

## Feature From the National Science Foundation

# Undergraduate Research Experiences in Biology: Alternatives to the Apprenticeship Model

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This is the first in a series of articles exploring some of the approaches advocated in the American Association for the Advancement of Science's (AAAS) *Vision and Change in Undergraduate Biology Education* (AAAS, 2011a), an effort within the biology community to address the needs of undergraduate education in the life sciences (Woodin *et al.*, 2009, 2010) in response to the dramatic and rapid transformations in biology in recent decades (National Research Council, 2009). The *Vision and Change* report describes a number of ways to meet the needs of the 21st-century undergraduate. Here, we address one of the changes advocated in that report—the call to “introduce the scientific process to students early, and integrate it into all undergraduate biology courses.” We review a representative sampling of recent innovations integrating scientific research experiences within the biology curriculum. Most (but not all) of the examples given are drawn from the recent literature and from projects presented at a recent meeting of principal investigators from the National Science Foundation's Course, Curriculum and Laboratory Improvement/Transforming Undergraduate Education in Science, Technology, Engineering and Mathematics (STEM) program (AAAS, 2011b). We hope that this sampling will provide new insights and ideas that will encourage more faculty members to consider ways to involve their undergraduate students in research. In addition to outlining a variety of approaches being used, this article briefly addresses, first, the way in which different biological subdisciplines (e.g., ecology, molecular biology, genomics) and different types of institutions are incorporating this approach into their curriculum and, second, the outcomes that are beginning to emerge and

the tools being developed to document and evaluate these outcomes.

The opportunity to conduct independent research as an undergraduate has often been cited as the compelling experience that launches a scientific career (National Research Council, 2003; A. Roe, as cited in Lopatto, 2010). The benefits of such experiences have been chronicled both anecdotally (Cejda and Hensel, 2009) and in studies that span institutional types and disciplinary approaches (Russell *et al.*, 2007; Lopatto, 2010). The apprenticeship model, in which students conduct independent research projects in an individual faculty member's laboratory, is a well-established approach to providing independent research experiences. As the demand for undergraduate research experiences increases, the strain on institutions and faculty trying to meet this demand becomes more evident. Whereas this approach is critical for providing students with an inside view of how science proceeds and for socializing them into the scientific community, it requires a great deal of financial and faculty resources. Thus, its reach is very limited. The apprenticeship model is especially difficult for institutions where research is not a large part of their institutional mission, and many students, particularly those from populations currently underrepresented in the STEM professional community, may not seek out these opportunities. The need for alternative ways of bringing the benefits of undergraduate research experiences to students and engaging them in the scholarly community is becoming increasingly evident.

## INTEGRATING SCIENTIFIC RESEARCH EXPERIENCES THROUGHOUT THE BIOLOGY CURRICULUM

As faculty and departments recognize that the benefits of engaging in the scholarship of science apply to a broad spectrum of students, they have been finding creative ways of providing these experiences to a broader population. The following sections attempt to describe some of the many approaches being used to accomplish this goal. The projects highlighted here are a small sampling (see Table 1) that collectively represent a spectrum of approaches; these approaches range

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**Table 1.** Undergraduate research experiences: examples of alternative approaches

