Inquiry-based and research-based laboratory pedagogies in undergraduate science

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Undergraduate research experiences help retain students in science majors and prepare our workforce for increasingly competitive jobs. Course-based approaches to research and inquiry allow educators to reach larger numbers of students and provide an entry into further research experiences.

Much has been said and written about the benefits of active learning pedagogies for revitalizing traditional lecture-based courses. For example, collaborative learning approaches in the classroom can be used to engage students in discussion and problem solving to greater effect[1,2]. Peer-led team learning encourages students to learn through discussions facilitated by a near-peer on topics covered in the course, thus benefiting all the students involved[3]. Large lecture courses have benefited from the recent introduction of technologies that facilitate interaction, such as student response systems ("clickers") or in-class computers connected in such a way as to allow students to submit and show their work to the instructor and the class. The recognized importance of engaged pedagogies in the classroom has even led to the redesign of learning spaces to greater facilitate these types of interactions[4].

Though most science lecture courses are combined with a 'hands-on' component, the same broad variety of innovative pedagogies does not seem to exist for these laboratory experiences. In part, this has to do with much lower uniformity in the topics and experiences covered in laboratory courses, and in the teaching materials used. While many science textbooks have a laboratory manual as an ancillary, it is very common to find that institutions will 'publish' their own manuals that often consist of no more than photocopied and bound notes developed by one or more instructors involved with the course. Often the need for customized materials is due to the need to adapt experiments for instrumentation and supplies that are available on site.

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Another reason why there seem to be fewer universally popular laboratory reforms in the literature is that there is precious little agreement on exactly what the function of the laboratory component of a course is meant to accomplish[5]. Instructors focus on everything from "critical thinking skills" to "glassware manipulation" as important learning outcomes for students in laboratory courses. Many feel strongly that the laboratory topics should closely parallel the lecture topics, implying that the purpose of the laboratory is to reinforce or demonstrate the materials learned in lecture—yet there is little evidence that this actually takes place. Students, too, expect the topics to occur in lock-step progression[5], as they are accustomed to this approach from their early experiences with laboratory courses.

Inquiry-based laboratory curricula

To add to this potpourri of views, there are many proponents of laboratory teaching approaches that are referred to as "inquiry based." The term is broad, but the focus of the idea is similar in its many incarnations across different implementations: engaging students in the discovery process at some level. Inquiry-based teaching has been discussed and proposed for nearly 50 years[6]. Project 2061 (ref. 7) is an initiative of the American Association for the Advancement of Science (AAAS) to advance scientific and technological literacy. It is a more recent proponent of approaches that promote inquiry activities among students. The National Science Education Standards from the US National Research Council (NRC) provide a set of standards that "outline what students need to know, understand, and be able to do to be scientifically literate at different grade levels"[8]. Throughout this report, "science as inquiry" is recommended as one major category of the content standards for all grades from K through 12. Four years later, the NRC followed this report by a publication devoted entirely to defining the term 'inquiry' and detailing how it can be implemented in teaching. The approach promotes pedagogy in which students "engage in many of the same activities and thinking processes as scientists"[9]. These activities include making observations, formulating questions, gathering evidence in a reproducible manner, making scientific claims based on evidence and existing scientific knowledge, communicating results, and revising the explanation or revisiting the experiment based on feedback and critique from the community. There are numerous authors who have proposed specific terminology and groupings for these processes[10–12], but while the details may vary, the overall ideas are well aligned. We proposed a simple model, the "elements of inquiry"[13], which would achieve the goals of the NRC inquiry mode when carried out by

Table 1 The elements of inquiry and degrees of inquiry implementation

Elements of inquiry	Traditional lab experiments	Less open inquiry	⟷	More open inquiry
Observation				X
Questioning			X	X
Experimental design		X	X	X
Data collection	X	X	X	X
Data analysis	X	X	X	X
Repeating			X	X
Reporting/peer review				X

X indicates that the element is determined primarily by the student. Otherwise, the element is prescribed by the instructor or laboratory manual.

the students themselves, rather than having those elements detailed by their instructors or a laboratory manual (**Table 1**).

