It Takes a Village to Make a Scientist: Reflections of a Faculty Learning Community

By Cinzia Cervato, William Gallus, Michael Slade, Steve Kawaler, Massimo Marengo, Keith Woo, Barbara Krumhardt, Dave Flory, Mike Clough, Alexis Campbell, Elizabeth Moss, and Martin Acerbo

Lab components of undergraduate science courses typically have students complete highly directed cookbook-like laboratory activities. These experiences rarely engage students in a meaningful manner and do not accurately convey what the work of science entails. With funding from the Howard Hughes Medical Institute (HHMI), we have created more authentic science research experiences in a variety of undergraduate science courses, including introductory courses. Achieving this among the diversity of freshmen and sophomore science courses—each typically serving hundreds of students on our campus—required careful planning and adaptation. This article describes the many challenges we faced in our effort to create more authentic undergraduate student research experiences and the significant progress we have made in making such experiences more common for our students. Improvements in first-year science, technology, engineering, and mathematics (STEM) retention over the last 2 years suggest that the experiences may be having a positive impact.

As scientists and postsecondary science teachers, we may have difficulty accepting that many students soon leave their science major because they find science classes—and, by association, science itself—lacking engagement, creativity, and meaning (Eccles, 2005; Tobias, 1990). How can that be? Seymour and Hewitt (1997), in an extensive study of why undergraduates leave the sciences, wrote: "One serious cause of loss of interest was disappointment with the perceived narrowness of their [science, math and engineering] majors as an educational experience . . ." (p. 180). Introductory science courses are too often taught via lecture and directive laboratory experiences where students merely follow directions to achieve an already well-established conclusion. Schaefer (1990, p. 4) noted that the "science professoriate [has] a comfortable 'elsewhere' focus, for advocating K–12 reforms rather than coming to grips with the hemorrhaging of the student pipeline that occurs during the college years."

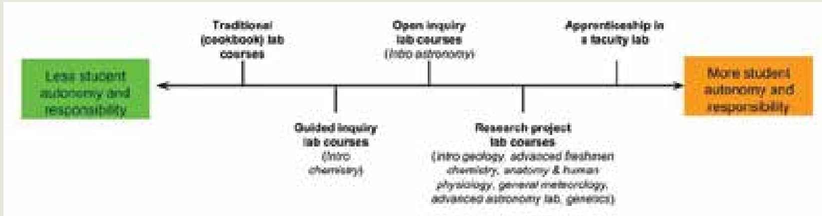
Enthusiastic teachers, relevant content, active engagement of students, inquiry experiences, and discussion of science and science-related careers are all important for highly effective science teaching (NGSS Lead States, 2013) and assist in retaining science majors (Oakes, 1990; Woolnough, 1994). Active learning has been singled out as a key aspect in efforts to retain science majors (President's Council of Advisors on Science and Technology, 2012). Making science classes more like science in the sense of creating highly engaging, inquiry-based learning experiences, even at the introductory level, is one goal of a project funded by Howard Hughes Medical Institute that began at our institution in 2010. Undergraduate research experiences have potential to improve science students' graduation rate, especially among minorities (Nagda, Gregerman, Jonides, von Hippel, & Lerner, 1998; Russell, 2006). The most common research experiences for undergraduates involve one-on-one mentoring by faculty members or graduate students. However, at our research-extensive university, the large number of students enrolled in freshmen- and sophomore-level science courses made this approach impractical. Instead, we embraced the research-based lab approach piloted by the CASPiE (Center for Authentic Science Practice in Education) project for introductory chemistry (Weaver, Russell, & Wink, 2008). In this model, both science and non-science majors in first- and second-year science labs become involved in authentic research. This article describes how we transformed and adapted CASPiE's single discipline model for the cross-disciplinary context of our project and our identified learning outcomes.

It takes a village to make a scientist

Whether or not students begin college as science, technology, engineering, and mathematics (STEM) majors, they typically take introductory science courses during their first two years. Structuring these courses so that they actively engage students and accurately convey what science is, what scientists do, and how science works is crucial for promoting scientific literacy. Achieving this among the diversity of freshman and sophomore science courses on our campus—each typically serving hundreds of students—required careful planning and adaptation. Efforts were made to move away from traditional, highly directive cookbook laboratory experiences and promote inquiry-based teaching and learning in classrooms and research experiences in science labs. Figure 1 (adapted from Weaver et al., 2008) conveys the experiences promoted in the diversity of science courses (noted in parentheses) that were part of our project.