Project, institution, principal investigator	Project description	Outcomes	Comments, subject area, website
Introducing students to research; demystifying science and scientists through close investigations of individual research labs			
Consider, Read, Elucidate the hypotheses, Analyze and interpret the data, and Think of the next Experiment (CREATE), City College of the City University of New York, Sally Hoskins	<p>Focuses on the research of an individual scientist to give students a sense of how scientific progress is made and how research unfolds over time.</p> <p>Using novel and adapted pedagogical tools, students read and analyze a series of four research papers from a single laboratory, design their own follow-up experiments, vet these in a "grant panel" activity, and interact with the laboratory involved by posing a set of questions in the form of an email survey sent to each author.</p> <p>Thoughtful responses from authors illuminate "the research life."</p>	<p>Student Assessment of Learning Gains (SALG) surveys indicate students develop greater interest in science and greater confidence in their ability to understand science.</p> <p>Critical Thinking Tests (adapted from Field-tested Learning Assessment Guide) and class observations indicate improved student scientific problem-solving and critical thinking abilities.</p> <p>Postcourse interviews indicated gains in understanding of "who does science and why," decreased misconceptions about the research life, increased confidence in ability to become scientists, and increased enthusiasm for research careers.</p> <p>Outside evaluations of CREATE implementations on multiple campuses found student gains in critical thinking abilities, understanding the nature of science, and attitudes toward science and scientists.</p>	<p>A low-cost approach to engaging students with the research community, readily adaptable to a range of institutions and levels (CREATE Cornerstone is being developed as a freshman-level adaptation of the CREATE method).</p> <p>CREATE Intensive workshops will be offered in 2012 and 2013 to faculty in 2- and 4-yr institutions.</p> <p>Subject area: approach can be adapted to a variety of disciplines or research subjects.</p>
Connecting Researchers, Educators, and Students (CREST), Center for BioMolecular Modeling, Milwaukee School of Engineering, Tim Herman	Undergraduate student teams interact with a research lab investigating an intriguing protein and learn about the research and the protein; develop a physical model of the protein; and work closely with an undergraduate educator to develop instructional materials that incorporate the physical model and the research as a means of highlighting protein function and structure.	Proposed outcomes include student understanding of complex protein structure and function and the process and culture of science.	Physical models are available for loan. Subject area: protein structure and function <a href="http://cbm.msos.edu/stupro/crest/index.html">http://cbm.msos.edu/stupro/crest/index.html</a>
Experiencing the process of science: integrating scientific research into the student laboratory			
<i>Approaches that are based on and contribute to faculty research</i>			
Authentic Research Experience in Microbiology (AREM), Brooklyn College of the City University of New York, Theodore Muth	In AREM courses, students isolate a strain of the plant pathogen <i>Agrobacterium tumefaciens</i> from an environmental sample they have collected; examine its infectivity using <i>Arabidopsis</i> root segments; and use bioinformatics tools to relate genomics to host-pathogen interactions.	Preliminary results suggest that content knowledge, as measured by standard exams, is equal for those in AREM sections and those in traditional labs (AAAS, 2011b). However, as measured by the California Critical Thinking Skills Test, students in AREM courses showed gains in some aspects of critical thinking compared with those in traditional labs.	<p>Example of a course-based research experience at a diverse, urban college with a dominant commuter population.</p> <p>In a recently introduced urban metagenomics approach designed to study urban bacterial community dynamics, students analyze 16S RNA sequences amplified from samples they collect from local sites.</p> <p>Subject area: microbiology approach can be adapted to a variety of disciplines or research subjects.</p>

(Continued)

