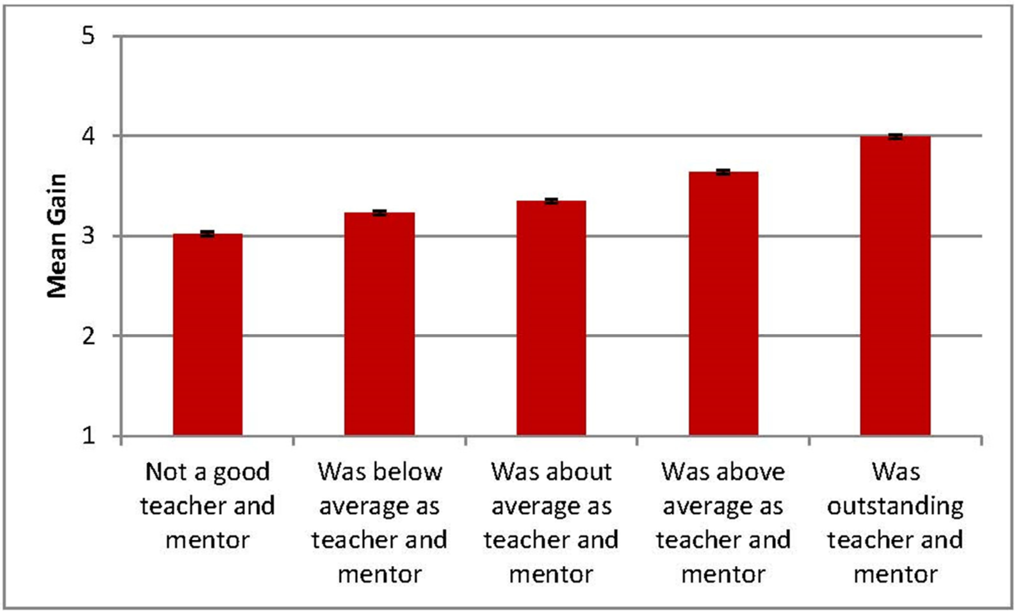

FIGURE B-3. Summer research (URE) students evaluated a set of 21 learning gains on the SURE survey, which were then averaged (Y axis). As part of the same survey, students evaluated their research mentor on a 5-point scale (X axis). The results show an orderly relationship between ratings of the mentor and the mean rating of learning gains. The analysis was based on about 2500 survey responses.

"how to" manuals (e.g., Handelsman, et al., 2005; Merkel and Baker, 2002; NRC, 1997) mentoring remains one of the least controlled variables influencing undergraduate science education experiences. The course instructor, together with her team, that may include graduate or undergraduate teaching assistants, serves the role of mentor in the CURE experience. In my experience with programs that are conducted across institutions of higher learning (Lopatto et al., 2008, 2014), I have been impressed with the level of talent and dedication that course instructors bring to their task. For example, the Genomics Education Partnership currently includes faculty from over 100 institutions, united in their determination to bring genomics into the undergraduate biology curriculum. My intuition is that the ubiquity of the GEP lies in part with the nonspecific influence of course instructors. The course instructor, like the research mentor, is the adversary to experimental control. The instructor engages in a continuous transaction with students that involves ongoing formative assessment, remediation, and fine tuning of the CURE program—in short, the ongoing confounding influence that experimental methodology forbids. I suspect that the efforts of the instructor to ameliorate any problems encountered by students will never be eliminated from the study of CUREs, nor should it be. The effectiveness of the CURE experience, however influenced by the talented instructor, will continue to challenge efficacy studies of CURE component variables. Effectiveness, rather than efficacy, may emerge as the more important and possibly even primary objective of CURE investigations.

External validity and reference populations

External validity, or generalization, depends on our ability to define reference populations of students to which a research outcome might generalize. Ordinarily we assume a fairly homogenous population from which samples should be drawn for research. We assume that the best argument for a representative sample is random selection. I suggest that in the study of CUREs we should turn more of our attention to the definition of populations, which in turn may inform our concerns about random samples. In the study of CURE programs, the research settings (otherwise called colleges and universities) are not homogenous enough to constitute a reference population. Despite efforts to bundle institutions with Carnegie classifications or U.S. News lists, institutions differ on too many variables to be regarded as one homogenous population. The lack of a reference population obviates the need for random selection of institutions for a CURE program. Instead, a promising tactic for replicating a program is to select multiple sites, intending to take advantage of the inherent diversity of these sites, and to demonstrate the effectiveness of a CURE program despite this diversity (Cook and Campbell, 1979). This approach supports the consortium model of CURE programs, in which willing participating institutions join one or more CUREs that have some programmatic uniformity across a group of campuses (Jordan, et al., 2014; Shaffer, et al., 2010). For example, the initial demonstration of the success of the SEA-PHAGES program for first-year students was obtained by studying a consortium including 30 research universities, 18 master's institutions, 22 baccalaureate colleges, and 3 associate degree granting colleges. The success of the Genomics Education Partnership was studied with a consortium that included schools with small and large student populations, residential and commuter schools, schools with predominantly traditional students and others with a high proportion of non-traditional students, as well as schools with greater than average populations of first-generation and minority students. During various efforts to study the success of the Partnership (Shaffer, et al., 2010; Shaffer, et al., 2014) we investigated the institutional characteristics of the members, including public versus private institution, total enrollment, residential versus commuter school, etc., and failed to find a significant influence of institutional characteristics on student self-reported learning gains, attitudes toward science, or content test scores. We concluded that the program had a robust effect across institutions, but did not argue that the institutions were representative of the domain of higher education.

A second discussion of reference populations in CURE research concerns the population of humans experiencing CUREs (undergraduates). While some students are involuntary participants in a science course (e.g., through specific degree requirements), I am interested in those students who start down the path toward a science degree. It is generally recognized that these students are non-randomly selected (via tests, grade point averages, or applications) and self-selected (via their willingness to engage in the study of at least one of the sciences). Further departures from randomness result from specific attempts to study the effect of CUREs in retaining nontraditional students or students from underrepresented groups in the STEM pipeline. Regardless of how they are selected, all undergraduate students are "nested" in their institutions, complicating any attempt to study the interactions between student characteristics and program components. There is, however, one characteristic that students in CUREs share, namely, that they are ostensibly within the STEM community, and therefore at risk of attrition. Risk for attrition may be the only dimension that defines a reference population for STEM students. While programs that may attract other students to science are of great interest, attraction and attrition may be treated as different concepts, and CUREs that reduce attrition may include effective characteristics that do not generalize to the programs designed for attraction. In other words, the observation that research on the nature of CURE programs is flawed because the students/research participants are non-randomly willing to be engaged with STEM programs is not a serious objection to the research methodology that yields results applicable to other students engaged with STEM programs.

Related to the discussion of sampling from reference populations is the issue of assigning research participants into treatment or comparison groups. The lack of random assignment of participants to groups may lead to the conclusion that no valuable information may be gleaned from non-randomly assigned comparison groups, but according to Cook and Campbell (1979) that conclusion is not correct. Nonequivalent control groups may yield comparative information about outcome variables. The challenge for the researcher is to explicitly identify the "rival hypotheses" that may invalidate a comparison. For example, if a course using an innovative math pedagogy yields higher math test scores than a course using traditional math pedagogy, then a critic might argue that the difference was due to an initial between-group difference in previous math achievement. This specific threat to the credibility of the result may be met by an inspection of the participants' history, such as standardized test scores.

Tactics for variable selection

The components of the URE and CURE models consist of configurations of independent variables, mediating and moderating variables, and first order and second order outcomes. One comprehensive model (Auchincloss, et al., 2014) includes a depiction showing 3 contexts by 9 activities by 24 short- and long-term outcomes. Another approach is to explicate sets of dimensions that might characterize a CURE. For example, Beckman and Hensel (2009) identify 8 sets of dimensions (e.g., student process centered versus outcome, product centered).

There are analytical tactics to reduce this complexity. For example, we could take the goal of the PCAST report faithfully and specify that the chief outcome variable is achievement of a bachelor's or associate's degree in a STEM field. This outcome is relatively easy to measure and serves as a proxy for a series of behaviors in which the student must have engaged on the path to the degree. But most researchers are not satisfied with this approach, which reveals nothing about dispositional variables such as persistence and scientific identity that may index a longer-term effect. While I agree that there are more interesting outcomes of the CURE than simply graduation in STEM, I think it necessary to raise a caution about placing our faith in dispositional constructs, i.e., those that imply personality formation or life span development. I will attempt to clarify this view with reference to two widely discussed student characteristics: persistence and scientific identity.

Persistence, for example, is a widely used term variously described as either the behavior of a student within a CURE experience or the continuation of the student's journey from one science course to the next, perhaps then extending to a URE and an application to a STEM graduate program. The first difficulty with this term is its negative connotation. We tend to talk about persistent problems or persistent illnesses, not persistent happiness or enjoyment. To describe a student as persisting in the CURE experience suggests a dogged, determined worker who is conscientious enough to slog his way through the course but not very happy about it. Better descriptors of the effortful behavior of the student within the CURE experience might be conscientiousness, intrinsic motivation, or creativity. Persistent behavior may include trouble shooting a malfunctioning instrument, repeating a procedure, or continuing to work independently beyond expectations. If persistent behavior within a CURE experience is of interest, then unobtrusive observations of how much time a student spends on the project beyond what is required or how often the student raises procedural questions may provide an index of the behavior.

Persistence is also used to describe the longer engagement with the journey toward a STEM degree and beyond. It might more accurately be named commitment. By using persistence to describe both a within-course behavior and a following-course behavior, we may be confusing the relationship between persistence and the benefits of longer engagement with undergraduate science. Within a CURE, longer instructional time is positively correlated with student-reported learning gains (Shaffer, et al., 2014). A CURE experience also increases the percentage of students who register for the next course in the discipline (Jordan et al., 2014). A decision to make a longer-term commitment to the science education path, however, is vulnerable to the developmental pressures described by psychologist Daniel Levinson (1978). Levinson, studying the development of young people, wrote that "A young person has two primary yet antithetical tasks…to keep his options open, avoid strong commitments and maximize the alternatives…versus…to create a stable life structure…and make something of his life." While some writers suggest that the development of scientific behaviors emerges only after several semesters of a URE (Linn, et al., 2015), the prolonged commitment to such programs will inevitably be challenged by attrition. Several years ago I had the opportunity to assist a consortium of mathematics faculty with a program that included two consecutive summers of

TABLE B-2. Comments made by students in the summer after their first year of LURE (left column) and after withdrawing from the program (right column). Each row represents the comments from the same student. The question in 2007 was "Are you looking forward to continuing research over the next year?" The comments in 2008 were solicited by two prompts, including "Students sometimes discontinue participation in a program for reasons unrelated to the program, including health, finances, family, etc." and "Students sometimes discontinue participation because something more attractive has come along, such as travel, other research opportunities, or other career opportunities." [Lopatto, D. (2009). Long-term Undergraduate Research Experiences (LURE): The experience of students who completed the program and those who did not. Unpublished document.]

Comments in the summer of 2007	Comments in the spring/summer of 2008
I am not doing research over the next year because research just is not something I enjoy that much.	To sit for the CPA exam in Virginia, I have to have 150 credit hours and I did not want to take another year of school, so I am taking classes over the summer to fulfill this requirement. Also, I decided that being in a math research program wouldn't have as much impact on a future career in business. It might help me to get a job, but other than that, I don't think knowing how to analyze different situations using math will be helpful.
Yes, certainly – I've had a fantastic time this summer in research .	Another research program was my primary cause for not participating in a LURE project this summer. Although I found LURE to be a stimulating and interesting experience, I wanted to broaden my summer research experiences to include some of my other interests.
Definitely.	This summer, I'm working for DRS Technologies in St. Louis. It's an internship program where we get to work on important but not "mission critical" projects in teams. Like the LURE program, there is a lot of exploration and discovery involved, but the setting is much more professional, formal, and business-oriented. I realized after a couple weeks that I very much prefer informal academic settings, but I'm still glad I took this opportunity because, in my opinion, self-discovery is better earlier rather than later.
I would be, but I don't believe I will. Next summer I will likely be moving on to other endeavors, and the upcoming semester will prove to be very trying for me.	Mathematics is not my intended field of study. If I were a mathematics major, I would likely have remained in the program. However, I felt it was necessary to keep my options open with regards to my actual field of study, and I was not able to commit to the program for a second year.
Yes I am looking forward to continuing this research over the next year.	I received an actuarial internship at an insurance company and I figured I should take that since it is directly related to what I will be doing after college.