FIGURE 1

Range of student autonomy and responsibility in the lab experiences (adapted from Weaver, Russel, & Wink, 2008).



To promote these laboratory experiences, during the fall of 2010 a faculty learning community (FLC; Addis et al., 2013) was established to focus on implementing research modules within existing primarily introductory science courses. Faculty involved in teaching a science lab course were invited to participate and offered a modest amount of professional development funds; about 15 faculty ranging from lecturers to full professors joined the FLC in the first year. The FLC met for 90 minutes every other week throughout the academic year and included instructors and/or lab coordinators from anatomy and human physiology, astronomy, biology, chemistry, geology, and meteorology. During the 2010–2011 and 2011–2012 academic years, the FLC focused on how to implement research modules in these courses. Sessions included extensive discussion of relevant literature; speakers invited from other institutions that had implemented undergraduate research experiences in similar courses; and our FLC participants, who shared their experiences implementing research modules. Although the precise roles of the FLC are not the intent of this article, peer support was crucial for initiating and supporting desired changes and also in mitigating issues as they arose.

Opportunities and challenges

The opportunity to create more authentic science experiences for students raised several challenges. First, concerns about the dangers inherent in chemistry lab work, along with the large size of the introductory chemistry courses with lab section enrollment exceeding well over 1,000 students, made implementing student-driven research projects in introductory chemistry impractical. In this course, traditional "cookbook" laboratory exercises were converted into guided inquiry investigations. In the Anatomy and Human Physiology course with over 300 students in 20 lab sections, each supervised by a teaching assistant (TA), research projects were introduced in a stepwise process. Students in this course worked in groups that built on techniques already studied, thus requiring fewer additional materials and equipment. This was possible because the lab experiences presented fewer and less severe safety concerns, allowing students more responsibility in the choice and conduct of their research.

Second, regardless of course size, the opportunity to have students more seriously understand authentic science research and more deeply address particular concepts raised the familiar issue of depth versus coverage. That is, because more authentic and extensive laboratory experiences demand additional time, the familiar issue of what science content must be removed arose. This challenge is particularly acute for introductory courses that are expected to provide the foundation for upper level science courses.

Third, at large research universities like ours, graduate TAs are often responsible for teaching laboratory sections and supervising students' work. This presents an opportunity to prepare these TAs, many who will be future faculty, to implement research experiences and more effectively assist students in these experiences. However, this also presents two associated challenges. TAs rarely possess the needed pedagogical understanding to implement and support student research experiences, and they may not be interested in or committed to promoting such experiences. To address this challenge, we created TA learning communities directed at particular disciplines and course types (i.e., biology, physics/chemistry intro labs, and research-project labs). These TA learning communities address the rationale for undergraduate research experiences, the critical role of the teacher in supporting students in these experiences, and effective pedagogical practices. The turnover among TAs due to graduation or alternate assignments is an ongoing issue and makes the TA learning communities all the more important. Like the FLC, the TA learning communities, although not the focus of this article, were important for supporting desired changes and mitigating problems.

Fourth, the very nature of particular scientific disciplines impacts the kind of student laboratory research experiences that can be created. For instance, some scientific disciplines such as astronomy and geology rely more extensively on systematic observations, whereas other disciplines such as chemistry rely more extensively on experiments. Thus, for some courses the development of research questions and the determination of pertinent data necessary to answer those questions were emphasized, whereas in other courses experimental design and control of variables were more prevalent in students' laboratory research. Authentic research also raises the opportunity to understand the challenges associated with field research. For instance, introductory geology research projects were united around the common theme of water, but with the severe 2012 Midwest drought, studying water flow in streams and rivers was a challenge.

Other challenges inherent in implementing authentic research projects in laboratory courses include the following:

- having to "evolve" the curriculum/menu of research projects to maintain authenticity of research as the construction of *new* knowledge;
- alleviating the frustration of students who are accustomed to and expect laboratory activities to have previously established "correct" answers;
- overcoming students' views that the content of the laboratory experience should be closely aligned with the content of the classroom portion of the course (this raised the opportunity to teach students that what appears in science textbooks is far from new knowledge);
- quickly and efficiently providing sufficient support/background/skills to students so they can then be applied to a novel project and transferred to other applicable situations;
- acquiring additional instrumentation when needed;
- sustaining the momentum of any changes made to a course/curriculum if the course responsibility moves to another instructor; and
- articulating and assessing desired learning outcomes of research experiences.