Within the elements of inquiry model, a traditional laboratory would be distinguished from an inquiry laboratory in that only data collection and analysis would be carried out by the student, and these would be largely prescribed through a series of procedures in a laboratory manual. As a curriculum becomes more inquiry based, more of the elements are left to the student to determine. It should also be noted that implementations of inquiry-based curricula occur on a continuum, with some being very guided by the instructor and others being very open-ended. Windschitl[10] outlines a hierarchy of levels of inquiry, including confirmation experiments, structured inquiry, guided inquiry and open inquiry. These differ from one another in the degree to which the student makes decisions about the procedures and analysis, in contrast to having explicit directions provided for them by an instructor or the laboratory manual.

A large number of studies have described the benefits to students of inquiry-based laboratory curricula. These have reported that students in inquiry-based curricula have more positive attitudes about their course subjects and better content comprehension[14–16]. Instructors that we have worked with often find it challenging to transition to an inquiry style of teaching. Teachers are initially surprised by a sense of "chaos" in their classrooms, which is the result of having students involved in different aspects of a project at the same time and being actively engaged in their learning. Students also find the transition unnerving initially, because they are generally not accustomed to making their own decisions about experimental procedures, and this makes some students very uncomfortable. In fact, as we have worked with students we have noticed that the high achievers are generally more unsettled by this shift, and that students in the middle or lower end of the performance curve often shine under these new circumstances. Ultimately, however, students and teachers become more comfortable with the approach and generally report that they enjoy it more overall than the traditional approach.

Existing undergraduate research models

A well-known approach to undergraduate research involves direct mentoring by a scientist, such that an undergraduate student works in the lab of that scientist, in many cases as part of a research group. These traditional research experiences involve the student in a full immersion into the research environment, and they generally take place outside of the normal course load for a student's major requirements. The approach to undergraduate research that we are focusing on in this feature, however, is different from these better known models in that it is integrated into the coursework of students, rather than being an additional component such as a summer project, internship or "independent studies" experience. In fact, the course-based approach to research fills a niche in the transition from inquiry-based learning to professional science practice (**Fig. 1**).

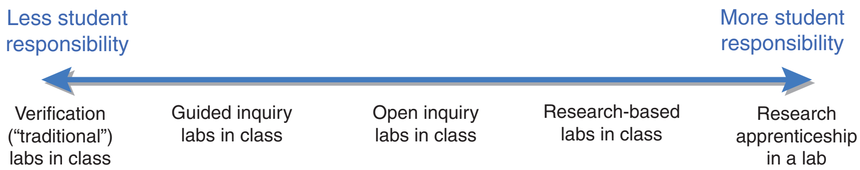

Figure 1 Inquiry and research exist on a continuum, from a pure verification experience in class to a full-fledged research experience. The levels of student intellectual autonomy and responsibility increase from left to right.

Numerous studies[17–20] have described the benefits of traditional undergraduate research experiences to the development, recruitment and retention of undergraduate students, including impacts on their future career choices. The research also indicates that students develop a deeper understanding of the field they are working in, show increased confidence in their ability to do and understand science, gain skills in interpreting results, and learn about the construction of scientific knowledge and the use of evidence to support assertions.

A review of federally funded undergraduate research programs was commissioned by the US National Science Foundation (NSF) and carried out by SRI International starting in 2003 (ref. 21). The study surveyed students involved in NSF-funded research, and also surveyed representative populations of STEM graduates (science, technology, engineering and mathematics) to assess their involvement in undergraduate research. Among the findings, the report pointed out that undergraduate researchers are primarily in their third and fourth years of university and have relatively high grade point averages[21]. It also showed that undergraduate research opportunities increase the likelihood of obtaining a PhD. This finding is in general agreement with Nagda *et al.*[18], that undergraduate research experiences have a positive impact on retaining students to graduation. Furthermore, the SRI report noted that "blacks and, especially, Hispanics/Latinos were more likely than Asians or non-Hispanic whites to have shown gains in understanding, confidence, and awareness"[21].