No. Although I enjoyed this experience during the summer, I've come to realize that this is not something I want to do for the rest of my life.	I got the opportunity to do research in computer science during this summer, which is related to my honors thesis.
No, I am not continuing the research experience next year. I am not in love with math so I do not want to pursue math research since it is not one of my passions.	I wasn't sure what I was going to do this summer at the time that I made my decision, but I figured I would find something more attractive and interesting to me. I figured that my major would be Chemistry or Biochemistry and if I continued with undergraduate research (not even for this summer necessarily), I would want to conduct it in one of these areas. So I figured that if I was going to do research, doing math and chemistry research might be distracting or overwhelming. I just wanted to focus on one area and I'm more interested in chemistry.
My project was able to be completed in one summer, so I will not be continuing with the research.	I went into LURE thinking that I might want to do something with mathematics in the future and realized that this was not something that I would enjoy long term.
I am looking forward to continuing the research next school year, but not next summer. I hope to widen my summer experiences, and possibly do research in another field, or try and find a company to do an internship with.	Two members of my family were both having health problems this spring and I needed to be home this summer to help them out around the house.

undergraduate research (Hoke and Gentile, 2008). Intuiting that students might leave the program over the two-year period, we asked them about their commitment in both the first and second year. Some students dropped out of the program the second year. Table B-2 shows the comments from LURE (Long-Term Undergraduate Research Experience) students made at two times in the program. The comments from students who were initially excited about the program, but later found that they could not continue, illustrate the increasing pressures that result in attrition over a long program. Many of their reasons for not participating in the second year are reasonable, and reflect the "options open" versus "stable life structure" described by Levinson.

The formation of a stable life structure might be another way of saying that young people desire to form an identity. The term has a long and varied history in psychology and sociology. The URE/CURE research literature hypothesizes a construct, scientific identity, which serves as a mediator between learning experiences and commitment to a science career. This identity variable is both an outcome of experience and an influence on motivation. Professional identity formation may be facilitated by participation in a learning community (Graham, et al., 2013). This enhanced science identity may be related to a sense of ownership of a research project or to a sense of belonging to a science community (Corwin, et al., 2015). Despite its current widespread use, I feel that we should use the term identity sparingly. I think we mean the term to signal a complex of behaviors related to doing science. These behaviors need an environment that will allow for their expression. The display of the scientific identity, for example, is constrained by other dynamics in the life of the student. Most undergraduates experience either a prescribed general education curriculum or course selection in other disciplines that stems from a personal or imposed (e.g., by parents) desire to broaden their education. These students may find that behaving as a scientist is a suboptimal strategy for succeeding in the humanities, art, or social science. These students may learn to be adaptive—to behave as scientists, humanists, etc. in response to situational cues. Although scientific identity is suggested as related to career persistence (Corwin, et al., 2015), there are life-span influences that may require the abandonment of this identity, including failure to achieve a graduate degree, failure to find a professional position, failure to win grants, etc., moments that may favor adaptive behavior over scientific identity.

Of course, one might hypothesize that even in the absence of curricular or professional signs of scientific identity, students who experienced CURE or URE programs continue to think like a scientist. A few years ago my colleague Carol Trosset and I had the opportunity to conduct a survey of science alumnae at a liberal arts college (Lopatto and Trosset, 2008). We categorized the respondents as having had a URE experience or not while undergraduates, and then posed questions regarding their use of their science education after graduation. The responses were varied. Some respondents pursued a career in science while some did not. While some respondents could articulate a relation between their undergraduate science education and their later lives, I recall two comments that I think illustrate the difficulty of using the term scientific identity. One respondent, reflecting on her situation 5 years after graduation, reported "after completing my MS degree, I decided I was tired of working in the sciences and wanted to do something completely different." Another respondent wrote, "I was at a wonderful Ph.D. program…with the path of many, many career options ahead…but I had been apart from my husband for years and wanted to be with him and have children. My science education argued for BOTH cases…I know the biological downsides to waiting to have kids, but I also had an appreciation for the stats: If I left, I'd probably never finish my degree." It seems that the respondent's scientific identity was conditioned on situations, rather than a permanent source of motivation to do science.

If we continue to think about the establishment of a scientific identity as a disposition or personality variable, then the door is open to the study of other identities as well. Gender and race loom large as identities that may interact with the formation of a scientific identity. A student who has experienced the life of a White male in the United States may enter college with a different identity than a student who identifies as a Hispanic female. The White male student may be far less actively engaged with considering or defending his identity than the Hispanic female, who may face challenges to her identity through microaggressions (Harwood, et al., 2012) or stereotype threats (Steele, 1997). Her effort to establish a scientific identity among her other identities may involve more cognitive and emotional energy than his. The study of how a person navigates among identities is termed "intersectionality" (Cole, 2009). The challenge of intersectionality complicates the formation of a scientific identity in ways that have not been fully studied.

The consortium as (quasi-) experiment

By a consortium I mean a group of programs or institutions organized around a common set of activities, in the present context to promote undergraduate science education. I leave it to others to point out the possible economic and resource advantages of a consortium over an unaffiliated collection of programs. My interest is in discussing the advantages for research on CUREs afforded by the consortium over a piecemeal inspection of programs at individual institutions.

According to Campbell, a quasi-experiment is an experiment that has "treatments, outcome measures, and experimental units, but does not use random assignment to create comparisons from which treatment-caused change is inferred. Instead, the comparisons depend on nonequivalent groups that differ from each other in many ways other than the presence of a treatment whose effects are being tested…In a sense, quasi-experiments require making explicit the irrelevant causal forces hidden within the ceteris paribus [other things being equal] of random assignment" (Cook and Campbell, 1979; see also Campbell and Stanley, 1966). Many published accounts of CURE programs qualify as quasi-experiments; however, studies of a single institutional program lack the richness of information that is provided by the study of a CURE over multiple settings. One program that has yielded rich information about the nature and impact of a CURE is the Genomics Education Partnership.

The Genomics Education Partnership was founded by Prof. Sarah Elgin and originally supported by the Howard Hughes Medical Institute (Lopatto, et al., 2008). Several descriptions of the program are in print, so rather than compose another I quote from the article:

> The GEP is a consortium in which more than 100 colleges and universities (mostly primarily undergraduate institutions, or PUIs) have joined with Washington University in St. Louis (WUSTL) with the goal of providing undergraduates with a research experience in genomics (see http:// gep.wustl.edu). The GEP is investigating the evolution of the Muller F element, a region of the Drosophila genome that exhibits both heterochromatic and euchromatic properties, and the evolution of the F element genes. Undergraduates are involved in both finishing (improving the quality of draft sequence) and annotating (creating hand-curated gene models based on all available evidence, mapping repeats, and identifying other features) designated regions of the Drosophila genome. They work on 40-kb "projects," which, after quality control checks, are reassembled to generate large domains for analysis. GEP materials have been adapted to many different settings, from a short module in a first genetics course to the core of a semester-long laboratory course to an "independent study" research course. A common student assessment is carried out using the central website. Pre/post-course quizzes demonstrate that GEP students do indeed improve their knowledge of genes and genomes through their research (Shaffer et al., 2010, 2014). Post-course survey results from 2008 and 2010–2012 on science attitudes are consistent and show an overall pattern and numerical scores very similar to those of students in a dedicated summer research program (Lopatto, 2007; Lopatto et al., 2008; see especially Shaffer et al., 2014). All student projects are completed at least twice independently, and a reconciliation process is carried out by experienced students working at WUSTL during the summer. Student annotations are deposited in GenBank and form the core of our scientific publications, which analyze the reassembled regions as a whole (e.g., Leung et al., 2010). A paper based on comparative analysis of the F element of four Drosophila species, now in preparation, will have more than 1000 student and faculty coauthors. Thus, by both pedagogical and scientific

> measures, the GEP appears to have assembled a group of faculty who each has successfully developed a CURE on his or her campus. (Lopatto, et al., 2014, 713)

The original GEP description (Lopatto, et al., 2008) used the phrase "original research experiences within the framework of course curricula." This phrase is a reasonable working definition of the CURE. Undergraduate research experiences have been defined by several authors (Lopatto, 2003, 2007); the key constraint on the CURE compared to the URE is time. Whereas a URE may include 10 weeks of dedicated summer research, a CURE must somehow fit in the time allotted for a course that might cover 14 weeks (more, if the course continues over several terms, e.g., Jordan et al., 2014; less in other academic schedules), and the CURE competes for the student's attention with other programs with which the student interacts concurrently.

The GEP includes a large sample of institutions varying on the dimensions of size, student body, etc. as mentioned earlier. The full force of this large consortium is not to parse the institutional characteristics in a search for interactions with treatment, but rather to make the argument that the program has an effect despite the error introduced by the varying institutional characteristics. The treatment is a complex package including workshops for faculty, workshops for teaching assistants, a central website with shared curriculum and a wiki for sharing additional information, and a central support system provided by the staff at Washington University in St. Louis (see Lopatto, et al., 2014). The treatment is administered locally by one or more instructors, who determine the "dose" in the sense of how much instructional time is devoted to genomics. While no randomly assigned control group for comparisons is possible, nonequivalent control groups provided some basis for comparisons.

Measurement of outcomes

If we consider only the succinct text of the PCAST report, the minimal outcome we need be concerned about as practitioners is the increase in the number of STEM degrees. Researchers of the CURE programs, however, are often interested in more than the outcome of awarding of degrees. They endeavor to create instruments that yield information about student's experiences and learning gains. To increase the credibility of individual instruments, methodologists pursue the path of classical test theory, in which validity and reliability of the instrument are demonstrated through correlational procedures. The advice stemming from the study of quasi-experiments calls for multi-operationism, that is, the use of multiple measures that may converge on a credible finding (Cook and Campbell, 1979). The assumption of multi-operationism is that measures that ostensibly tap into the same construct should correlate or converge on the same "signal", the effect of the construct under study; however, just as important to the assumption is that two measures that share the same "signal" do not share the same "noise", that is, that their sources of error should be different. For example, a survey eliciting student ratings of a CURE experience may correlate with a measure of student lab attendance. To the extent that they do not correlate perfectly, the sources of error for the survey may be that students misinterpret survey questions or have reading difficulties, while for attendance students may have non-voluntary absences due to illness. This independence of errors makes the any correlation between the measures more meaningful.

Multi-operational evidence in the GEP

The multi-operational approach to measurement serves to reassure us that a finding is credible. For the GEP, multiple measures indicate that the class-based URE (i.e., the CURE) is in fact a URE experience. One source of evidence is the recognition that genuine research contributions are emerging from the program. The GEP has generated published research papers (e.g., Leung, et al. 2010; Leung, et al. 2015). A second source of evidence is the report of the GEP students framed against a benchmark of similar reports from students who completed a dedicated summer research experience (URE). Such a comparison is possible because the version of the post-course survey used by the GEP employed a set of 20 learning gain items used in the Survey of Undergraduate Research Experiences (SURE; Lopatto, 2004). The comparative results are shown in Figure B-2. Generally, the GEP students report learning gains comparable to those reported by the URE students. In addition to the close proximity of the mean scores, the pattern of results, i.e., how the means compare within a group, appears similar for the GEP and URE students. This similarity has proven reliable (Figure B-4). Additionally, every year qualitative comments are recruited from GEP students that comport well with the quantitative measures.

GEP students become acquainted with genomics practices such as annotation and finishing (see above). The group of instructors who are GEP members have designed quizzes to measure gains in these two knowledge areas. The quizzes are given pre- and post-course. At first glance, any increase from pre- to posttest in esoteric knowledge might be sufficient to convince us that learning has occurred. However, the quasi-experimental approach encourages us to think about rival hypotheses that might account for the gain. In the course of the GEP implementation, three nonequivalent control groups emerged. Two of these permitted us to discard two rival hypotheses to the view that students were learning not only about annotation and finishing, but more deeply about genes and genome: namely, test sensitization and maturation. Test sensitization is the hypothesis that students will improve their posttest scores by virtue of having seen the test before as the pretest. When the GEP first introduced the annotation and finishing quizzes, we used the same test for pre- and posttest. By chance some of the GEP students across institutions did not complete the pretest but did complete the posttest. I compared the posttest scores for students who saw the pretest with scores from students who did not. The results are shown in Figure B-5. It appears that test sensitization did affect posttest scores. In response, the GEP instructors created two equivalent form tests so that the pretest is not identical to the posttest. (Students are randomly assigned to one or the other for their pretest, and receive the other for their posttest.) This "equivalent forms" approach has eliminated the test sensitization confound.

Maturation is the hypothesis that performance on a test improves simply because the student aged, matured, or profited from nonspecific life experiences. If maturation holds as a rival hypothesis, then we lose our trust in pretest-posttest gains. For that reason, GEP instructors volunteered to recruit non-GEP students from biology courses to take the annotation and finishing quizzes. These nonequivalent controls were exposed to biological knowledge during the semester. They presumably aged and matured at the same rate as the GEP students. Their test performance is shown in Figures B-6 and B-7. The figures illustrate that the GEP students' posttest mean was greater than both their own pretest mean and the posttest mean of the nonequivalent comparison group.