Several of these challenges were alleviated by abandoning a single approach to student research experiences for all science courses. We also rejected common learning outcomes and assessments in favor of those that are more appropriately aligned with the research experiences in a particular course. Several course-specific approaches to authentic student research projects are described next.

Examples of implementation of research labs

Chemistry

The students in the freshmen-level advanced chemistry lab (enrollment ≈ 55) become collaborators in the faculty member's research group and explore the electrochemical reduction of carbon dioxide to useful hydrocarbon feedstocks such as ethylene. From an instructional standpoint, this project mitigates the practical (reagent availability) and safety (reagent compatibility and/or hazards) issues that chemists must consider. From the students' perspective, their work is situated in an exciting and relevant real-world context. Global climate change and energy consumption are unmet problems that may ultimately be impacted by such work, and students are motivated by the possibility that their findings might guide future research directions. After spending the first 7 weeks developing typical practical laboratory skills, the latter half of the semester is devoted to the research project. Students are introduced to the apparatus, replicate literature conditions, and then engage in authentic experimental research by adjusting the protocol and modifying electrode materials to optimize the reaction.

Astronomy

In astronomy, large data sets are available through public facilities such as NASA space telescopes and ground-based facilities. Research sponsored by NASA and the National Science Foundation has also resulted in public computing resources that can be accessed through the web and are freely available as teaching and research tools. These resources are extensively used in our junior-level courses. Research modules are presented in our Introduction to Astrophysics course and professional data analysis software is used in Astronomy Lab. In both courses, homework and guided labs are replaced by open-ended research proposed and driven by students. Instructor approval is required prior to students beginning their work. Students must submit a formal proposal conveying a clear research plan and the feasibility of the project on the basis of what has been learned in the guided-learning portion of the course. Examples of such projects include studying aspects of stellar evolution not discussed in class, reproducing results found in peer-reviewed publications using data collected by the student, or measuring stellar parameters (e.g., age, distance, mass) of stars and extrasolar planets using public data or observations carried-on by the students at our local observatory. The results of the project are then presented in a final written report.

Geology

Approximately 75 students typically enroll in Introductory Geology Lab, a one-credit lab taught independently from the introductory physical geology lecture. Approximately two thirds of these students are nonscience majors. As in astronomy, researchers in geology cannot control every aspect of their experimental setup (Frodeman, 1995). Although the spatial and temporal scale of geological processes are difficult or impossible to reproduce locally, research that is relevant and engaging for students abound. Examples include, but are not limited to, soil erosion, mass movements, earthquake and volcano monitoring, weathering of roads, and surface and groundwater hydrology. Our local area periodically experiences droughts and floods, thus we selected water as the research theme for the lab. With field-based research an essential aspect of geology, we established a state-of-the-art hydrology field station with eight wells and two stream monitoring gauges on campus, following the approach of Rathburn and Weinberg (2011) and Moss, Cervato, Ogilvie, and Ihrig (2013). The primary learning outcome of the 6-week research experience is to have students understand the physical and chemical connection between surface and groundwater flow. Students work in teams of four to identify a research question, test its feasibility with a stream table and "ant farm" model, and design their data collection and analysis plan. Most of the questions are related to water quality. Students check out basic water quality equipment and collect data outside of lab hours, augmenting their results with data collected by students in previous semesters that is accessible online. Their research is summarized in posters that are evaluated by their peers and a team of content experts during a poster session.

Anatomy and human physiology

Each spring, over 300 students, mostly prehealth and kinesiology majors, enroll in Fundamentals of Human Physiology Lab. A primary goal of the lab is developing physiological data collecting skills. Previously, the lab included a capstone personal health assessment project, but beginning in the spring of 2011 students have been required to choose an idea from a list provided by the instructor, prepare a research proposal, and complete the investigation. Each student research group prepares six research proposals using skills and/or techniques learned earlier in the laboratory. Graduate TAs provide feedback so that each research team improves their best proposal. The final proposal, presented orally, must include an explanation of the physiological phenomena being measured, why the research is important, how the data would be collected, how sources of error and safety issues would be minimized, and references that could not include the course lab manual or textbook. Graduate TAs provided feedback via a rubric that was available on Blackboard. Groups worked on the accepted projects the following week. Groups whose proposals were not accepted conducted an experiment in the course lab manual investigating fluid and salt homeostasis. After having conducted their respective lab work, groups orally presented their findings the final week of class. The presentation was required to have all the components of a standard lab report, and a rubric for its evaluation was available on Blackboard. With each passing year, the instructions for proposal writing and rubrics for evaluation are improved, and the quality of student research proposals has improved. Students and teaching assistants have conveyed that they value learning about physiology and the processes of science in this manner. Having students orally present their research proposals and lab work permits the TAs to provide more accurate and valuable feedback while reducing time outside of class assessing students' work.

