INQUIRY LEARNING

Teaching Scientific Inquiry

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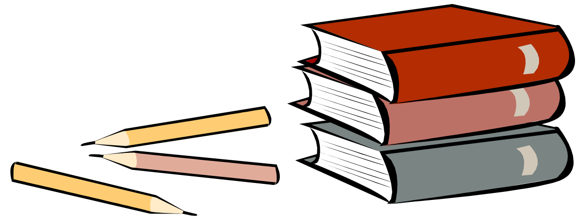

Working in research laboratories to generate new scientific information can give high school students a taste of real scientific investigation.

Science teachers in kindergarten to 12th grade (K–12) classrooms face a curious paradox. On one hand, according to the generally accepted theory, scientific inquiry in the classroom is "at the heart of the science and science learning" (*1*). In essence, the teaching of science should mirror the processes used by professional scientific researchers. On the other hand, a school classroom is not a research laboratory. Scientific research typically involves complex methods and problem-solving approaches (*2*), resulting in conclusions that are subjected to worldwide evaluation (*3*–*6*). Capturing these characteristics of professional science within the K–12 school classroom is daunting (*7*).

The goals of scientific research and current pedagogical practice are at odds (*8*, *9*). In our culture, schools are designed to present established understandings, not to promote discovery of new knowledge. The focus on persuading students of the correctness of stated information is intensified by increased reliance on broad-based standardized testing, which—especially in the United States and the United Kingdom—has become a popular mechanism for making schools accountable. The ensuing culture of conformity with established knowledge is the very antithesis of scientific inquiry (*8*).

Problems with implementing scientific inquiry in the classroom include the following: (i) Teachers may manipulate classroom science to obtain the expected results (*10*). (ii) Teachers' demonstrations merely simulate scientific inquiry. (iii) The incomplete development of students' reasoning abilities may limit their ability to construct complex scientific arguments (*9*–*12*). (iv) Scientific inquiry often requires detailed knowledge of a topic that students have yet to master.

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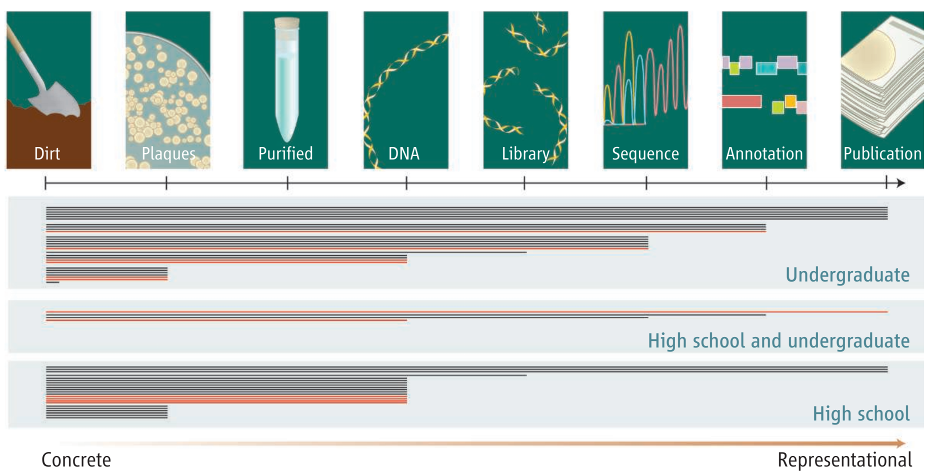
Beyond the Classroom

If the classroom cannot be readily transformed into a research laboratory, can a research laboratory be used as a classroom? The advantages of successfully doing so are obvious: The research laboratory is where scientific advances are made and where professional scientists—at different levels of career development—work, and scientific inquiry is their core activity. Undergraduates benefit from doing research (*13*, *14*), and similar benefit may be expected for high school students. Integration of students into the laboratory environment thus seems desirable for the students, provided that they are the designers, executors, and interpreters of their experiments, not simply spectators of the performances of others.

Because K–12 students are limited in knowledge and available time, one challenge in facilitating their participation in research lies in finding appropriate research projects that are within reach of their skills and knowledge, are readily adapted to more than just one or two high-achieving students, and reflect substantial rather than incremental scientific discovery.



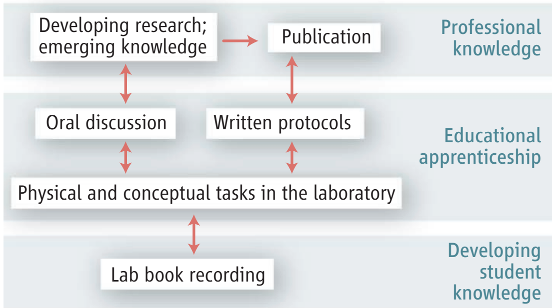
The PHIRE program. The phage-discovery process begins with a concrete activity and proceeds through increasingly representational milestones. The progress of each student is shown by a horizontal line; red lines indicate students still in the program. Most high school students participated for one summer term; four continued as undergraduates. Undergraduates average more than three terms in the program.