**Table 1.** Continued

Project, institution, principal investigator	Project description	Outcomes	Comments, subject area, website
Project Laboratory in Genomics and Genetics, Brandeis University, Waltham, MA, Susan Lovett	Engages students in research through a three-stage approach: 1) read primary literature and complete training exercises to learn key concepts and techniques; 2) collaboratively develop and conduct group projects; and 3) individually develop and conduct independent research projects. Students isolate random <i>Escherichia coli</i> transposon mutations affecting rates of genetic variation; analyze these mutants to discover functions essential to genetic stability; integrate their findings with information found in public domain genomic information resources; and write a research paper reporting their results.	On the SURE survey, students self-report increased understanding of the process of scientific research, increased interest in science, and enhanced reading and writing skills. Using a principal investigator-generated survey to find out how the course helped students, the students report that the writing component enhanced their understanding of course content and general writing skills (AAAS, 2011b).	Principal investigator reports that the percentage of underrepresented minorities in the course is higher than the college's or major's percentage. This approach seems to have a beneficial effect on their feeling of being able to be a scientist. Subject area: genomics approach can be adapted to a variety of disciplines or research subjects. For example, a Neurobiology Project Lab has been developed for 2011.
<i>Approaches that provide opportunities for students to participate in original collaborative research and/or contribute to a broader research effort</i>			
National Genomics Research Initiative, Howard Hughes Medical Institute–Science Education Alliance (SEA)	A two-semester course supported by the Howard Hughes Medical Institute. In semester one, students isolate and characterize bacteriophage from local soils and name the newly identified life form; extract and purify its DNA; and send one phage DNA sample to the U.S. Department of Energy Joint Genome Institute for sequencing. In the second semester, students use bioinformatics tools to annotate the sequenced genome.	Pooled survey data from the first-year's cohort indicate that students taking SEA labs, compared with their peers in introductory laboratory courses, were more likely to complete their course (only 2–5% dropped out vs. a school-wide average of 14%) and scored better on exams in introductory biology courses by an average of 6 of 100 points. Both of these findings were true regardless of school size or whether the students were honors, at-risk, biology majors, or undeclared majors ( <a href="http://www.hhmi.org/news/SEA20091217.html">www.hhmi.org/news/SEA20091217.html</a> ).	SEA provides instrumentation, reagents, and protocols and support for faculty through training, workshops, and a learning network. The undergraduate research has resulted in a peer-reviewed paper with 192 authors, most of them undergraduates (Pope <i>et al.</i> , 2011). By 2012 the course will be offered at 60 schools in 29 states and Puerto Rico ( <a href="http://www.hhmi.org/grants/sea/institutions.html">www.hhmi.org/grants/sea/institutions.html</a> ). Subject area: genomics bacteriophage <a href="http://www.hhmi.org/grants/sea">www.hhmi.org/grants/sea</a>
Genome Education Partnership, Biology Department and Genome Sequencing Center, Washington University, Sarah Elgin	A collaborative venture providing access to databases, Web-accessible tools, curriculum materials, and other resources to support: undergraduates in upgrading draft-quality <i>Drosophila</i> genomic sequences to high-quality and/or thoughtful and detailed annotation of these sequences; generating curated gene models; pooling of data and ideas from student courses in many institutions to result in significant improvement in existing databases; and joint publication in the scientific and science education literature.	Based on a postcourse survey adapted from Lopatto's SURE and CURE surveys, students reported professional and learning gains similar to students in apprenticeship experiences (Lopatto <i>et al.</i> , 2008).	This project has resulted in peer-reviewed papers in both scientific (Leung <i>et al.</i> , 2010) and educational (Shaffer <i>et al.</i> , 2010) journals. Subject area: genomics <a href="http://gep.wustl.edu">http://gep.wustl.edu</a>