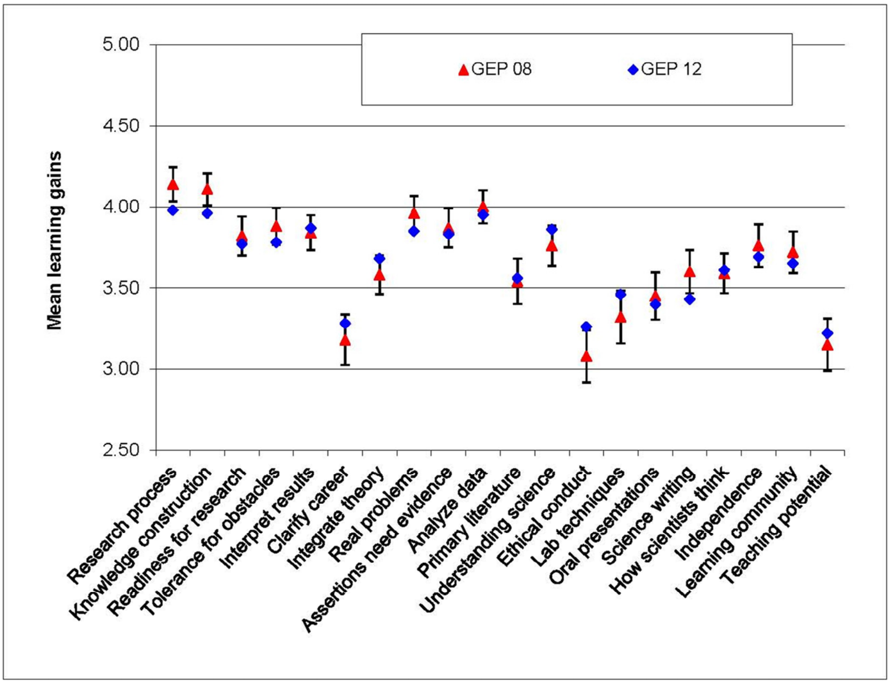

FIGURE B-4. Students in the GEP program in 2008 (N = 308) rated 20 items for learning gains. Students in the GEP program in 2012 (N = 397) evaluated their experience in a similar pattern (error bars represent 2 standard errors about the 2008 means).

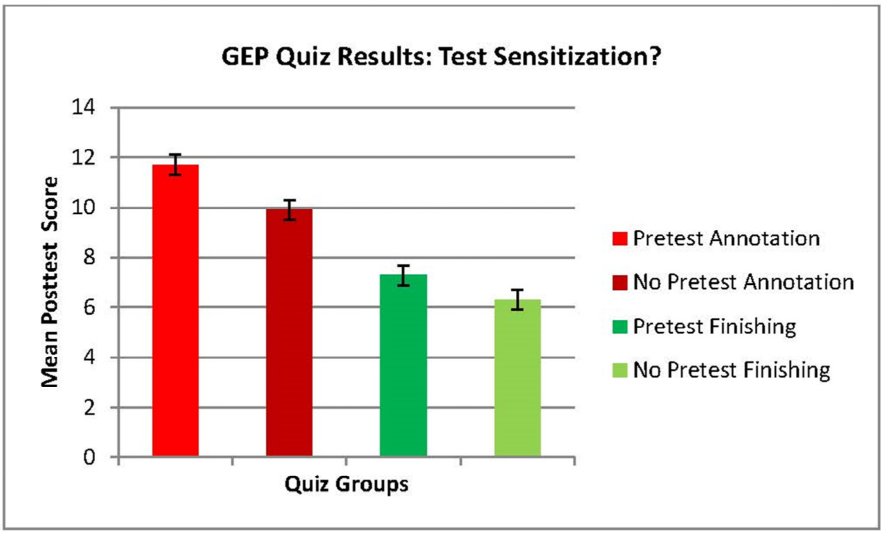

FIGURE B-5. GEP students were given quizzes regarding annotation and finishing techniques, and understanding of eukaryotic genes and genomes. In the first year of the quizzes the pretest was identical to the posttest. Mean posttest scores are shown on the Y axis. Nonequivalent control groups were formed from students who did not take the pretests. A comparison shows a possible effect for test sensitization and led to the creation of two equivalent forms for use pre/post (overall N = 233).

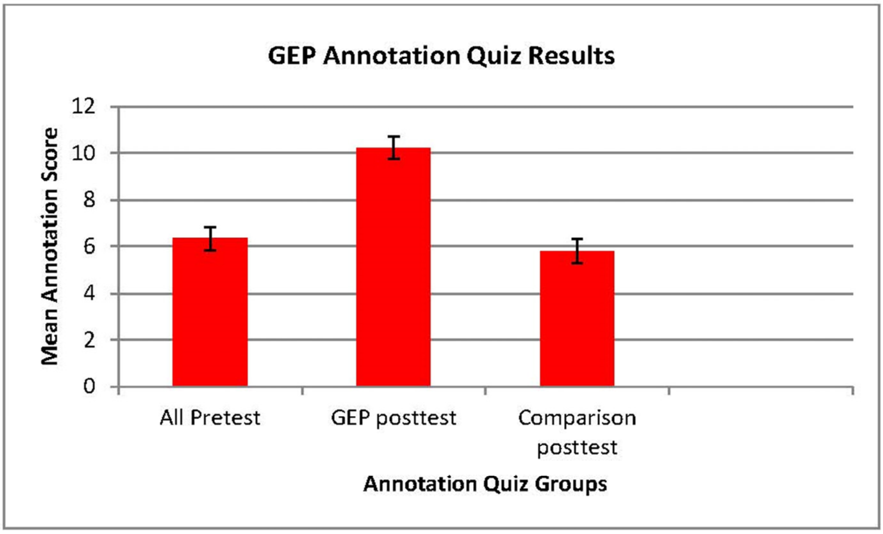

FIGURE B-6. Mean scores on the annotation quiz for GEP students and students from a nonequivalent control group. Pretest scores were indistinguishable between groups and so are combined. The higher mean score for the GEP posttest combined with the lack of change in the control group argues against the rival hypothesis that posttest gains were due to maturation (162 GEP students and 106 comparison students).

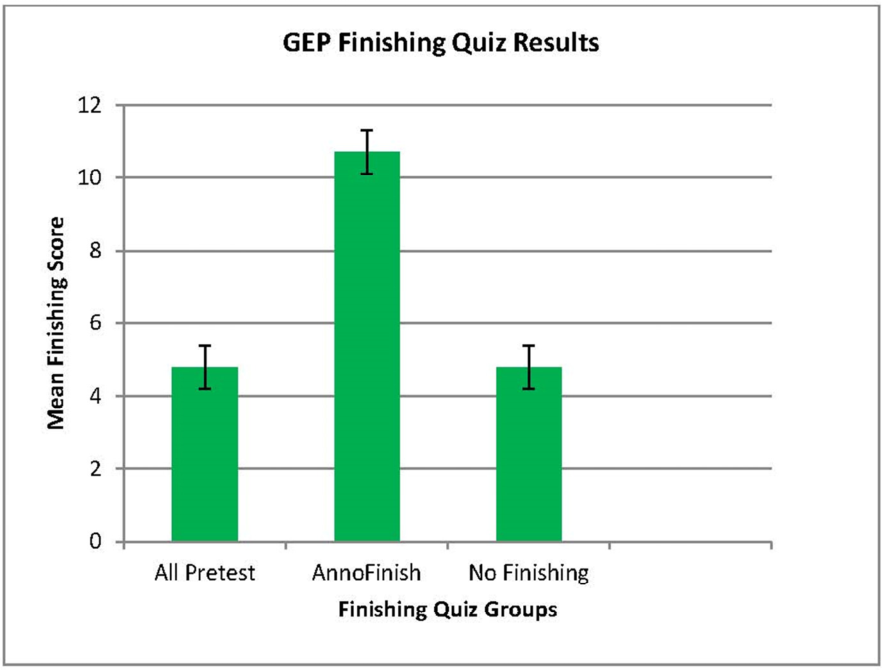

FIGURE B-7. This figure is similar to Figure B-6, but shows the mean scores on a finishing quiz. All of the students had instruction in annotation, but some did not have instruction in finishing. (N = 46 for the finishing group versus N = 116 in the no finishing group.)

In addition, Figure B-7 shows the third quasi-control group. Instruction on annotation and instruction on finishing are separable, with many more GEP sites teaching annotation than both annotation and finishing. To better understand the added value of instruction in finishing, the scores on the finishing quiz were examined for students who had explicit training in both annotation and finishing (the "annofinish" group) compared to students who had only annotation instruction (the "no finishing" group). The results show higher mean score for students who had finishing instruction and research participation in this area, and argue against any general gains in knowledge by virtue of instruction and research in annotation.

Taking the multi-operational approach, we explored the relationship between quiz scores as a measure of gains in content knowledge and student self-report of learning gains. The student survey used for the GEP includes both the items mentioned above as part of the SURE survey as well as items specifically related to features of the research project. We found that the relationship between quiz scores and self-report depended on the specificity of the survey question with the course activity (for example, Figure B-8). Where a survey item was specific to a course activity, the correlation between the quiz score and the item was in the range of 0.2 to 0.3 (statistically different from 0, modest in magnitude); more general survey items did not correlate with quiz scores. Both quiz scores and survey scores were sensitive to "dose" effects of instruction (Figures B-9 and B-10). A fuller presentation of this relationship is found in Shaffer, et al. (2014).

The effectiveness of the features that characterize the GEP as a consortium—faculty training, teaching assistant training, shared curriculum, a central support system provided by Washington University in St. Louis, diverse faculty implementation strategies on different campuses—are indirectly validated by the student data. The multi-operational approach suggests that data collected from another group of "subjects," the GEP faculty, would provide some convergent validation to the argument that the consortium is a successful CURE program. We undertook to recruit faculty information and reported strong evidence for the key role of the central support system (Lopatto, et al., 2014) via both structured survey items and qualitative responses to prompts.

Does the success of the GEP generalize to reference populations of institutions and students? As discussed above, it is not clear that a homogenous reference population of institutions exists. The GEP demonstrates a CURE that affects student learning despite the differences among institutional members. The next step in the search for generality would be to replicate the effect with a new institution. The ease of replication is an additional attractive feature of the consortium as experiment, that is, a candidate for replication need only join the consortium.

Multi-operationism—what is related?

Recent literature suggests many domains of outcomes that could be affected by CUREs (Corwin, et al., 2015), as well as several directions for future measurement (Laursen, 2015). Going forward, it will be useful to sort out which outcome variables serve as key indicators of CURE success, and which outcome variables may not correlate with each other despite their equal significance. In other words, in mapping the outcomes of the CURE, should we adopt a one-to-many mapping or a many-to-one mapping? A one-to-many mapping would consist of

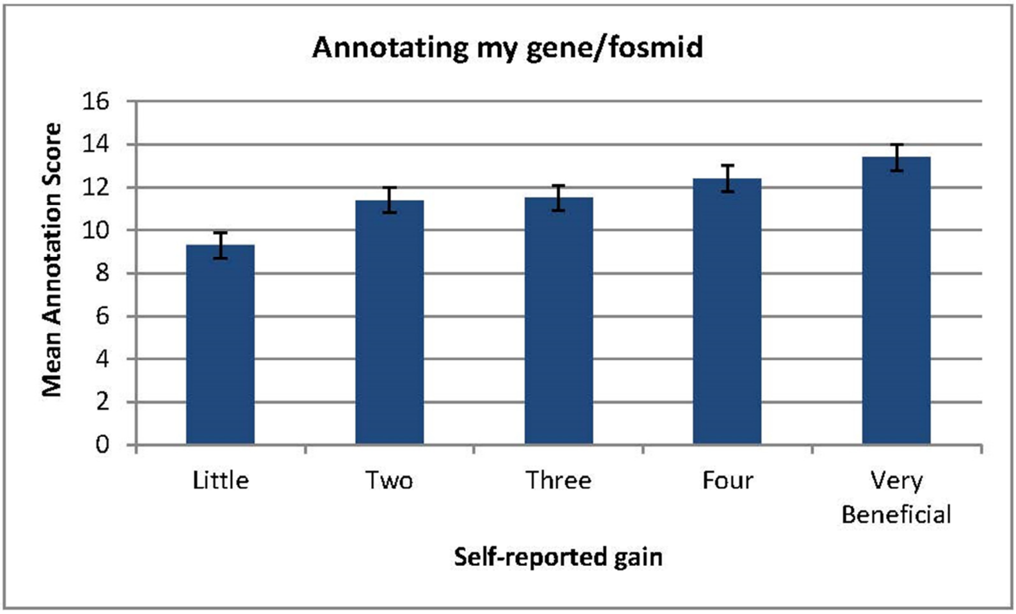

FIGURE B-8. One example of the relationship between a GEP student self-report question (how beneficial was training on annotating my gene/fosmid) and the mean annotation quiz score for the same student. Self-evaluation items correlated with quiz scores in the range of 0.2 to 0.3, using Pearson's r. (N = 243; see Shaffer et al., 2010).

finding a key indicator of CURE success and then concluding that other indicators shown to be correlated with the key are also present. For example, if it can be shown that "ownership" (Hanauer and Dolan, 2014) routinely correlates with characteristics such as interest in the field or the ability to work independently, we may be able offer a simplified assessment program to CURE practitioners focusing on the ownership measure. On the other hand, we may discover that two commonly measured outcomes, such as content knowledge test scores and student self-reports, correlate poorly in a CURE program. In the GEP assessment (Shaffer et al., 2010) we found evidence of correlations between a content test of the practice of annotation in genomics and student self-reports of knowledge gain. These relationships were modest, however, and confined to self-report items that specifically asked about content learning. More global items, such as those related to self-confidence or working independently, did not relate to content test scores.