However, of the STEM graduates surveyed who had not been involved in undergraduate research, three of the four most common reasons given were "I didn't have time" (37% of nonresearch students), "I was not aware that research opportunities were available to me" (28%), and "It never occurred to me to do research" (19%)[21]. Traditional models of undergraduate research that depend on students seeking out extracurricular opportunities, then, have a high probability of missing a large fraction of the student population who could conceivably benefit greatly from such experiences. In addition, data from the National Science Board's Science and Engineering Indicators report[22] provide evidence that the largest fraction of students dropping out of the sciences is between the first and second years. Again, because the traditional model is serving primarily students who are later in their studies, the noted retention benefits of undergraduate research are not being used where they may be most needed. To this end, the SRI report includes the following among its recommendations[21]: "we recommend that NSF encourage its PIs to find ways to include college freshmen and sophomores in their research programs."

In order to reach students in earlier years and to reach students who will not, for various reasons, take the initiative to explore research opportunities, course-based approaches to undergraduate research are an option. An important question remains about whether a course-based research experience can result in the same or equivalent educational benefits to students and can be authentic research—that is, scientific activity that can, at some level, contribute to publishable work.

Current work in research-based laboratory curricula

An extension to inquiry-based curricula, and an alternative to traditional research models, is the development of research-based laboratory curricula. The goal in these is to involve students in authentic research experiences as part of their formal coursework. From a skill-set perspective, a research-based laboratory curriculum would have the same components as that of a fully implemented inquiry-based curriculum, as described in **Table 1**. However, a critical difference exists in the purpose of the experiments. In a research-based laboratory, the students are part of the discovery process of a scientist. There is no information in any textbook, laboratory manual or journal article about their expected results, because these are being discovered as part of the learning experience. This creates an environment in which students are participants in the development of new knowledge, and where the instructors are facilitating this process as research mentors. In this environment, the reporting and peer review elements consist of data submitted to the scientist, to serve as contributions to a larger research effort and to the eventual generation of publications or presentations. This differs from a situation in which a student simply submits an assignment to an instructor for final grading.

In 2003 the Division of Chemistry at the NSF hosted a workshop to explore the concept of supporting the development of innovative models of undergraduate research that would specifically target first- and second-year students, including those at two-year institutions[23]. The workshop resulted in the Undergraduate Research Centers/Collaboratives (URC) program[24], from which five URCs were funded over three years. Each of these URCs proposed different models for engaging younger students in undergraduate research, three of which were primarily through classroom-based approaches[25] (see also the Freshman Research Initiative at the University of Texas at Austin, http://cns.utexas.edu/current_students/research/freshman_research_initiative/, and the REEL program at Ohio State University, http://www.ohio-reel.osu.edu/). In addition, researchers have been individually exploring ways to link teaching and research by involving students in their classes in projects related to their own research interests. An example of this was reported by Hanauer *et al.*[26] in which students from high school and college isolated and purified bacteriophages, contributing to a library of sequenced genomes that can be compared with already-sequenced genomes. In another example[27], researchers at the University of California at Los Angeles created a curriculum in functional genomics in which students who enroll in a course each explore different mutations of genes in the *Drosophila melanogaster* eye and upload their data into an online database.