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**Table 1.** Continued

Project, institution, principal investigator	Project description	Outcomes	Comments, subject area, website
Community College Genomics Research Initiative, Bellevue Community College (ComGen), in partnership with the U.S. Department of Agriculture's Agricultural Research Service group at Washington State University, Pullman, WA, Gita Banger	The student laboratory centers on sequencing of DNA from the biocontrol bacterium <i>Pseudomonas fluorescens</i> , which attacks the plant pathogen that causes take-all, a fungal disease of wheat and barley.	On modified CURE surveys, students report gains in scientific skills such as laboratory techniques, understanding how knowledge is constructed, and how to read and understand primary literature; and personal development, including tolerance for obstacles faced in the research process and understanding how scientists solve problems.	Website includes materials so others may emulate this approach. Subject area: genomics <a href="http://scidiv.bellevuecollege.edu/comgen/CGabout.html">http://scidiv.bellevuecollege.edu/comgen/CGabout.html</a>
Partnership for Research and Education in Plants for Undergraduates (PREP-U), Virginia Polytechnic Institute and State University, Blacksburg, VA, in partnership with University of California, Davis, and Richard Bland College, Petersburg, VA, Erin Dolan	This project challenges students to develop an interdisciplinary approach to biology by examining interactions between <i>Arabidopsis</i> (both wild type and mutant) and herbivores at the genetic, biochemical, organismal, and population levels. Students design their own experiments to investigate whether changes in <i>Arabidopsis</i> genes affect their interactions with herbivores; share their findings via video chat or email, and add them to the PREP Online Lab Notebook, a site accessible to scientists and other students ( <a href="http://www.prep.biochem.vt.edu">www.prep.biochem.vt.edu</a> ).	In progress	The module offers experimental and analytical techniques adaptable for both beginning and advanced laboratories and to the addition of other components such as molecular genetics and bioinformatics. Subject area: general biology; plant biology; behavioral ecology; genetics; bioinformatics. <a href="http://www.prep.biochem.vt.edu">www.prep.biochem.vt.edu</a>
Bringing Field Research into the Classroom, Rocky Mountain Biological Laboratory, Ian Billick	Provides improved access to online databases and curricular materials (this part of the project is in development). Enables students to use related long-term climate, weather, and biodiversity data to address ongoing problems of environmental and ecological interest; and track the stepwise progression of a particular research project done by others from planning to publication.	In progress	Introduces students to the work of individual scientists. Subject area: ecology, evolutionary biology, environmental science
Online Research in Biology (ORB), Cornell Lab of Ornithology, Nancy Trautmann	Facilitates student research using ecology and animal behavior data from online databases such as the Cornell Lab's collection of citizen-science-generated databases (i.e., eBird, Great Backyard Bird Count) or the Macaulay Library's collection of animal sounds and videos. Currently creating and piloting Web-based curriculum resources that make use of visualization and analysis tools such as Raven sound software and Science Pipes scientific workflow software.	In progress	Subject area: ecology, conservation, animal communication, and animal behavior <a href="http://www.birds.cornell.edu/orb">www.birds.cornell.edu/orb</a>
Projects that provide faculty support and address barriers to adoption and implementation			
Community College Undergraduate Research Initiative (CCURI), Finger Lakes Community College, James Hewlett	Designs, implements, and evaluates a model for integrating undergraduate research into community college science curriculums. Model involves the use of inquiry-based materials and activities in freshman courses, which are then expanded into an undergraduate research experience at the sophomore level.	In progress	Sophomore course with research experience will be credit bearing and transferable to 4-yr institutions. Addresses barriers to undergraduate research in community colleges, such as lack of resources and limited access to research collaborations and networks.

(Continued)