One may well wonder if content knowledge has a significant relationship with longer term commitment to a STEM career. Jordan and her colleagues created a test of biological concepts to be administered both to students in an experimental SEA PHAGES program and to controls. The intent of the testing was to demonstrate that the mean scores for the two groups would not differ, thus resisting the criticism that involvement in a CURE program might interfere with learning course content, and indeed they did not (Jordan, et al., 2014). If the students in the SEA PHAGES program go on to contribute to the increase of 1,000,000 degrees in STEM demanded by the PCAST report, it will not be due to the inferior or superior acquisition of content knowledge.

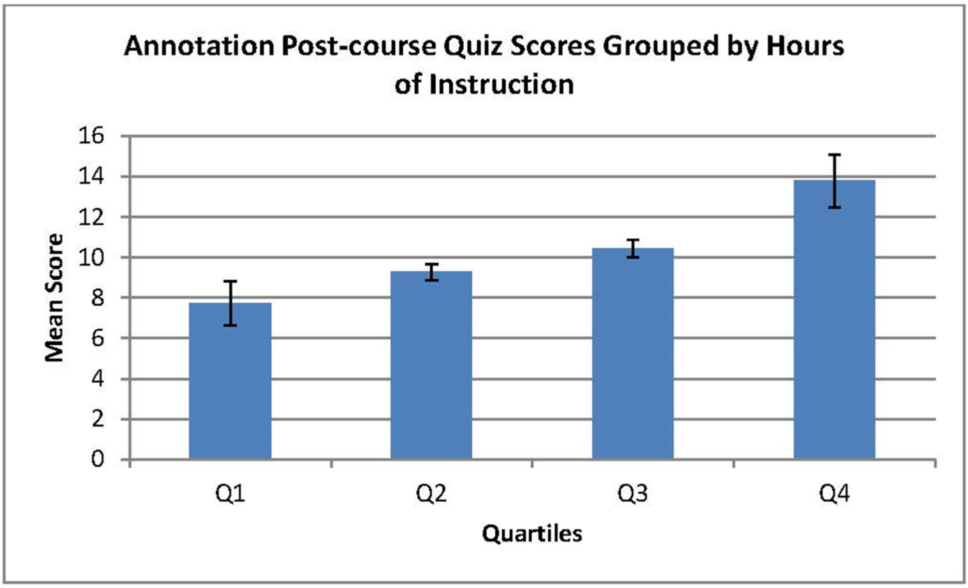

FIGURE B-9. Data from GEP instructors were used to construct four quartiles of hours of instruction (including lecture, discussion, lab time) in annotation. The quartiles reflect groupings of 1-9 hours, 10-23 hours, 24-39 hours, and more than 40 hours of instruction. These quadrants (X axis, least to most) are displayed with mean annotation quiz scores. The figure depicts the effect of instructional time (see Shaffer, et al., 2014; overall N = 773).

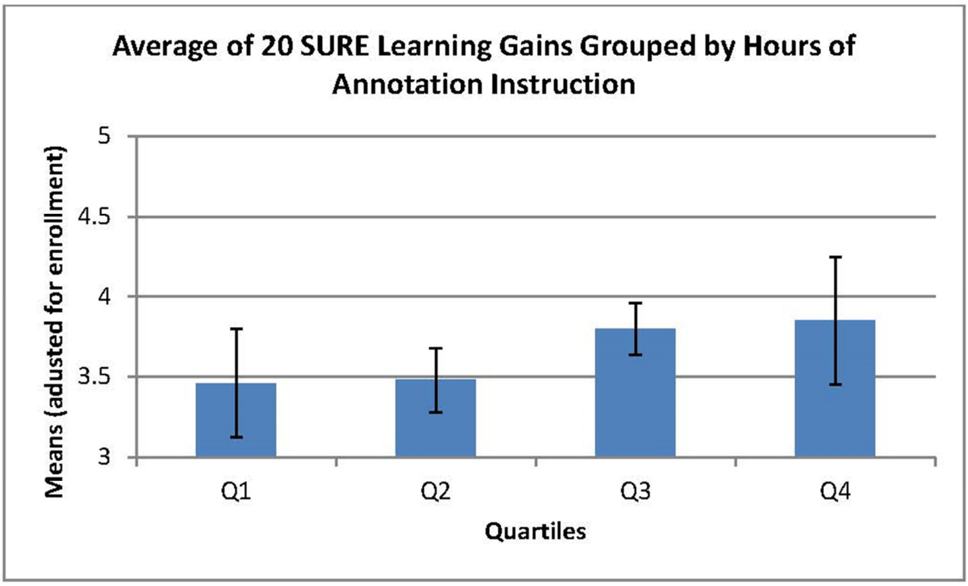

FIGURE B-10. The same four quartiles of instructional time shown in Figure 9 were used to display mean student scores on 20 self-reported learning gains. The students in Q3 and Q4 have significantly higher mean learning gain scores than the students in Q1 and Q2 (overall N = 773; see Shaffer et al., 2014).

Ultimately, the selection of appropriate measures for assessing the success of CURE programs depends on the objectives of the programs. The minimal PCAST objective, yielding more bachelor's or associate's degrees in the STEM fields, might be sufficiently assessed through grades and registration patterns. If, as I suspect many CURE researchers believe, the CURE program is an occasion for shaping scientific motives and ways of thinking that may result in an interest in STEM fields beyond just graduation, then we should acknowledge the importance of self-report measures. Some 20 or so years ago the conversations regarding assessment of student learning generally fell into describing a dichotomy between "direct" and "indirect" measures of learning. Direct measures consisted of content and procedural learning as measured by local tests or standardized tests such as the GRE (Graduate Record Exam) or the CLA (Collegiate Learning Assessment). Descriptions of experience given by students through surveys, interviews, and focus groups were said to be indirect measures of learning, and were treated with some suspicion because student responses could be boastful, cautious, or merely delusional. But, as I have suggested (Lopatto, 2007) the question we need to ask is, the direct measure of what?

> In the current research the student respondent was promised anonymity, precluding the matching of student survey responses with information from other sources. Beyond the tactical difficulties of identifying student responses or recruiting observations from supervisors, however, the challenge of validity is complicated by the concept of the "direct measure." Within the standard science curriculum, a direct measure is often equated with an exam or laboratory exercise in which the student demonstrates memory for and skill in the use of the disciplinary information taught by an instructor. Other measures, such as the student's self-reflection, are considered "indirect." Skeptical of indirect measures of course behavior, researchers often demand that the indirect measure be validated with the direct measure. Within the undergraduate research experience, however, there are learning and experience goals that may be most directly measured by student report. Estimates of personal development, including tolerance for obstacles, readiness for more research, and self-confidence, are best made by the person who has direct access to these estimates. Estimates of the student's likelihood to continue with science education and a science career can only be forecasts, and the person best positioned to make the forecast is the student. Some of the most desirable outcomes of an undergraduate research experience, including maturity, positive attitude toward science, and an intention to continue in the field, are most directly measured by student report. In short, the requirement for a direct measure needs to be clarified by posing the question, "The direct measure of what?"

If we wish to know if an undergraduate science major plans to go on to graduate school, we need to ask her. Her future in graduate school will not be predicted by content or critical thinking scores if she does not intend to submit an application. I am convinced that the study of student motives and attitudes, best known, however imperfectly, through direct report by the student, will be crucial to understanding the impact of any undergraduate pedagogy. The psychologist Kurt Lewin (1943) asserted that behavior depends on the sum of the person's experience, which he called the psychological field, at the time of the behavior. The psychological field consists of the influence of the past and future on the person in the present time. An undergraduate in a CURE program will respond in a way affected by his or her past experience, his or her present experience of the CURE, and his or her expectations of the future, as he or she views them at that time. The most direct means to knowing these is to ask.

The thrust of this article has been commentary salted with data for the purpose of suggesting a research strategy for the study of CURE effectiveness. The magnitude of the goal set out in the PCAST report requires that we move toward a research strategy that yields results to facilitate change. As presented above, I have argued that the main features of this strategy should be to emphasize the effectiveness of teaching and learning practices in the learning environment, to distinguish between attrition and attraction of potential science graduates, to avoid describing student success in dispositional terms, and to understand the advantages of a multi-operational approach to research in a consortium. Using the scope and diversity of the science education consortium, we should be able to discover the commonalities and contrasts in practice that will expand successful undergraduate science education.

Appendix C
Participant List

David Asai	Howard Hughes Medical Institute
Pranoti Asher	American Geophysical Union
Gita Bangera	Bellevue College
Cynthia Bauerle	Howard Hughes Medical Institute
Lida Beninson	AAAS / NSF
Elizabeth Boylan	Alfred P. Sloan Foundation
Elizabeth Brenner	NRC
Sara Brownell	Arizona State University
Jim Burnette	University of California, Riverside
David Burns	National Center for Science and Civic Engagement
Goldie Byrd	North Carolina A & T State University
Malcolm Campbell	Davidson College
Niccole Cerveny	Mesa Community College
Vincent Cordrey	Northern Virginia Community College
Edward Coyle	Georgia Institute of Technology
Beth Cunningham	American Association of Physics Teachers
Sean Decatur	Kenyon College
Erin Dolan	University of Texas at Austin
Meredith Drosback	Office of Science and Technology Policy
Sarah C. R. Elgin	Washington University in St. Louis
Arthur Ellis	City University of Hong Kong
Linnea Fletcher	Austin Community College/Co-PI, Bio-Link
Robert Full	UC Berkeley
S. James Gates, Jr.	University of Maryland

Nathan Gaul	Northern Virginia Community College
James Gentile	Hope College
Jo Handelsman	OSTP
Graham Hatfull	University of Pittsburgh
James Hewlett	Community College Undergraduate Research Initiative
Gail Hollowell	North Carolina Central University
Sally Hoskins	City College of the City University of New York
John R. Jungck	University of Delaware
Patrick Killion	University of Maryland
Mary Kirchhoff	American Chemical Society
Angela Kolesnikova	NRC
Gül Kremer	National Science Foundation
Jay Labov	National Academy of Sciences
Matt Lammers	NRC
George Langford	Syracuse University
Marcia Linn	University of California, Berkeley
John-Hanson Machado	George Washington University
John Matsui	University of California, Berkeley
Margot McDonald	California Polytechnic State University, San Luis Obispo
Dave Micklos	Cold Spring Harbor Laboratory
Cathy Middlecamp	UW-Madison
Wendy Newstetter	Georgia Institute of Technology
Steve Olson	NRC
Jillian Paillin	Howard University
Dawn Rickey	National Science Foundation
Margaret Riley	U. Mass Amherst
Courtney Robinson	Howard University
Anne Rosenwald	Georgetown University
Troy Sadler	University of Missouri

Heidi Schweingruber	NRC
David Shaffer	University of Wisconsin, Madison
Erica Siebrasse	American Society for Biochemistry and Molecular Biology
Sarah Simmons	Howard Hughes Medical Institute
Susan Singer	NSF
Mary Smith	North Carolina A & T State University
Gabriela Weaver	UMass Amherst
Jodi Wesemann	American Chemical Society
Donald Wink	UIC Chemistry
Robin Wright	University of Minnesota

Appendix D
Biographical Sketches of Organizing Committee Members and Workshop Speakers

CHAIR

Sarah C.R. Elgin is Professor of Biology, Professor of Genetics, Professor of Education, and Victor Hamburger Professor of Arts & Sciences at Washington University in St. Louis (WU). She developed an interest in biochemistry/molecular biology in high school, so majored in chemistry at Pomona College. A summer spent at Caltech led to an interest in the role of chromatin structure in control of gene expression that continues to the present. Completing a PhD with James Bonner exploring the role of nonhistone chromosomal proteins, Dr. Elgin also did postdoctoral research at Caltech with Leroy Hood, working to develop tools to characterize chromatin in Drosophila. Following a move to a faculty position at Harvard, work with her students led both to a method to determine the distribution of specific proteins in the polytene chromosomes using immunofluorescence, and to methods for analyzing the nucleosome array, including identification of accessible regulatory sites. Work at WU led to a detailed picture of the chromatin structure of an inducible gene, hsp26, and to the identification of Heterochromatin Protein 1 (HP1), shown by genetic and cytological analysis to play a key role in heterochromatin formation and gene silencing. Current work focuses on the establishment of heterochromatin, investigating both targeting mechanisms and maintenance. Dr. Elgin has taught undergraduate and graduate lecture/discussion courses on chromatin structure/function; a large introductory course in molecular genetics (lecture/ lab/ discussion); a lecture/lab course on genetics for non-science majors; “DNA Science” both for K-8 and high school teachers; phage bioinformatics for freshmen; and an upper level lab course that engages junior/senior undergraduates in research in Drosophila genomics. She served as Director for WU’s HHMI Undergraduate Biological Sciences Education Program from 1992-2004, and has been an HHMI Professor since 2002. In 2006 she founded the Genomics Education Partnership (http://gep.wustl.edu) to engage undergraduates in genomics research, and continues to direct this project. Dr. Elgin has received awards for her contributions to science education from ASCB, ASBMB, and GSA, and is a Fellow of AAAS and the American Academy of Arts & Sciences. She currently serves on the editorial boards of Chromatin & Epigenetics and CBE-Life Science Education, as well as the Board on Life Sciences (NAS), the SAB for iPLANT, and the Advisory Board for CourseSource.