Meteorology

General Meteorology is a spring semester, sophomore-level course taken by 25 to 30 students, almost all majors. The class meets four times each week for 50 minutes. Having no dedicated lab, an average of one meeting per week was committed to the introduction of an inquiry-based lab. Initially this occurred for only 8 weeks but now encompasses the full 16-week semester. Students, in research groups of three or four, individually develop two or three scientific questions or items of interest about meteorological aspects or phenomena. The group members share their questions and select a single topic for their group research project. The research group then refines the scientific question or hypothesis, outlines their research procedure, and describes their expected outcome.

These ideas then undergo an anonymous peer review process by other groups and additional feedback by the instructor. Complete freedom is generally given to groups in selecting a research topic as long as a testable hypothesis can be developed. In subsequent weeks, students work to collect and analyze their data, reflect, and collect more data if necessary, draw conclusions, and give oral presentations of their results at the end of the semester. Students are encouraged to either seek out data available online at professional sites or collect their own data by recording temperature and relative humidity using Maxim iButton Thermochrons. Over the 3 years, approximately 20% of the student groups have chosen to collect their own data.

Principles of genetics

Biorenewable Feedstock is an undergraduate laboratory module for about 200 students, mostly sophomore-level, life science majors. A key element in this approach is the direct involvement of students in a faculty research project following the CASPiE model (Weaver et al., 2008). The objective of the students' research is the production of biorenewable feedstock from fatty acids with the intention of replacing petroleum-based products. Fatty acids are very similar in chemical structure to products derived from petroleum, so designing a yeast strain that can produce large quantities of fatty acids is a desired trait for the biorenewable chemicals industry. This module spans 5 weeks and is driven by combining bioinformatics as a tool for hypothesis generation and molecular genetics to further validate this novel regulatory network and microbial factories for the purposes of increasing the cell's fat content. This research project brings in educational content applicable to both academic and industrial contexts.

Future assessment of the project

During the 2012–2013 academic year, effort shifted primarily to appropriate evaluation tools and key tasks and concepts that students in science courses should learn from their research experiences. Sadler, Burgin, McKinney, and Ponjuan (2010) noted that learning outcomes targeted in authentic research experiences are difficult constructs to measure. For instance, they wrote the following:

> Consider, for example, the measurement of content knowledge. In a program that partners 20 students with scientists, the range of content that might be learned is likely to be very broad. If the participants are assigned to various disciplines, then the task of validly assessing content understandings related to the experience is daunting. (p. 252)

Because of the wide range of research experiences and variables that contribute to student learning, we did not assess student content learning. However, we have determined that the first-year STEM retention increased in each of the last 2 years by 2.8% (2012) and 4.5% (2013; C. Ogilvie, personal communication, April, 2013). However, we cannot be certain that this is attributed solely to this project.

In an effort to frame future assessment of our project, during the 2012–2013 academic year the FLC developed a list of 42 common outcomes for each course that implements a student research project, and these desired outcomes are guiding the selection of assessment instruments. Common desired outcomes appear in Table 1 and are grouped into four categories that we feel increase in cognitive complexity from the left column to the right column (Heer, 2008). The four categories in increasing cognitive complexity are as follows:

- factual—the basic elements students must know to be acquainted with a discipline or solve problems in it;
- conceptual—the interrelationships among the basic elements within a larger structure that enable them to work together;
- procedural—how to do something, methods of inquiry, and criteria for using skills, algorithms, and methods; and
- metacognitive—knowledge of cognition in general as well as awareness and knowledge of one's own cognition.

Sadler et al. (2010), in their review of the literature regarding authentic research experiences, recommended using more direct measures in assessing desired outcomes of such experiences. No single assessment instrument targets all of our identified outcomes, and we have thus far identified the following instruments to assist us in our assessment efforts:

- Student Understanding of Science and Scientific Inquiry (SUSSI), an instrument developed by Liang et al. (2008) to assess students' understanding of science and scientific inquiry;
- Classroom Undergraduate Research Experience (CURE), http://www.grinnell.edu/academics/areas/psychology/assessments/cure-survey (Lopatto et al., 2008);
- Survey of Undergraduate Research Experience (SURE III), http://www.grinnell.edu/academics/areas/psychology/assessnebts/sure-iii-survey (Lopatto, 2008); and
- Test of Scientific Literacy Skills (TOSLS; Gormally, Brickman, & Lutz, 2012).