**Table 1.** Continued

Project, institution, principal investigator	Project description	Outcomes	Comments, subject area, website
			Approach can be adapted to a variety of disciplines or research subjects. www.ccuri.org
Science in society: connecting research experiences to real-world issues			
Bring Your Own Cassava, University of Puerto Rico, Mayaguez, Dimuth Siritunga	Incorporates research to assess the genetic diversity of cassava populations in Puerto Rico into Genetics and Cell Physiology courses. Students in the Genetics course locate, transport, extract, and quantify DNA and then use simple sequence repeat DNA markers to assess genetic diversity from cassava leaves collected from around their homes. Students in the Cell Physiology course characterize the structure of root cells of cassava varieties and perform analysis on root contents.	Surveys and content tests created by the principal investigator, administered premodule and postmodule, show student gains in both content learning and confidence in a variety of scientific skills, such as “constructing a testable hypothesis” and “designing an experiment to test a hypothesis.” Student data are contributing to an understanding of the genetic diversity of Puerto Rican cassava and cassava conservation (Montero Rojas <i>et al.</i> , 2011). Novel cassava accessions found by the students have been added to the Puerto Rican cassava germplasm maintained in vitro in the principal investigator’s lab and in the field at the Isabela Agricultural Research Station.	Reaches a student population that is 99% from underrepresented groups and 59% regarded as economically disadvantaged. Project is being expanded to investigate the sweet potato. Impacts approximately 800 students per year. Subject area: genetics, cell physiology
Application-Based Service Learning (ABSL), Duquesne University, Pittsburgh, PA, Nancy Trun	Incorporates service learning and uses community-based problems to engage students in scientific research. Course has two components: First, students learn about a specific community-based problem in the service portion of the course. Then, in laboratory classes they conduct research to help understand and solve the problem.	Pre- and posttests, surveys, and content exams show preliminary results including a 40% increase in retention of knowledge 5 mo postcourse when compared with a lecture-only class (55% retention without ABSL vs. 95% with ABSL). Student evaluations indicate strong positive attitudes about the course (100% would recommend the class) (AAAS, 2011b).	Approach can be adapted to a variety of disciplines or research subjects. <a href="http://serc.carleton.edu/sencer/application-based_service/index.html">http://serc.carleton.edu/sencer/application-based_service/index.html</a>
Community-Based Participatory Research (CBPR), Crow Environmental Health Steering Committee, Little Big Horn College, Mari Eggers; Montana State University, Bozeman, Anne Camper; University of New England, Biddeford, ME, Tim Ford	CBPR projects are incorporated into the life sciences curriculum and undergraduate research and internship programs. Students do standard water quality tests, as appropriate, on water from local rivers and wells (pH, temperature, conductivity, coliforms/ <i>E. coli</i> , etc.), and deliver samples to another lab for inorganics and metals testing. This summer they will be adding the use of polymerase chain reaction to detect <i>Cryptosporidium</i> . Findings are related to local health risks, and results are disseminated in the community.	When this project began in 2006, few tribal members had undergraduate degrees in biological or environmental sciences and none had graduate degrees in the field. Now persistence rates to degrees for research interns are near 100%. Twelve Little Big Horn College students are earning 4-yr degrees, and two have earned master’s degrees in the disciplines. The students and the community have developed an understanding of risk assessment and testing methodologies and an appreciation of local water issues.	Research involves students collaborating with a local steering committee of community members; researchers from Montana State University, the University of New England, and the University of Wyoming, Laramie, WY; federal agencies such as the U.S. Geological Survey, the Environmental Protection agency, the Fish and Wildlife Service, and the Indian Health Service; and the nonprofit Hopa Mountain, Bozeman, MT, and other organizations. Subject area: natural resources, environmental science, environmental health <a href="http://www.epa.gov/osp/tribes/NatForum10/ntsfl0_3t_Ford.pdf">www.epa.gov/osp/tribes/NatForum10/ntsfl0_3t_Ford.pdf</a> , <a href="http://www.lbhc.edu/waterquality">www.lbhc.edu/waterquality</a>

from literature-based investigations that are amenable to lecture classrooms to research activities within the lab, and include research projects that bring students out of the classroom and into their communities to address local problems. Although these approaches may vary in the resources they require and the contexts for which they are best suited, they all share the ability to actively engage and inspire students.

### ***Introducing Students to Research; Demystifying Science and Scientists through Close Investigations of Individual Research Labs***

Most students who seek apprenticeship-type research experiences are already self-identified as science majors (Lopatto, 2010), and many students, particularly underrepresented minorities, may not consider participating in apprenticeship-type undergraduate research experiences because they are uncomfortable or unfamiliar with the idea of research. One approach that can reach broader populations of students is to engage students in “thinking like a scientist” and to introduce them to the work of individual scientists in the classroom. This can be accomplished, for example, through close investigations of scientific literature in the classroom, as is done in the Consider, Read, Elucidate the hypotheses, Analyze and interpret the data, and Think of the next Experiment (CREATE) approach (Table 1), in which students study a series of research papers from a single research laboratory and interact with scientists in the focal lab through email surveys, or through meaningful collaborations with scientists, as achieved by students developing physical models of specific proteins of interest in the Connecting Researchers, Educators, and Students (CREST) program at the Milwaukee School of Engineering, Milwaukee, WI (Table 1).