There is no large-scale evaluation of the effects of research-based curricula on student success. However, we can draw some comparisons to the data described above from the SRI reports and others that have looked at traditional undergraduate research programs. For example, STEM students who participated in NSF-sponsored undergraduate research self-reported the types of activities that they participated in[21]. Of 17 activities listed in the survey, "collecting and analyzing data" was the most common activity, with 80% of students saying that they had engaged in it. "Understood big picture" was selected by 59% of the students, and "provided input into project design" by 50% of students. The activity of "authoring or co-authoring a paper submitted for publication" was second to last, with only 13% of students reporting to have engaged in this activity. Only the statement "did little or no real research" received a lower score, at 7%. It is noteworthy that the average amount of time that the STEM graduates reported having been involved in research (not including those who did no research) was 11.8 months[21], because they engaged not only in summer research but also in other types of academic-year research activities and thesis projects. Therefore, though most researchers would agree that any exposure to undergraduate research will benefit a student's skills, their efforts may not show up as publications until they have had an opportunity to remain in the pipeline for a much longer time. This further supports the premise that introducing students to research as early as possible would benefit both them and the research itself. In fact, course-based research early in the academic career can provide critical introductory training in basic research skills, which come only gradually and informally in a pure research setting. This means that a research-based curriculum can have the additional benefit of better preparing students for the more traditional research experiences that we would like them to have in their third and fourth years.

We have been involved with one of the NSF-funded URC programs since 2004. The Center for Authentic Science Practice in Education (CASPiE; http://www.caspie.org/) engages researchers as authors of experimental mod-

Figure 2 Students carrying out measurements on contact angle goniometers. Using advanced instrumentation is one element of providing students with an authentic research experience.

ules that can be carried out by first- and second-year students in their laboratory courses over a period of half a standard semester[25]. Because the courses meet on a standard schedule of 3 h once per week, students are introduced to research with projects that last only 18 to 24 h total. However, the cumulative contributions of many students at several partner institutions are able to provide the researchers with data for their work. The students themselves benefit from the more challenging learning experience compared with traditional lab experiments (**Fig. 2**).

Third-party evaluation of our program has demonstrated statistically significant differences between CASPiE participants and non-participants in measures of increasing interest in science, understanding the connection between science and everyday life, and seeing lab experiences as representative of real science experiences, and it has also shown a difference in the impact of laboratory experiences on future careers. A study was carried out comparing our research-based curriculum model to a long-established inquiry curriculum and to a traditional curriculum[16]. Qualitative and quantitative data analyses from this study have demonstrated that, compared to the other two curricula, students in the research-based curriculum demonstrate a much deeper understanding of the main scientific concepts in their experiments. They also report significantly more confidence in their ability to explain their experiments, and they were better able to propose further investigations that could be carried out for their experiment. Statistical analyses show significant increases in agreement for students in the research classes to, among others, the statements "In this lab course, I must understand the big ideas behind each experiment in order to do well," "I have a better understanding of the process of scientific research as a result of this laboratory experience" and "The lab experiences in this chemistry course made me realize I could do science research in a real science laboratory." It is worth noting that, for students in the traditional course, we saw significant decreases in agreement to those same statements.

What will the next generation of laboratory pedagogies look like?

There are definitely some challenges involved with developing and implementing research-based laboratory curricula as a regular part of student coursework. Training of teaching assistants to function as research mentors, for example, is an aspect that will take more time and effort than with traditional labs. On the other hand, it could lead to great benefits for those teaching assistants by improving their own skills as future researchers. The costs of materials and supplies may also increase over more traditional rote experiments that use common chemicals. However, many of the difficulties of transitioning to such a model can be ameliorated by learning about the models that already exist and that are being implemented successfully—such as some of the models described here. As in scientific research, it is important in educational innovation to build on the knowledge and successes of others in the field.

Our own experiences have convinced us that research-based pedagogies provide students with immense benefits over traditional laboratory experiences, and even over inquiry-based laboratory experiences. Furthermore, there are demonstrated benefits for researchers who engage their own classes in these types of activities. Inclusion of first- and second-year undergraduates in research projects has the potential to change the nature and management of research projects themselves. One way this occurs is by allowing different perspectives or questions to be raised by a diverse set of participants, possibly opening up new areas of research. As our educational system looks for ways to better address the decline in the technical competitiveness of our workforce in the global marketplace, a marriage between the research and teaching missions of our universities may become the best remedy.

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