COMMITTEE

Gita Bangera is currently Dean of Undergraduate Research at Bellevue College, a community college in Bellevue, WA. She is a PULSE (Partnership for Undergraduate Life Science Education) leadership fellow and Principal Investigator of an NSF-supported project, C-ARE: ComGen - Authentic Research Experience Expansion. She is also Adjunct Professor in Plant Pathology at Washington State University, and an inventor and technical consultant for Intellectual Ventures with over 75 patent applications. As Dean she is building a new division called RISE Learning Institute focused on bringing Research, Innovation, Service and Experiential Learning to curricula across the Bellevue College campus. Dr. Bangera was invited to be a participant in the community that helped develop the recommendations in the AAAS report, Vision and Change in Undergraduate Biology Education, because of her early work with the ComGen program which introduced undergraduates at community colleges to authentic research experiences. ComGen has been profiled as a pioneering program by Science magazine (13 Sept. 2011). Faculty from approximately 15 institutions (colleges and universities) in Washington State are trained and are now implementing the ComGen pedagogical technique. Her current focus is the impact of classroom based undergraduate research as a way to diversify the scientific community. Previously Dr. Bangera was a Senior Scientist at Combimatrix Corporation and conducted Post-doctoral Research at Harvard Medical School, University of Washington Medical School, and University of Copenhagen. She received her doctorate in Microbiology at Washington State University, Master's in Biology from Carnegie Mellon University, and a Master's in Microbiology from University of Mumbai.

Sean M. Decatur became the 19th president of Kenyon College on July 1, 2013. He served previously as the dean of the College of Arts and Sciences at Oberlin College. He also was a professor of chemistry and biochemistry at Oberlin. Dr. Decatur joined the faculty at Mount Holyoke College in 1995 as an assistant professor of chemistry. As an associate professor of chemistry, he served as department chair from 2001-04. In 2005, he was appointed the Marilyn Dawson Sarles Professor of Life Sciences. He also was an associate dean of faculty for science from 2005-08. On the faculty at Mount Holyoke, Decatur helped establish a top research program in biophysical chemistry. He also developed unique courses, including a race-and-science lecture series; a course exploring ethical, social, and political questions related to scientific topics; and a team-taught course that integrates introductory biology and chemistry. During his time as dean and under his leadership at Oberlin, Dr. Decatur helped lead a review of major curricular requirements with a number of significant changes under way that have brought more focus to the academic program. He also helped strengthen the Oberlin faculty and planned a new system for post-tenure faculty review and pushed for a deep curricular connection between Oberlin College and the Allen Memorial Art Museum. He has won research grants from NSF and NIH and from private foundations including the Alzheimer's Association, Dreyfus Foundation, and Research Corporation for Science Advancement. He is the author of numerous scholarly articles and has received a number of national awards for his scholarship, including a NSF CAREER award in 1999 and a Henry Dreyfus Teacher-Scholar Award in 2003. He was named an Emerging Scholar of 2007 by Diverse: Issues in Higher Education magazine.

He earned a bachelor's degree at Swarthmore College and a Ph.D. in biophysical chemistry at Stanford University.

Erin Dolan has held tenure-track and tenured faculty positions at Virginia Tech and the University of Georgia, where she also held the position of Senior Scholar in Biology Education. Dolan is the founding Executive Director of the Texas Institute for Discovery Education in Sciences (TIDES) in the College of Natural Sciences at The University of Texas at Austin. The mission of TIDES is to catalyze, support, and showcase innovative, evidence-based undergraduate science education. TIDES promotes experiential learning for undergraduates, especially through research experiences such as the Freshman Research Initiative (https://cns.utexas.edu/fri) and summer research internships. TIDES also offers professional development on teaching for current and future faculty, and conducts education studies to evaluate program efficacy and impact and inform future programmatic directions. Dolan's research focuses on understanding science research as an educational context. Her group studies scalable ways of engaging high school and undergraduate students in science research, mentoring of undergraduate researchers, and research as a mechanism for undergraduates to access to social capital within the scientific community, especially for students from backgrounds that are underrepresented in the sciences. She is principal investigator or co-investigator on more than $6 million in grants from the National Institutes of Health, National Science Foundation, Howard Hughes Medical Institute, and other agencies. Her work has been published in peer-reviewed journals read by scientists, teachers, and education researchers. Dolan is also Editor-in-Chief of CBE – Life Sciences Education (http://www.lifescied.org/), which has been described as the premier journal of biology education research and practice. She has been an invited speaker at national meetings of scientific societies such as the American Society for Cell Biology and American Society of Plant Biologists. Dr. Dolan earned a B.A. in Biology at Wellesley College and Ph.D. in Neuroscience at the University of California at San Francisco.

Laura Guertin's is Professor of Earth Science at the Pennsylvania State University, Brandywine. Her primary research focus is the effective integration of innovative technologies to improve student learning in introductory-level geoscience courses. Research projects with students have included using Palm Pilots, iPods, GPS, Google Earth, and other technological tools for geoscience research and outreach. She has been awarded the Penn State – Commonwealth College Award for Teaching Excellence, Penn State's George W. Atherton Award for Excellence in Teaching, and in 2009 was recognized at the national level with the Biggs Earth Science Teaching Award, an award that places her in the Geology Hall of Fame. She is the campus coordinator for the environmental inquiry minor. She has received funding from NSF, EPA, and the Society of Women Environmental Professionals. She is a co-principal investigator on a $9.2 million NSF-Targeted Math Science Partnership grant to improve middle school Earth and space science teaching in Pennsylvania. She is the past chair of the Geoscience Division of the Council on Undergraduate Research and a former councilor-at-large with the National Association of Geoscience Teachers. She currently serves on the Executive Committee of the Pennsylvania Earth Science Teachers Association and serves on the Board of Trustees of Tyler Arboretum. She blogs for the American Geophysical Union (AGU) on geoscience education and educational technology at GeoEd Trek. Dr. Guertin received her B.A. in Geology from Bucknell University and her Ph.D. in Marine Geology and Geophysics from the University of Miami's Rosenstiel School of Marine & Atmospheric Science. In 2015 she was named one of the Top 100 Women in STEM by *INSIGHT into Diversity* magazine and a Fellow of the Geological Society of America.

Wendy Newstetter served as the Director of Learning Sciences Research in Georgia Tech's Department of Biomedical Engineering (BME) from 2000-2012, where she pioneered the development of problem-driven environments for learning. These efforts resulted in the BME department winning the 2013 Georgia Regents Excellence in Teaching Award for departments. These problem-driven models for educational reform were informed by ethnographic investigations of the cognitive and learning practices found in interdisciplinary research laboratories or in vivo settings and then translated into in vitro models for interdisciplinary classes and instructional laboratories. This authentic to synthetic or translational model of educational reform seeks to achieve greater fidelity between the socio-cognitive practices deployed on the frontiers of science and those that students are apprenticed to in science and engineering classrooms and instructional laboratories. Science as Psychology: Sense-Making and Identity in Science, the book reporting on research findings in tissue and neuroengineering laboratories, co-authored by Dr. Newstetter, won the American Psychological Association William James Book Award in 2012. As a senior editor for the Journal of Engineering Education from 2009-2012, she conceived and instituted Special Issues to promote a greater focus on important topics in engineering education. In 2012, Dr. Newstetter was named a top twenty engineering and science professor in Georgia. She is most recently the PI on an NSF I-Corps Learning grant to explore translating a learning innovation into a viable commercial product. She received a Ph.D. in Linguistics from Lancaster University in the United Kingdom.

Elvyra San Juan leads the Capital Planning, Design and Construction (CPDC) department in providing system wide management, administration and long-range planning of the physical development aspects of The California State University (CSU). This includes preparation and administration of an annual state and non-state capital outlay program. Ms. San Juan provides system wide policy leadership for development of the campuses and provides training utilizing campus model practices and lessons learned to improve the twenty-three campuses and their off-campus centers. Responsibilities also include land use and environmental planning, sustainability, public/private partnerships, utility management, and maintenance of the systemwide physical plant. She has been a leader in a innovative initiative, "The Campus as a Living Laboratory," to provide opportunities for faculty and students across the 23 campuses of the CSU system to work with leaders of the physical plants on those campuses to undertake research that benefits those communities. She is a member of the National Association of College and University Business Officers, the U.S. Green Building Council, the Society of College and University Planning, and the Association of Higher Education Facilities Officers. She received a bachelors degree at San Jose State University and postbaccalaureate education at the University of California, Berkeley.

Mary Smith is Professor of Biology and Chairperson of the Department of Biology at North Carolina A & T State University. She has led in transforming the biology program to embrace student-centered instruction, and in motivating biology faculty to adopt active learning practices in the classroom. Collaborating with STEM Chairpersons and Dean of the College of Arts and Sciences, she contributed to developing a STEM Center of Excellence for Active Learning. Under her leadership, the Department of Biology has become an enriched environment for undergraduate research in offering multiple research based-courses, the Genomics Education Partnership program, Science Education Alliance-Phage Hunters Advancing Genomics and Evolutionary Science (SEA-PHAGES) project, and other sophomore research courses that include wet-lab or survey research experiences. She has procured multi-million dollars in federal funding to support research training for undergraduate and graduate students and to enhance research infrastructure and faculty development at North Carolina & T. She is PI/PD of the Maximizing Access to Research Careers (MARC) program; former PI/PD of a Graduate Assistance in Areas of National Needs (GAANN) program, and former PI/PD for NIH/NCI P20 Feasibility Cancer grant award that focused on junior faculty development in research. Dr. Smith is the recipient of several recognitions and awards, a Ford Foundation Fellowship; North Carolina-Louis Stokes Alliance for Minority Participation Outstanding Mentor Award; North Carolina A & T College of Arts and Sciences Award for Excellence in Teaching; the University of North Carolina (UNC) Board of Governor's Award for Excellence in Teaching; and a Partnership for Undergraduate Life Sciences Education (PULSE) Vision & Change Leadership Fellow. Dr. Smith earned her BS degree from Morgan State University in Baltimore, MD, Ph.D. in Plant Science at Cornell University in Ithaca, NY and did postdoctoral work at Michigan State University, E. Lansing, MI.

Gabriela Weaver serves as Vice Provost for Faculty Development, and Director for the Center for Teaching and Faculty Development, University of Massachusetts, Amherst. She served as an Assistant Professor in the Department of Chemistry at the University of Colorado at Denver from 1994 to 2001. During that time she shifted the focus of her research work from physical chemistry to STEM education. From 2001 to 2014 she served on the faculty at Purdue University as Associate Professor and Professor of Chemistry and Science Education and later as the Jerry and Rosie Semler Director of the Discovery Learning Research Center. She served for one year as the Associate Head of the Department of Chemistry, resigning that position to become the Director of the DLRC. In 2012, Weaver was elected as fellow of the American Association for the Advancement of Science for distinguished contributions to transforming science education at the undergraduate and pre-college levels through the use of inquiry-based pedagogies and innovative technologies. Weaver has been a co-author on two different first-year chemistry textbooks, numerous book chapters on topics in science education and the 2015 book Transforming Institutions: Undergraduate STEM Education for the 21st Century. From 2004-2012, she served as Director of the NSF-funded multi-institutional CASPiE project (Center for Authentic Science Practice in Education) dedicated to involving first- and second-year undergraduate students in real research experiences as part of their regular laboratory course curricula. Her research interests include the development, implementation and evaluation of instructional practices that engage students and improve their understanding of science, and the institutionalization of such practices through the transformation of cultures and processes in higher education. Dr. Weaver received her B.S. degree in Chemistry in 1989 from the California Institute of Technology and her Ph.D. in Chemical Physics in 1994 from the University of Colorado at Boulder.