### ***Experiencing the Process of Science: Integrating Scientific Research into the Student Laboratory***

There are several approaches to accomplishing the key recommendation of *Vision and Change* for faculty to integrate research activities into classrooms and student laboratories that can be applied to a broad spectrum of institutional types and subdisciplines within biology. One approach that is often used by faculty with active research programs is to develop projects that integrate teaching with research efforts. For example, the Authentic Research Experience in Microbiology (AREM) project (Table 1) engages students in research projects that contribute to the research objectives of an individual faculty member; in one course, students isolated strains of the plant pathogen *Agrobacterium tumefaciens*, the subject of the instructor’s research, and explored the biology of this bacterium through a variety of research-based modules. The Project Laboratory in Genetics and Genomics course (Table 1) is another example in which students engage in original research projects that are inspired by local faculty research interests.

Another approach that is gaining momentum is to provide opportunities in the classroom for students to participate in original collaborative research and contribute to a broader research effort. These approaches make research more accessible and affordable for faculty members who do not have active research programs (or are engaged in research that

does not translate well to a group project) and can be used in many types of institutions, including community colleges. Genomics represents one such fundamental area of modern biology that has the potential to engage students in cutting-edge research. Genomics research is especially amenable to collaborative research (Shaffer *et al.*, 2010), in part because teaching and research materials are both easily accessible and readily distributed and because raw data can be available at low cost (often free, from nationally funded databases). Furthermore, genomics can be readily adapted to create projects of varying complexity. A growing number of efforts are using genomics to engage students in research in the classroom, including the National Genomics Research Initiative developed by Howard Hughes Medical Institute’s Science Education Alliance (SEA; Table 1), which engages freshmen in a national experiment on bacteriophage genomics; the Genomics Education Partnership at Washington University, St. Louis (Table 1), which currently focuses on a problem in *Drosophila* evolution, working primarily with upper-level undergraduates (Lopatto *et al.*, 2008; Shaffer *et al.*, 2010); and the Community College Genomics Research Initiative at Bellevue Community College, Bellevue, WA (Table 1), which focuses exclusively on bringing genomics research into community college biology classrooms. This collaborative approach is not limited to genomics. For example, the Partnership for Research and Education in Plants for Undergraduates (PREP-U) project (Table 1) engages students in studying interactions of *Arabidopsis* with small herbivores at the genetic, biochemical, organismal, and population levels; students share data online with scientists at a distance via video chat, email, or the PREP Online Lab Notebook ([www.prep.biochem.vt.edu](http://www.prep.biochem.vt.edu)).

In other fields where research is typically conducted in natural settings, integrating research opportunities into courses is often challenging. However, newly developing online approaches offer economical and accessible ways to bring field research into classrooms and laboratories. For example, at the Rocky Mountain Biological Laboratory (RMBL), Crested Butte, CO (Table 1), cyber resources are being developed that will enable students to access the extensive collection of datasets at RMBL, including those mapping regional climate, weather, and biodiversity trends, as well as supporting materials for inquiry-based activities. The Cornell Lab of Ornithology, Ithaca, NY, is also developing online resources for cyber-enabled research investigations. The project, Online Research in Biology (Table 1), provides access to the Cornell Lab’s world-class databases about birds, other animals, and their habitats, including citizen-science-assembled bird population data and the Macaulay Library’s archives of animal sound recordings and videos. Cyber-based approaches may lack some of the appeal of fieldwork, but they offer students unique opportunities to engage with data gathered across time and from multiple, often remote sites while avoiding the logistical challenges to gathering such data. As online collections of scientific data continue to grow, so do the accessibility and appeal of this approach.

### ***Science in Society: Connecting Research Experiences to Real-World Issues***

One of the core competencies outlined by *Vision and Change* for undergraduate biology students is the ability to understand the relationship between science and society. Research

experiences that are connected to real-world issues and problems help to develop this competency. For example, in the Bring Your Own Cassava project (Table 1), students engage in research that is literally in their backyards and contribute to the understanding of an important local issue—the conservation of a common food in Puerto Rico, the cassava plant (Montero Rojas *et al.*, 2011). Other projects explicitly integrate student research experiences with societal issues; in the Application-Based Service Learning project (Table 1), students first take a service-learning course to understand the problem that they will then research as part of a subsequent biology course. Similarly, the Community-Based Participatory Research projects<sup>1</sup> (Table 1; Cummins *et al.*, 2010) immerse students in the scientific and social dimensions of a local issue (e.g., water quality) by collaborating with community stakeholders throughout the process of conducting their research on the problem. This approach can be a very powerful way to engage students in biology and to help them appreciate why an understanding of biology matters to their lives.