After each desired outcome in Ta-

TABLE 1

Desired project outcomes and proposed assessment instruments (1 = SUSSI; 2 = CURE; 3 = SURE III; 4 = TOSLS).

Factual outcomes	Conceptual outcomes	Procedural outcomes	Metacognitive outcomes
Identify data/variables appropriate for research (2,3)	Comprehend the signifcance of numbers that are orders of magnitude different	Replicate data to validate methodology or experiment	Develop clear and testable quantitative hypotheses
Follow a data collection protocol (2,3)	Understand phenomena that operate on different scales and order of magnitudes	Design alternative methodology to validate data	Demonstrate creative thinking
Collect data (2,3)	Propose (conceive) multiple examples of a specific effect or phenomenon	Develop alternative applications of model to other contexts	Experience different approaches to scientific research (1)
Organize data according to appropriate criteria	Transfer or extrapolate from specific examples to general phenomena	Read and understand graphs of scientific data (4)	Understand significance of the big picture in science
Summarize results with appropriate methodology		Read and understand tables with scientific data (4)	Develop a complete research plan
Display data in graphs using appropriate chart format, units, labels		Analyze data (2,3)	Understand the difference between confidence and certainty in science (4)
Create data tables with relevant and pertinent information		Interpret data (2,3)	Develop complex thinking skills
		Question, analyze and interpret results (2,3,4)	Develop understanding of complex systems
		Search for primary scientific literature (2,3)	Learn how science works (1,2,3,4)
		Read and understand primary scientific literature (2,3)	Learn how science is based on evidence and reason (1,2,3,4)
		Use standard method of literature citation (2,3)	Learn how scientific community reaches a consensus (Tools: 1,2,3,4)
		Perform statistical analysis of data sets (4)	Understand the significance of redundancy
		Understand the meaning of statistical results (4)	Work in teams (1,2,3)
		Understand the significance of repetition of experiments (4)	Understand ethical aspects of science (1,2,3)
		Understand the significance of data regression analysis (e.g., linear, exponential) and correlation factors (4)	Learn the importance of reliability and accountability for scientific research (1,2,3)
		Work on a scientific project (2,3)	

Note: SUSSI = Student Understanding of Science and Scientific Inquiry; CURE = Classroom Undergraduate Research Experience; SURE III = Survey of Undergraduate Research Experience; TOSLS = Test of Scientific Literacy Skills.

ble 1, the instrument(s) that target that outcome appear in parentheses. Where no number appears, none of these four instruments directly assess that outcome. Clearly there is a need for assessment instruments that specifically address these outcomes.

Lessons learned and implications

Engaging large numbers of undergraduate students, including those in introductory courses, in laboratory science research projects is challenging, particularly at a large university. The HHMI funding was critical for initiating these reforms at our university, and they are now part of the institutional culture. Similar seed funding would likely be crucial at other universities. Creating learning communities was critical to our success. The FLC promoted a collegial environment for achieving desired project ends; was a source of creative ideas and support for overcoming challenges; and sustained faculty engagement in the project despite the already existing teaching, research, and service demands that faculty have at research-intensive universities. The TA learning communities were crucial for encouraging TA commitment to desired project ends and assisting them in the pedagogical practices necessary for promoting authentic undergraduate student research experiences.

No single approach for creating student research experiences is appropriate for all science courses. The numbers of students in a course lab section, the nature of the science discipline, safety issues, and/or cognitive demands of the research are just some of the factors that impact the kind of undergraduate student research experiences that work best in science courses. Traditional highly directive labs can be modified or replaced with more authentic research experiences ranging from guided inquiry to faculty lab apprenticeships (Figure 1), and this is exemplified in our efforts.

Assessing the extent that desired outcomes of a project like ours are achieved presents its own challenges. Existing assessment instruments target particular desired student outcomes (e.g., nature of science understanding, science content knowledge understanding, quantitative reasoning proficiency, students' self-efficacy and attitude toward research experiences, etc.), and we are still searching for existing instruments that target other desired student outcomes. Teaching to and assessing all desired student outcomes requires much pedagogical expertise and time.

The most important lesson learned is that faculty commitment to creating undergraduate student research experiences, along with initial support to do so, has resulted in far more students having a more authentic science research experience during their undergraduate education and increased retention of STEM majors. As the project matures and students reach upper level courses, we will assess whether these students are better prepared for these courses. ■

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