Susan R. Wessler is the Neil A. and Rochelle A. Campbell Presidential Chair for Innovations in Science Education and Distinguished Professor of Genetics at the University of California Riverside and home secretary of the National Academy of Sciences. She is a molecular geneticist known for her contributions to the field of transposon biology, specifically on the roles of plant transposable elements in gene and genome evolution. Her laboratory has pioneered the use of computational and experimental analyses in the identification of actively transposing elements. Following a position as postdoctoral fellow of the American Cancer Society at the Carnegie Institution of Washington from 1980-1982 she began her career at the University of Georgia in

1983 where she remained until moving to the University of California, Riverside in 2010. Dr. Wessler has contributed extensively to educational initiatives, including co-authorship of the widely used genetics textbook, Introduction to Genetic Analysis, and the popular reference book The Mutants of Maize. As a Howard Hughes Medical Institute Professor, she adapted her research program for the classroom by developing the Dynamic Genome Courses where incoming freshman can experience the excitement of scientific discovery in the state-of-the art Neil A. Campbell Science Learning Laboratory. She is the recipient of several awards including the Creative Research Medal (1991) and the Lamar Dodd Creative Research Award (1997) from the University of Georgia, the Distinguished Scientist Award (2007) from the Southeastern Universities Research Association (SURA), the Stephen Hales Prize (2011) from the American Society of Plant Biologists, the Excellence in Science Award from FASEB (2012) and the McClintock Prize (2014) from the Maize Genetics Community. She is a member of the National Academy of Sciences and a fellow of the American Association for the Advancement of Science, the American Academy of Arts and Sciences and the American Philosophical Society (2012). She received her bachelor's degree in biology from the State University of New York at Stony Brook in 1974 and her Ph.D. in Biochemistry from Cornell University in 1980.

SPEAKERS

Elizabeth Ambos is Executive Officer for the Council on Undergraduate Research (CUR), the leading non-profit organization providing undergraduate research programs, services, and advocacy to close to 11,000 members at more than 740 member institutions. Prior to becoming Executive Officer in May 2012, she served as Assistant Vice Chancellor for Research Initiatives and Partnerships at the California State University Chancellor's office, from 2006-2012. In this capacity, she supported California State University (CSU) system research and sponsored programs efforts. Before her appointment at the CSU system office, Beth Ambos held several administrative appointments at California State University, Long Beach, including Associate Vice President for Research and External Support, Graduate Dean and Associate Dean in the College of Natural Sciences in Mathematics. She held a professorship in the Department of Geological Sciences at CSULB, and her research, and that of her students, has focused on two main areas: crustal and upper mantle structure, particularly at plate boundary zones; and high resolution geophysical imaging of shallow subsurface features, principally active faults and archaeological sites.

David Asai is Senior Director in Science Education at the Howard Hughes Medical Institute. He directs the HHMI Undergraduate and Graduate programs, which include: (i) grants to colleges, research universities, and HHMI Professors; (ii) research fellowships to undergraduates, graduate students, and medical students; and (iii) the Science Education Alliance. Before moving to HHMI in 2008, David was on the faculty for 19 years at Purdue University where he was Head of Biological Sciences, and for 5 years at Harvey Mudd College where he was Stuart Mudd Professor and Chair of Biology. He is an elected member of the Purdue Teaching Academy and was inducted into Purdue's "Book of Great Teachers." David served as a member of the boards of trustees of the National PTA and the Higher Learning Commission-North Central Association, and on the advisory committee to the Biology Directorate of the National Science Foundation. Currently, he serves on several advisory committees, including the Progress Through Calculus project of the Mathematical Association of America, the Interdisciplinary Teaching About Earth for a Sustainable Future (InTeGrate) NSF STEP center, the University of Delaware NSF ADVANCE Institutional Transformation project, the Minority Affairs Committee of the American Society for Cell Biology, Understanding Interventions, the Committee on Opportunities in Science (COOS) of the AAAS, Research Enhancement for BUILDing Detroit, and the NIH Advisory Committee of the Director's Working Group on Diversity. Dr. Asai received the B.S. in chemistry and M.S. in biology from Stanford University, and the Ph.D. in biology from the California Institute of Technology. He was a Muscular Dystrophy Association postdoctoral fellow at Caltech, and an NIH NRSA postdoctoral fellow at the University of California, Santa Barbara. Until 2010 when he closed his lab, his group studied the structure and functional diversity of the molecular motor dynein in sea urchins and Tetrahymena thermophila.

Betsy Beise is a Professor of Physics and the Associate Provost for Academic Planning and Programs at the University of Maryland College Park. Her current responsibilities include oversight of the development and implementation of new academic programs and oversight of graduate and undergraduate curriculum changes across the campus. In 1998, she received the Maria Goeppert-Mayer Award from the American Physical Society (APS), which recognizes outstanding achievement by a woman physicist in the early years of her career. From 2004 to 2006, she was a Program Director for Nuclear Physics at the National Science Foundation. In 2008, she received the Physics department's George Snow Award for helping to advance the representation of women in the field of physics and she was a co-PI on UMD's NSF-ADVANCE grant to support retention and recruitment of women faculty. In 2012 she was recognized as a UMD Distinguished Scholar Teacher. Dr. Beise earned her B.A. in Physics from Carleton College, and her Ph.D. in Physics from the Massachusetts Institute of Technology. She is a Fellow of the American Physical Society and of the American Association for the Advancement of Science.

Elizabeth S. Boylan directs the Alfred P. Sloan Foundation's programs on STEM (science, technology, engineering, and mathematics) Higher Education, both for the education and professional advancement of underrepresented groups and for the improvement of student learning and performance in STEM fields. She serves on the Board of Directors of the Teagle Foundation, and is a Fellow of Education section of the American Association for the Advancement of Science. In December 2015 she begins a term on the Advisory Committee for NSF's Directorate of Education and Human Resources. Dr. Boylan came to the Sloan Foundation in 2011, after 16 years at Barnard College where she served as Provost and Dean of the Faculty and Professor of Biological Sciences. There she led many efforts on faculty career enhancement, curriculum reform, international education, and capital projects. She served on the Commission for Higher Education of the Middle States Association of Colleges and Schools, the Leadership Network for International Education of the American Council on Education, and the Advisory Board of Project Kaleidoscope. Prior to her work at Barnard, Boylan was associate provost for academic planning and programs at Queens College/CUNY. As a tenured member of the biology faculty at Queens College and the CUNY Graduate Center, she served as Deputy Chair of Graduate Studies in Biology, chaired of the Queens College Academic Senate, and co-chaired University task forces on STEM reform and on secondary education. Research in her laboratory was supported by the National Cancer Institute and the American Federation for Aging Research, as well as University grants. A specialist in developmental biology and hormonal carcinogenesis, Boylan earned a Ph.D. from Cornell University and a bachelor's degree from Wellesley College. She was a pre-doctoral fellow at the Marine Biological Laboratory at Woods Hole and a postdoctoral fellow in biochemistry and oncology at the University of Rochester Medical Center.

Sara Brownell is an Assistant Professor in the School of Life Sciences at Arizona State University. She received a B.S. in Biological Sciences from Cornell University, a M.S. in Biology from The Scripps Research Institute, and a Ph.D. in Biology and M.A. in Education, both from Stanford University. Sara completed postdoctoral training in biology education research at San Francisco State University and the University of Washington. Trained as a neuroscientist and turned full-time education researcher, she teaches undergraduate biology courses while building a research program in biology education at ASU. Her main research interests focus on exploring the impact of course-based research experiences on students and faculty, identifying gender differences in undergraduate biology, and developing tools for biology departments to use to align with the goals of Vision and Change.

James Burnette's passion is bringing authentic research into the classroom . During the past ten years, he has developed college and high school courses where students learn state-of-the art techniques and bioinformatics skills and apply them to novel research projects. Along with Dr. Susan Wessler, he has developed the plug-and-play model for the Dynamic Genome (DG) course for freshmen at UC, Riverside. In this model all sections of the course use the same curriculum for the first half. During this time students learn core biological concepts and research techniques. In the second half of the course, a faculty member "plugs" in with a module related to ongoing research in the lab while the DG staff continue to handle the routine administration. The DG staff work with the professor to modify protocols and employ scientific teaching principles in module design. The plug-and-play model decreases the time required to develop and offer an authentic research experience to undergraduates and increases faculty buy-in. Over the past three years, seven professors and post-docs have "plugged" into the course. To enrich the DG experience for students, he has initiated a program where former DG students serve as undergraduate laboratory assistants. These students perform most of the duties of a graduate teaching assistant in addition to near-peer mentoring. Finally, he runs a robust outreach program to increase the excitement of middle and high school students in scientific research.

William David Burns is the Executive Director of the National Center for Science and Civic Engagement, co-founder and principal investigator of SENCER, publisher of Science Education and Civic Engagement - An International Journal, and research professor in the Department of Science and Technology at Stony Brook University. Science Education for New Civic Engagements and Responsibilities (SENCER), aims to improve STEM learning and strengthen civic capacity by connecting learning to the most compelling civic issues of our day. Established in 2001, SENCER, now national in scope, has been called a "community of transformation" (Kezar, 2015) in a recent study of STEM reform networks sponsored by the National Science Foundation. Burns also currently serves, or has recently served, as principal investigator for several of the National Center's projects and programs, including: the Great Lakes Innovative Stewardship Through Education Network (GLISTEN) project, supported by the Corporation for National and Community Service and the EPA; the W.M. Keck Foundation-supported Science and Civic Engagement Western Network (SCEWestNet); SENCER-ISE, an NSF and Noyce Foundation supported initiative to connect formal science education at the college level with informal science educators; Engaging Mathematics, an NSF-supported program to apply the

SENCER approach to college-level mathematics courses, with the goal of using civic issues to make math more relevant to students; and, with the support of the Institute for Museum and Library Services, Partnership Champions: Creating the SENCER-ISE eMentor Program. A Woodrow Wilson National Fellow, Burns (along with SENCER co-founder, Karen Oates) were the recipients of the American Society for Cell Biology's Bruce Alberts Award for Excellence in Science Education.

Goldie S. Byrd is Professor of Biology and Dean for the College of Arts and Sciences at North Carolina Agricultural and Technical State University. Dr. Byrd received her PhD at Meharry Medical College and has served on the faculties at Tennessee State University and North Carolina Central University. In addition, she has served as visiting professor of genetics at UNC-Chapel Hill and Duke University. Prior to becoming Dean, Dr. Byrd was Chair of Biology and the Nathan F. Simms Endowed Professor of Biology. Dr. Byrd has contributed significantly to research and training in STEM disciplines and was a recipient of the Presidential Award for Excellence in Science Mathematics and Engineering Mentoring (PAESMEM). Dr. Byrd co-founded the North Carolina A&T Stem Center of Excellence for Active Learning where a mathematics emporiums and scale-up laboratories were created to advance active learning in STEM disciplines. She serves on numerous panels and study sections for the National Institutes of Health, the National Science Foundation, the North Carolina Biotechnology Center, the North Carolina Institute of Medicine, and the Alzheimer's Association.

A. Malcolm Campbell earned his Ph.D. in cell and molecular biology from The Johns Hopkins University in 1992. Campbell was awarded a Pew Teacher-Scholar postdoctoral fellowship during which Jan Serie at Macalester College taught him how to teach. Campbell is a Professor of Biology and the director of the James G. Martin Genomics Program at Davidson College. He is the founding director of the Genome Consortium for Active Teaching (GCAT), which connects undergraduates with research-quality genomic learning materials. With his colleague Laurie Heyer, he wrote the first true genomics textbook for undergraduates, Genomics, Proteomics and Bioinformatics. He has received the American Society for Cell Biology's Bruce Alberts Excellence in Education Award, the Elizabeth W. Jones Award for Excellence in Education, and the Hunter-Hamilton Love of Teaching award from Davidson College. He served as co-Editor-in-Chief of CBE-Life Sciences Education and is a charter member of the Society for the Advancement of Biology Education Research (SABER). His scholarship covers both education research and undergraduate-driven synthetic biology. Heyer and Campbell collaborate with their students to perform synthetic biology research. In August, 2014, Campbell, Heyer and Chris Paradise published an innovative introductory e-textbook that aligns very well with Vision and Change (www.bio.davidson.edu/icb).