## CROSS-CUTTING ANALYSES

### *Tools to Aid Resource-limited Institutions*

A number of resources have been instituted to help institutions whose main mission is not research to offer their students the opportunity to participate in a course-based research experience.<sup>2</sup> These are probably most fully developed in the field of genomics and include rich resources offered by the SEA phage project, such as reagents and instrumentation, instructional materials, technical support, shared databases, and opportunities for networking; the databases, instructional material, and opportunities for data sharing offered by the Genomics Educational Partnership fly chromosome project; the databases and technical training offered by the Interpret a Microbial Genome Annotation Collaboration Toolkit project ([www.jgi.doe.gov/education/annotation\\_tools.html](http://www.jgi.doe.gov/education/annotation_tools.html)); and the background materials and microarray support offered by the Genome Consortium for Active Teaching (GCAT) project at Davidson College, Davidson, NC ([www.bio.davidson.edu/GCAT](http://www.bio.davidson.edu/GCAT)).<sup>3</sup> In addition, as described earlier, online resources are opening venues for classroom-based research investigations of field-based phenomena by using the growing collections of online biodiversity databases. Computer-based simulations and analytical challenges are also available from a variety of sources to help develop research skills and thinking; BioQuest ([www.bioquest.org/BQLibrary](http://www.bioquest.org/BQLibrary)) is an excellent example of this type of resource.

A growing number of efforts are also providing support to community colleges to help their faculty incorporate stu-

dent research into the curriculum (Cejda and Hensel, 2009). The Community College Undergraduate Research Initiative (CCURI) at Finger Lakes Community College, Canandaigua, NY, is developing a model to facilitate this goal. The model takes into consideration several of the barriers faced by community colleges, including the issue of student transfer to 4-yr colleges; in the CCURI model, research experiences provide course credit that is transferable to 4-yr institutions. Other projects address this issue by forming partnerships between 2- and 4-yr institutions to enrich the research experience, as is the case for the Community-Based Participatory Research project. Such partnerships can also facilitate continuity for transfer students, as illustrated by the California State University (CSU), Chico, and Butte Community College, Oroville, CA, partnership, where a two-tiered set of labs in cell and molecular biology provides a smoother transition for students from Butte who transfer to CSU Chico. These students, having taken the first-tier lab at Butte, can enter the second-tier lab with the same background in the course topic as their CSU Chico classmates.

### *Suitability across Institutions and Biological Subfields*

This small sampling of both mature and newly developing projects that engage undergraduates in original research illustrates approaches that are feasible at a wide range of institutions, from community colleges to research-focused universities and from small private institutions to large public ones, including minority-serving institutions. Examples given in Table 1 range across a variety of biological topics and disciplines, from the cellular and molecular levels (genetics, genomics, microbiology) to the organismal and population levels (ecology, animal behavior). Given the diversity of approaches that faculties have developed and the successes they are documenting, we might surmise that the only limits to finding ways to engage students with biological research are the limits of our creativity; it is no longer possible to say this approach cannot be done on a particular campus or in a particular discipline. Rather, the question that faculty understandably wrestle with becomes whether a particular approach is appropriate for its unique situation and group of students.

### *Outcomes and Observations*

A number of tools have evolved for studying the outcomes of engaging students with the scholarship of the discipline. Several studies have documented the benefits of research experiences of the apprenticeship type (Russell *et al.*, 2007; Junge *et al.*, 2010; Laursen *et al.*, 2010; Lopatto, 2010). These have included, at a minimum, student surveys about attitudes toward science and perceptions of the value of the research experiences. One set of commonly used assessment tools is the Summer Undergraduate Research Experiences (SURE) survey and its cousin, the Classroom Undergraduate Research Experiences (CURE) survey, developed by David Lopatto (Grinnell College, Grinnell, IA). These surveys include pre-course and postcourse questions that ask about science attitudes and, in the postcourse survey, estimates of learning gains and perceptions of benefits from the course. Many of the projects described here report outcomes of SURE/CURE

<sup>1</sup>There are five independent undergraduate science research projects at Little Big Horn College, Crow Agency, MT. We highlight one of these projects—the Community-Based Participatory Research project on water quality led by Mari Eggers.