Playing with PHIRE

At the University of Pittsburgh, the Phage Hunters Integrating Research and Education (PHIRE) program was founded on the concept that bacteriophage discovery and comparative genomics allow students at multiple levels of development to engage in true scientific inquiry. In PHIRE, undergraduate and high school students may isolate a novel bacteriophage, grow it and extract its DNA, sequence the genome, and analyze the sequence relative to other genomes (see the chart below). The key scientific assumption is that the bacteriophage population is vast (estimated at 10^{31} particles globally), enormously diverse, and poorly understood. We have found that the genetic diversity is so great that phages isolated from the environment have a low probability of being identical to a previously characterized isolate. The prospect of discovering a genuinely new virus or many new genes provides strong motivation. The knowledge and technical skills required to isolate a phage from the environment are modest, ensuring that even middle school students can participate. The barriers to being a successful phage hunter and research scientist are minimal, opening the laboratory doors to all students, not just those labeled as academically gifted.

Comparative genomic analysis reveals that bacteriophage genomes are characteristically mosaic, composed of unique assemblages of individual and interchangeable modules (*15*). This fluid genetic exchange confuses attempts at taxonomic classification of entire phage genomes, because each of the constituent pieces has a different evolutionary history. We have therefore adopted a nonsystematic nomenclature that reflects this genetic individuality, leading to phage names such as Barnyard, Corndog, and Pipefish. The opportunity to name a new virus is exciting, and our student phage hunters often report that they consider their discoveries as being of great importance. Furthermore, the isolation of a new biological entity confers a strong sense of project ownership, and this—together with the thrill of discovery and the understanding that genomic analysis brings new knowledge of value to other scientists—promotes further engagement in the project.

We have used parallel research projects as a compromise between research independence and the ability to engage substantial numbers of students. The combination of undergraduate students and high school students facilitates peer- and near-peer mentoring, with undergraduates mentoring high school students, experienced undergraduates mentoring starting undergraduates, and experienced high school students mentoring starting undergraduates. Training mentors through programs such as the "Entering Mentoring" system (*16*) promotes an apprenticeship system (*17*) as part of the larger, multimodal structure with collective written experiences of detailed protocols, notebook reports, and published papers. The spirit of collective project ownership translates directly into collective authorship (see the chart on page 1880) (*18*, *19*). Integration of the research and educational missions promotes intertwined learning and understanding (see the chart above). The students progress from the concrete (handling biological specimens) to the representational (annotating genome sequences) (chart, page 1880). Students can participate at any or all of multiple points along this path of phage discovery and characterization (chart, page 1880).



The professional apprenticeship model. The three levels of knowledge defined within the laboratory are interconnected throughout the educational program.

Does PHIRE Work?

Early results (chart, page 1880) from the PHIRE program show that virtually every student succeeded in phage isolation and at least 75% of students achieved phage purification and DNA isolation. Of the total of 54 students from 2002 to 2006, 27 are female and achieved progress through the project similar to that of male students [attaining an average of 4.8 (female) and 4.7 (male) of the eight milestones]. More than 18% of all students in the program have coauthored a scientific publication, and another 22% have contributed to a body of work that warrants future coauthorship. Characteristics of PHIRE that set it apart from other research-like activities to which students may be exposed include scientific discovery, project ownership, time flexibility, technical facility, mentorship structure, and the potential for publication.

Adding Fuel to the PHIRE

The transition of a research laboratory into an educational facility is an evolutionary process that requires constant planning and evaluation. The educational program needs to be integrated with the scientific aims of the laboratory. Integrating education and research is relevant to other research settings beyond genomics. For example, in the field of astronomy, a Web-based program titled the "Sloan Digital Sky Survey" takes on the ambitious endeavor of mapping the universe. High school students are invited to study time-lapse, color-filtered photographs of the night sky with the purpose of identifying asteroids that are close to Earth. The asteroids' motion relative to that of the stars and planets is revealed as colored dots against the backdrop of space and more distant celestial objects. As with the PHIRE program, the specificities of the research project allow the creation of an integrated educational program that enhances high school science without degrading the quality or the aims of the research (*20*).

The PHIRE platform can be translated cost-effectively into numerous other settings. The most costly part of the project is the genomic analysis, but technological advances continue to lessen the per-base-pair cost of sequencing. Implementation of PHIRE should be within reach of many universities. We have also implemented the phage isolation component in high school classrooms. High school students isolate phages and can send them to the Pittsburgh Bacteriophage Institute for genomic sequencing. The sequence information is then returned to the student class for annotation and analysis. Since 2003, a total of 57 high schools and 3534 high school students have participated in the phage-isolation program (at a cost of about $8 per student), leading to the isolation of 94 bacteriophages; three of these have been completely sequenced. Student surveys indicate at the conclusion of the experience that more than 90% of students were able to identify key concepts in microbiology research and that more than 92% would recommend the program to other students.

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