Nicole Villa Cerveny is a Professor of Geography at Mesa Community College (MCC) who specializes in environmental sciences, conservation of cultural resources and undergraduate research. She obtained her doctorate from Arizona State University in 2005 under the direction of Guggenheim Fellow and Professor Ronald I. Dorn. Her research ranges from studying climatic relationships through quartz grains to the conservation and preservation of Native American rock art. Her research has been published in journals including Heritage Management, Physical Geography, Geoarchaeology, and Weatherwise. Although engaged in indigenous weaving techniques and local search and rescue activities, her current passion involves engaging first and second year college students in impactful undergraduate research experiences. She chairs the

Undergraduate Research Committee at MCC and coordinates the multidisciplinary undergraduate research laboratory. Over the past 5 years, Dr. Cerveny has facilitated workshops designed to engage first and second year college students in undergraduate research.

Edward J. Coyle is the John B. Peatman Distinguished Professor of ECE at Georgia Tech and a Georgia Research Alliance Eminent Scholar. He is the founder and director of the Vertically-Integrated Projects (VIP) Program, which integrates research and education by embedding large-scale, long term teams of undergraduates in the research efforts of faculty and their graduate students. Dr. Coyle was a co-recipient of the U.S. National Academy of Engineering's 2005 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education. He was also a co-recipient of the American Society for Engineering Education's 1997 Chester F. Carlson Award for Innovation in Engineering Education and the IEEE Signal Processing Society's 1986 Best Paper Award. Dr. Coyle was elected a Fellow of the IEEE for his contributions to the theory of nonlinear signal processing. His current research interests include undergraduate education, signal and information processing, and wireless sensor networks.

Arthur B. Ellis joined City University of Hong Kong as provost in September, 2010. Prior to joining CityU, he was vice chancellor for research at the University of California, San Diego (UCSD). Ellis joined UCSD after serving as chemistry division director at the U.S. National Science Foundation and as a faculty member at the University of Wisconsin-Madison. His honors include an inaugural NSF Director's Distinguished Teaching Scholar Award for his contributions to teaching and research; an NSF Director's Meritorious Service Award for his work as a division director; and a Guggenheim Fellowship.

Robert Full received his doctoral degree from SUNY Buffalo, conducted a post doc at The University of Chicago and is a Chancellor's and Goldman Professor of Integrative Biology and Electrical Engineering and Computer Science at the University of California at Berkeley. Professor Full is the Director of the Poly-PEDAL Laboratory, the Center for interdisciplinary Bio-inspiration in Education and Research (CiBER), and a NSF supported Integrative Graduate Education and Research Traineeship (IGERT). Professor Full has authored over two hundred research contributions in animal motion science leading to the design of insect inspired search-and-rescue robots and gecko-inspired, self-cleaning, dry adhesives. Full has designed interdisciplinary, discovery-based learning laboratories featuring layered mentoring, guided inquiry, and mutualistic teaming resulting in authentic research publications. His mentoring of undergraduate researchers has resulted in over one hundred and thirty journal articles, proceedings or abstracts published with at least one undergraduate author. Professor Full received Berkeley's Distinguished Teaching Award, was named Mentor in the Life Sciences by NAS, has briefed the US House of Representatives STEM Education Caucus on Undergraduate Research and American Innovation, and presented his ideas on discovery-based education at the Undergraduate Biology in the 21st Century Workshop, Council on Undergraduate Research Conference, NSF CCLI, Science Education for New Civic Engagements and Responsibilities, Re-inventing Undergraduate Education and TED Ed Meetings.

Sylvester James "Jim" Gates, Jr., is an American theoretical physicist. He received two B.S. degrees and a Ph.D. degree from Massachusetts Institute of Technology, the latter in 1977. His doctoral thesis was the first thesis at MIT to deal with supersymmetry. Gates is currently a University System Regents Professor, the John S. Toll Professor of Physics at the University of

Maryland, College Park, the Director of the String and Particle Theory Center, and serves on President Barack Obama's Council of Advisors on Science and Technology, and on the Maryland State Board of Education. He is known for his work on supersymmetry, supergravity, and superstring theory. In 1984, working with M.T. Grisaru, M. Rocek, W. Siegel, Gates co-authorized Superspace, the first comprehensive book on the topic of supersymmetry. He is a member of the board of trustees of Society for Science & the Public. Gates has been featured extensively on many NOVA PBS programs on physics, notably "The Elegant Universe" in 2003, and ''The Fabric of the Cosmos'' in 2011. In 2006, he completed a DVD series titled Superstring Theory: The DNA of Reality for The Teaching Company composed of 24 half-hour lectures to make the complexities of unification theory comprehensible to non-physicists. In 2012, he was named a University System of Maryland Regents Professor, only the sixth person to be so recognized since 1992. He is past president of the National Society of Black Physicists, and is a NSBP Fellow, as well as a Fellow of the American Physical Society, the American Association for the Advancement of Science, and the Institute of Physics in the U.K. He also is an elected member of the American Academy of Arts and Sciences, and the American Philosophical Society. In 2013, he was elected to the National Academy of Sciences, becoming the first African-American physicist so recognized in its 150-year history. On November 16, 2013, Prof. Gates was awarded the Mendel Medal by Villanova University "in recognition of his influential work in supersymmetry, supergravity and string theory, as well as his advocacy for science and science education in the United States and abroad." President Obama awarded Prof. Gates the National Medal of Science, the highest award given to scientists in the U.S., at a White House ceremony in 2013. He currently continues his research in supersymmetry in systems of particles, fields, and strings.

James M. Gentile is the Emeritus Dean and Kenneth G. Herrick Distinguished Professor of Biology at Hope College in Holland, Michigan, and the past president of Research Corporation for Science Advancement (RCSA), a Tucson, Az.-based foundation dedicated to science since 1912. He has conducted extensive research on the role of metabolism in the conversion of natural and xenobiotic agents into mutagens and carcinogens, with funding from the National Institutes of Health, the National Science Foundation, the U.S. Environmental Protection Agency, and the World Health Organization, among many other public and private foundations. He received his Ph.D. from Illinois State University and undertook postdoctoral studies in the Department of Human Genetics at the Yale University School of Medicine. He is the author of more than 200 research articles, book chapters, book reviews and special reports and has active Blogs on Tumbler and the Huffington Post. He is the former editor-in-chief of the international journal Mutation Research, past President of the U.S. Environmental Mutagen Society and the International Association of Environmental Mutagen Societies, and a founding member of Project Kaleidoscope. He serves on several national Boards and Committees, including the Science Friday Foundation Board, the Cures Now Foundation Board, The Biosphere2 Board, and many committees and task forces for the National Academies of Science, The National Science Foundation, the International Agency for Research on Cancer, and the National Institutes of Health.

Jo Handelsman is the Associate Director for Science at the White House Office of Science and Technology Policy, appointed by President Obama and confirmed by the Senate in June of 2014. Dr. Handelsman helps to advise President Obama on the implications of science for the Nation, ways in which science can inform U.S. policy, and on Federal efforts in support of scientific research. Dr. Handelsman is an expert in communication among bacteria that associate with soil, plants, and insects and helped pioneer the field of metagenomics, bridging agricultural and medical sciences. Handelsman is also recognized for her research on science education and women and minorities in science and in 2011 received the Presidential Award for Excellence in Science Mentoring. Dr. Handelsman co-chaired the PCAST working group that developed the 2012 report, "Engage to Excel," which contained recommendations to the President to strengthen STEM education to meet the workforce needs of the next decade in the United States. Prior to joining OSTP, Dr. Handelsman was the Howard Hughes Medical Institute Professor and Frederick Phineas Rose Professor in the Department of Molecular, Cellular and Developmental Biology at Yale University. She received a B.S. from Cornell University and a Ph.D. in Molecular Biology from the University of Wisconsin-Madison.

Graham Hatfull is Professor of Biological Sciences at the University of Pittsburgh. He received a B.Sc. (Hons) degree in Biological Sciences from Westfield College, University of London in 1978, and a Ph.D. in Molecular Biology from Edinburgh University in 1981. He did postdoctoral work at Yale University in the Department of Molecular Biophysics and Biochemistry with Dr. Nigel Grindley, and at the Medical Research Council at Cambridge University, with Drs. Fred Sanger and Bart Barrell. He has been at the University of Pittsburgh since 1988 and served as Chair of the Department of Biological Sciences from 2003 to 2011. Dr. Hatfull's research focuses on the molecular genetics of the mycobacteria and their bacteriophages, and their use for educational advancement. These studies take advantage of the intimacy of phage-host interactions to gain insights into the genetics and physiology of Mycobacterium tuberculosis, the causative agent of human TB. Through integrated research-education programs such as the PHIRE and SEA-PHAGES programs, a large collection of completely sequenced mycobacteriophage genomes provides insights into viral diversity and evolution, and represents a rich toolbox of new approaches for understanding M. tuberculosis. Development of vector systems, selectable markers, recombineering approaches, expression tools, and insights into mycobacterial biofilms reflect some of the useful applications of this genomic resource. The SEA-PHAGES program implemented at over 80 institutions with over 3200 undergraduate students (2015-6) offers a transformative experience for freshman undergraduates engaging in research, with notable advances in both scientific insights and in learning gains. Highlights of Dr. Hatfull's research accomplishments include publication of more than 160 peer-reviewed research articles, 35 book chapters or reviews, and four co-edited books. He has mentored 20 Ph.D. students, over 100 undergraduate student researchers, and 16 postdoctoral associates. Dr. Hatfull has received the University of Pittsburgh Chancellor's Distinguished Research Award at both the junior and senior level, the University of Pittsburgh Chancellor's Distinguished Teaching Award, and is the Eberly Family Professor of Biotechnology. He is a fellow of the American Academy of Microbiology, a fellow of the American Association for the Advancement of Science, and a teaching fellow of the National Academy of Science. He has been a Howard Hughes Medical Institute Professor since 2002.

James Hewlett currently serves as Professor of Biology and the Director of Biotechnology and Biomanufacturing at Finger Lakes Community College in Canandaigua, NY. In addition to teaching, he serves as the Executive Director of the Community College Undergraduate Research Initiative (CCURI) – a National $4M NSF funded program under the Transforming

Undergraduate Education in STEM (TUES) program. He is the New York Hub Director of the Northeast Biomanufacturing Center and Collaborative NBC2) and is the President and CEO of STEMsolutions, LLC, a New York based consulting firm specialized in developing customized higher education solutions to STEM curriculum reform efforts. In addition, he serves on the Editorial Board of the National Center for Case Study Teaching in Science at the University of Buffalo and is on the Editorial Board of The American Society of Cell Biology's CBE Life Sciences Education journal. He serves on the Advisory Board for Rochester Institute of Technology's Center for Bioscience Education and Technology (CBET) and is a member of the Steering Committee for the University of Georgia's RCN-UBE Course-based Undergraduate Research Experiences Network (CUREnet).

Gail Hollowell is an Associate Professor in the Department of Biological and Biomedical Sciences at North Carolina Central University (NCCU). She received her B.S. in Biology from NCCU and both her M.S. in Microbiology and Ph.D. in Molecular Biology from Howard University in Washington, DC. Before returning to her alma mater, she completed a postdoctoral fellowship on eukaryotic gene expression at the National Eye Institute, National Institutes of Health. Dr. Hollowell currently serves as PI on Peer Mentoring and Technology as a Model for Enhancing Success in Science and Mathematics Persistence at NCCU, which is funded by the University of Pennsylvania Center for Minority Serving Institutions. She is also co-Director of NCCU's HHMI science education grant which focuses on Course-based Undergraduate Research Experiences. Dr. Hollowell is also an institutional participant in the Preparing Critical Future Faculty program, funded by the American Association of Colleges and Universities which focuses on STEM faculty development. In addition to her scholarly work, Dr. Hollowell has been recognized for her stellar teaching as a recipient of the Outstanding Faculty Teaching Award, Department of Biology (2006) and the NCCU Award for Teaching Excellence (2007).

John R. Jungck is the Director of the Interdisciplinary Science Learning Laboratories at the University of Delaware. He is a tenured Professor of Biological Sciences and holds joint appointments in the Department of Mathematical Sciences and the Bioinformatics/Computational Biology Program. He is the former Editor of Biology International, Bioscene: Journal of College Biology Teaching, and the American Biology Teacher. He currently serves on the Editorial Boards of several journals including the Bulletin of Mathematical Biology, Evolutionary Bioinformatics, the American Journal of Undergraduate Research, and several others. He has also been the Editor of special issues of Mathematical Modelling of Natural Phenomena and on Bio 2010 in CBE Life Science Education. He is the immediate past Vice President of the International Union of Biological Sciences, immediate past President of the IUBS Commission on Biology Education, and former Chairperson of the U. S. National Academy of Science's National Committee of IUBS. His international commitments include long- term relations with NECTEC in Thailand, the Allan Wilson Centre for Molecular Evolution and Ecology in New Zealand, and BIOMAT – a consortium of South American mathematical biologists. He is the founder of the BioQUEST Curriculum Consortium (http://bioquest.org), He has served on Boards of such groups as the National Institute for Mathematical Biology Synthesis (NIMBioS) and Emerging Behaviors of Integrated Cellular Systems (EBICS). His awards/honors/offices include AAAS Fellow, Honorary Doctorate from the University of Minnesota, ASCB Bruce Alberts Award, AIBS Education Award, EDUCOM Educational software and curriculum awards, former Chairperson of the Education Committee of the Society for Mathematical Biology, former president of the Association of College and University Biology Educators, former president of Phi Beta Kappa and Sigma Xi chapters, and a Fulbright Scholar in Thailand.