<sup>2</sup>All of these programs provide websites with instructional and problem-solving activities. Typically, faculty members who wish to join the collaborative effort apply to attend a multi-day workshop to learn the experimental approaches, software tools, and such.

<sup>3</sup>GCAT now provides support in synthetic biology as well ([www.bio.davidson.edu/projects/gcat/Synthetic/synthetic.html](http://www.bio.davidson.edu/projects/gcat/Synthetic/synthetic.html)).

surveys or adapted versions of these tools; in all of these cases, students reported several benefits from their classroom-based research experiences, and in at least some cases they showed gains similar to those reported by students who had spent a summer in a research apprenticeship (Lopatto *et al.*, 2008). Some of these benefits include enhanced understanding of the scientific process, increased interest in science, and increased confidence in various scientific skills. Many projects have also devised content- and competency-based exams to determine whether engaging in classroom-based research experiences enhances students' abilities to learn and retain content knowledge and to develop understanding of the emerging core concepts and competencies for biology (AAAS, 2011a). Whereas assembling consistent patterns is difficult, given the diversity of approaches, some interesting observations have emerged. First, evidence is emerging that these approaches are introducing more underrepresented minorities to scientific research in the classroom. For example, in Project Laboratory courses, participation by underrepresented minorities was unexpectedly high, 40% (27 of 67 students) across multiple courses (James Morris, personal communication) compared with approximately 15% in the overall student population ([www.brandeis.edu/institution/alresearch/2009pdfs/CDS2009\\_2010.pdf](http://www.brandeis.edu/institution/alresearch/2009pdfs/CDS2009_2010.pdf)). Second, in many of the examples highlighted here, a common ingredient of success is identifying a suitable research problem that uses a set of common tools (which can be taught to the students as a group) but can be subdivided to provide students with individual projects. Often these parts are reassembled to derive more informative conclusions. Well-designed projects also provide extensive opportunities for peer interaction and mutual support. These elements likely contribute to a student's sense of responsibility, of ownership of his or her piece of the project, and of the importance of his or her contribution to a broader picture, both of which may be critical for developing an appreciation for scientific research.

## CODA

This article has pointed out a few of the promising emerging efforts to integrate research experiences into academic-year classes. This is by no means a comprehensive review. As noted in *Vision and Change*, no one approach is the best practice for all situations, all faculties, all institutions, or all students. The examples presented here represent approaches that have the potential to be successful practices in diverse settings. More comprehensive reviews of undergraduate research approaches can be found in two interesting publications, both available online. Each of these publications is wide ranging in the disciplines, approaches, and institutions considered. They each include many biology-related examples. One publication, *Developing Undergraduate Research and Inquiry* (Healey and Jenkins, 2009), has a somewhat global outlook (mostly Australia, Canada, New Zealand, the United Kingdom, and the United States); the other, a publication from the Council on Undergraduate Research, *Developing and Sustaining a Research-Supportive Curriculum* (Karukstis and Elgren, 2007), confines itself to work in the United States. Both publications include an extensive discussion of the philosophical and pedagogical basis for the approach presented. For additional examples of class- and laboratory-based undergraduate re-

search in biology the reader is directed to articles in this journal and others concerned with biology education. For example, the January/February issue of the journal, *Biochemistry and Molecular Biology Education* (Volume 39, Issue 1) highlights innovative laboratory exercises for undergraduates; four of the five examples feature research-based approaches, one of them concentrating on an introductory biology course that includes biology majors and students majoring in other fields (Bell, 2011).

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