Ryan Kelsey is a Program Officer for the Education Program at the Helmsley Charitable Trust where he primarily focuses on national work in undergraduate STEM education. He also contributes to the K-12 program in the area of teacher preparation and on effective uses of educational technology. Prior to coming to the Trust, Ryan spent 13 years at the Columbia University Center for New Media Teaching and Learning, most recently as the Director of Projects. At Columbia, Ryan led a team of educational technologists and design specialists partnering with faculty on innovative educational projects in the full range of academic disciplines, including simulations, case studies, health interventions and global learning initiatives with funding from multiple public and private sources. He has also served as an adjunct assistant professor and instructor at Teachers College and New York University, offering courses in the design and analysis of effective solutions for improving higher education classroom practice using purposeful technology. Ryan earned his Ed.D. and M.A. in Communication and Education from Teachers College and his B.S. in biology from Santa Clara University.

George M. Langford is Distinguished Professor of Neuroscience and Professor of Biology at Syracuse University and served as dean of the College of Arts and Sciences from 2008-2014. For the academic year 2014-15, he is on sabbatical at the Howard Hughes Medical Institute in Science Education. Throughout his multi-faceted career, Professor Langford has maintained an interdisciplinary approach to teaching, research, service, and enterprise. Prior to SU, he served as dean of the College of Natural Sciences and Mathematics at the University of Massachusetts-Amherst. Before that, he was the Ernest Everett Just Professor of Natural Sciences and professor of biological sciences at Dartmouth College. Dean Langford has also served on the faculty of The University of North Carolina Chapel Hill, in addition to holding leadership positions at the National Science Foundation and the Marine Biology Laboratory (Woods Hole, Mass.). An accomplished visionary, Professor Langford was appointed by President Clinton to the National Science Board, the governing board of the National Science Foundation. He is the recipient of more than two-dozen awards and honors including the 2009 Professional Achievement Award from the Illinois Institute of Technology, where he earned an M.S. and Ph.D. in cell biology. He was elected an AAAS Fellow of the American Association for the Advancement of Science in 2013. He received an honorary Doctor of Humane Letters in 2001 from Beloit College.

Marcia C. Linn is Professor of Development and Cognition, specializing in science and technology in the Graduate School of Education, University of California, Berkeley. She is a member of the National Academy of Education and a Fellow of the American Association for the Advancement of Science (AAAS), the American Psychological Association, and the Association for Psychological Science. She has served as President of the International Society of the Learning Sciences, Chair of the AAAS Education Section, and on the boards of the AAAS, the Educational Testing Service Graduate Record Examination, the McDonnell Foundation Cognitive Studies in Education Practice, and the National Science Foundation Education and Human Resources Directorate. Awards include the National Association for Research in Science Teaching Award for Lifelong Distinguished Contributions to Science Education, the American Educational Research Association Willystine Goodsell Award, and the Council of Scientific Society Presidents first award for Excellence in Educational Research. Linn earned her Ph. D. at Stanford University where she worked with Lee Cronbach. She spent a year in Geneva working with Jean Piaget, in Israel as a Fulbright Professor, and a year in London at University College. She has been a fellow at the Center for Advanced Study in Behavioral Sciences three times. Her books include Computers, Teachers, Peers (2000), Internet

Environments for Science Education (2004), Designing Coherent Science Education (2008), WISE Science (2009), and Science Teaching and Learning: Taking Advantage of Technology to Promote Knowledge Integration (2011). She chairs the Technology, Education—Connections (TEC) series for Teachers College Press.

Margot McDonald, AIA, NCARB, LEED BD+C is the Architecture Department Head at Cal Poly-San Luis Obispo. In the studio, her teaching focuses on integrated project delivery by working collaboratively with the disciplines of architecture, structural engineering, construction management, and landscape architecture on building/site proposals for real clients. She is the faculty advisor for an interdisciplinary Sustainable Environments minor, and chair-elect for the International Educational Advisory Council at Cal Poly. Professor McDonald is a licensed architect in the State of Oregon. She holds a Masters in Architecture degree from the University of Oregon as well as undergraduate degrees in Mathematics and French from the University of California at Santa Barbara. She is currently is a doctoral candidate (ABD) in the Geography Department at UC-Santa Barbara where she is designing a climate classification system for passive and low energy buildings in California.

Dave Micklos is founder and Executive Director of the DNA Learning Center (DNALC), the nation's first science center devoted to public genetics education. An operating unit of Cold Spring Harbor Laboratory (CSHL). With satellite centers in Nassau County and Harlem, the DNALC's six teaching laboratories provide hands-on science experiences to 30,000 students per year. DNALC Asia, to open in 2016 in Suzhou, China, will have twice the capacity of the CSHL DNALC. Approximately 300,000 students per year use methods and commercial lab kits developed by the DNALC. The DNALC's Internet portal and digital multimedia receive 7 million visitors and downloads annually. The DNALC's textbooks – *DNA Science, Laboratory DNA Science*, *and Genome Science* – have been the basis for intensive lab or Internet training provided to more than 9,000 high school and college science teachers at workshops conducted in all 50 United States and 14 foreign countries. Dave received the 1990 Dana Award for Pioneering Achievement in Education, the 2011 Science Prize for Online Resources in Education, and the 2012 Genetics Society of America Award for Excellence in Education. He is an AAAS Fellow and is the only CSHL staff member to receive an honorary Doctorate from its Watson School of Biological Sciences.

Cathy Middlecamp is a Professor in the Nelson Institute for Environmental Studies at the University of Wisconsin-Madison. Her scholarship focuses on designing, teaching, and assessing courses that connect environmental science to real-world societal issues. Middlecamp is the editor-in-chief of Chemistry in Context, a project of the American Chemical Society. She has served as the lead author for the chapters on air quality, acid rain, ozone depletion, nuclear energy, and sustainability. Cathy also serves as a senior scholar for SENCER (Science Education for New Civic Engagements and Responsibilities). Middlecamp is a fellow of the Association for Women in Science (2003), of AAAS (2004), and of the American Chemical Society (2009). She also is the chair-elect of the ACS Division of Chemical Education and of the AAAS Division Q (Education).

Anne Rosenwald is an Associate Professor of Biology at Georgetown University, where she serves as Director of Georgetown's innovative Biology of Global Health major. Her interests include bioinformatics education and she is a member of the Genome Consortium for Active Teaching and the Genomics Education Partnership. She is also member of the newly formed Network for Integrating Bioinformatics into Life Sciences Education. Finally, she is the developer of the Genome Solver Project, which takes advantage of the rich sequence data sources for comparative analysis of bacterial genomes.

Jeffrey Ryan is a Professor of Geology in the School of Geosciences at the University of South Florida in Tampa, FL. He received his B.S. in Geology in 1983 from Western Carolina University, and his Ph.D. in 1989 from Columbia, with postdoctoral training at the Carnegie Institution of Washington's Department of Terrestrial Magnetism. He is an active researcher the fields of igneous and metamorphic petrology, focusing on studies of the volcanic and metamorphic rocks encountered in modern and ancient convergent plate boundaries. He also pursues a range of geoscience education investigations, examining the instructional use of research instrumentation in undergraduate courses, the impacts of undergraduate research as an effective geoscience pedagogy, and innovative applications of geoinformatics and geospatial information platforms to facilitate student training in the tools of modern research. He was a National Science Foundation Program Director in the Division of Undergraduate Education from 2003-2005, and has since worked with geoscience faculty across the country to help them develop effective and potentially NSF-fundable interventions and instructional strategies for improving the undergraduate courses they teach. He has long been engaged in efforts to re-vision undergraduate education in the geosciences, as a co-convener of the ongoing "Summit on the Future of Undergraduate Geoscience Education" series of national meetings and workshops, and as the lead convener of the 2010 "Planning the Future of GeoCyberEducation" community workshop. He is a longstanding member and current Geoscience Division Councilor in the Council on Undergraduate Research, where he currently serves on the NCUR (National Conference on Undergraduate Research) Oversight Committee, helped develop and author the online resource collection "Undergraduate Research as Teaching Practice" (http://serc.carleton.edu/NAGTWorkshops/undergraduate_research/).

Troy D. Sadler is a Professor of Science Education at the University of Missouri (MU) with joint appointments in the College of Education and the Division of Biological Sciences. He serves as Director of the ReSTEM Institute: Reimagining & Researching STEM Education, a research and outreach center for K-12 STEM education. Sadler's research focuses on how students negotiate complex socio-scientific issues and how these issues may be used as contexts for science learning. He is interested in how issues-based learning experiences can support student learning of science and development of practices essential for full participation in modern democratic societies. Sadler has also been involved with numerous efforts designed to create opportunities for undergraduates and high school students, particularly those from backgrounds underrepresented in the sciences, to engage in authentic scientific research experiences.

David Williamson Shaffer is a Professor at the University of Wisconsin-Madison in the Department of Educational Psychology and a Game Scientist at the Wisconsin Center for Education Research. Before coming to the University of Wisconsin, he was a teacher, teacher-trainer, curriculum developer, and game designer. Dr. Shaffer studies how new technologies change the way people think and learn, and his most recent book is How Computer Games Help Children Learn.

Sarah Simmons is Senior Program Officer, Science Education, at Howard Hughes Medical Institute. Sarah joined HHMI in 2014 and prior to that held the position of Assistant Dean for Honors, Research and International Study in the College of Natural Sciences at The University of Texas at Austin where she administered multiple college initiatives including honors programs, international science initiatives and undergraduate research. Additionally, she was Director and PI of the HHMI- and NSF-funded Freshman Research Initiative (FRI) - a unique, large-scale program that engages undergraduates in research at The University of Texas at Austin.

Donald J. Wink is LSRI's Director of Graduate Studies and Professor and Director of Undergraduate Studies in Chemistry, where he served as Head for 2000-2005. Wink's projects share a theme of crossing boundaries, often using student pathways for direction. In undergraduate chemical education he has NSF-supported materials development projects that led to a 'math-aware' preparatory chemistry textbook (Practice of Chemistry) and project-based laboratories (Working with Chemistry). He was co-PI for the Center for Authentic Science Practice in Education that developed methods to have first and second year undergraduate chemistry students do research in their lab courses. Finally, he works in UIC's innovative natural science general education program for students in the BA urban education major. He has also been very active on issues of teaching in K-12 settings, including on NSF GK-12 projects for intervention in schools. His Learning Sciences work focuses on learning in chemistry and on teacher development. In addition, he contributes regularly to questions of how particular constructs—such as relevance, constructivism, and inquiry—work in science and science education.

Robin Wright earned a bachelor of science degree from the University of Georgia and a Ph.D. from Carnegie-Mellon University. After postdoctoral training at UC, Berkeley, she was on the faculty of the University of Washington (Zoology Department) for nearly 13 years. She moved to Minnesota in 2003, and is currently Senior Associate Dean for Undergraduate Initiatives in the College of Biological Sciences (CBS), Head of the Department of Biology Teaching and Learning, and professor of Genetics, Cell Biology, and Development. Prior to focusing exclusively on undergraduate education, her lab used genetic, cell biological, ecological, and evolutionary approaches to explore cold adaptation. In addition, her laboratory was well known as a great place for undergraduates to pursue research. Over the past 21 years, she has mentored nearly 100 undergraduate researchers. Prof. Wright has experience teaching both large and small classes, including freshman seminars, large introductory biology courses, and skill-oriented courses for honors students. She helped to develop and co-teaches the Nature of Life program and has been a leader in the development of Foundations of Biology, an innovative, team-based introductory biology course for biological sciences majors. She leads HHMI- and NSF-supported initiatives to deliver discovery-based research experience for the thousands of majors and non-majors who take biology classes in the College of Biological Sciences. Prof. Wright has served on the Education Committee of the American Society for Cell Biology and was as chair of the Education Committee for the Genetics Society of America. In addition, she was a senior editor of the Journal, Life Science Education and is the founding Editor-in-Chief of a new biology curriculum journal called CourseSource. She is a member of the Executive Committee for the HHMI/National Academies of Science Summer Institute on Biology Education. She has been named as a National Academies Biology Education Mentor for the past 12 years. She was elected as a fellow of the American Association for the Advancement of Science in 2012 and was recognized by the Genetics Society of America with the Elizabeth Jones Award for Excellence in Undergraduate Education.