Published in final edited form as:
Sci Teach. 2008 October 1; 75(7): 38–43.

Prepping Students for Authentic Science

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You can probably think of a time when your students conducted an experiment with a predictable outcome that yielded an unexpected result. When this happens, discussion often centers on, “What did we do wrong?” instead of “How do these data address our scientific question?” or “What alternative explanations could account for our findings?” (Hart et al. 2000).

Unexpected results can serve as an excellent teaching tool and “authentic science” can be used as a learning context for developing students’ understanding of the process and nature of science (AAAS 1990; Bencze and Hodson 1999; Hanauer et al. 2007; Means 1998; NRC 1996). Making discoveries is fun and exciting, and may be the impetus that propels young learners to pursue challenging course-work, further education, and careers in science (Markowitz 2004; Roberts and Wassersug 2008). Yet, scientific research usually happens in research laboratories or at field sites, and requires access to knowledge, supplies, and equipment not typically available in precollege classrooms.

Research internships provide an excellent way for high school students to participate in authentic research (Barab and Hay 2001; Knox, Moynihan, and Markowitz 2003; Markowitz 2004). However, such opportunities are often limited in scope and scale and involve only a handful of students. Yet, three factors are opening doors between classrooms and research labs: publicly available databases that contain massive amounts of biological information; stock centers that house and distribute inexpensive organisms with different genotypes; and the internet, which serves as conduit for dialogue and knowledge sharing.

In this article, we describe a large-scale research collaboration, the Partnership for Research and Education in Plants (PREP; see “On the web” at the end of this article), that has capitalized on these resources in response to interest from students. Through PREP, entire classes of students, with mentorship from teachers and scientists, are currently designing and conducting their own investigations while adding to the body of knowledge about genes and their functions.

Germination of a collaboration

A few years ago, the first author met with several teacher colleagues who noted that their students wanted opportunities to collect “real” data. Students were interested in moving beyond demonstration labs, with their predictable outcomes, and in a different direction than science fairs, where findings may only be shared with other students and their families, rather than the broader scientific community. The group brainstormed what experiments students could do in classrooms, keeping in mind their interests, district regulations, and required course content.

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Microbes are easy to maintain and manipulate, but preparation, safe handling, and disposal of growth media can be problematic and cost-prohibitive. Investigations with animals also present a host of concerns, including the regulations, logistics, and cost of care. In contrast, plants are uniquely flexible, scalable, and compelling tools for student investigations. Plants are large enough to be manipulated by young hands, inexpensive enough to grow in the scale required by classrooms, and robust enough for student caretakers (Lally et al. 2007).

Many teachers already use the Wisconsin Fast Plants curriculum to guide students in understanding plant biology, classical genetics, and scientific inquiry. Fast Plants have been bred to have a uniform, short flowering time and grow well in a small indoor space (see "On the web"). *Arabidopsis thaliana*, a relative of Fast Plants, is well characterized at the molecular level so many tools and resources are available for teaching concepts and skills related to genetics and biotechnology. More than 10,000 scientists around the world who study *Arabidopsis* continue to generate these resources and make them available at low or no cost. Other benefits of using *Arabidopsis* in the classroom include the attributes that make it a good model for research: rapid life cycle, abundant progeny, and small size. Most importantly, the National Science Foundation (NSF) has established the 2010 Project, the objective of which is to determine the function of all genes in *Arabidopsis* by the year 2010 to develop a comprehensive understanding of the biology of flowering plants (see "On the web").

Many of the scientists who have received funding as part of the 2010 Project have disabled their genes of interest, grown the resulting mutant plants, and looked for any changes in the plant's growth and development, finding no apparent phenotypes (Cutler and McCourt 2005). While it is likely that some genes can serve as "back-ups" for each other, it is also likely that many genes are not used unless the plant is responding to environmental stresses such as heat, humidity, or pathogen infection. Plants have had 500 million years of evolution to adapt to every biome on Earth. Their stationary nature would suggest that plants have an arsenal of genes that allow them to accommodate changes in their environment. Growing mutant plants under stress conditions allows for a more comprehensive analysis of gene function. This is the basis of PREP, which provides genuine research experiences to high school students and teachers while helping scientists discover the function of poorly characterized plant genes (see "How PREP works," p. 39).

The PREP "blueprint" for experiments was developed with guidance from a biology teacher and an *Arabidopsis* scientist (third and last authors, respectively). Students compare the growth of wild-type and mutant plants (i.e., plants with all functioning genes versus plants with one disabled gene, respectively) in controlled conditions (i.e., normal light, normal soil, normal watering) versus an experimental condition of their own choosing. This common structure enables efficient and realistic mentorship of entire classes of students by pairs of teachers and scientists. With support from the National Institutes of Health and the NSF, PREP has partnered 26 scientists with more than 60 high school biology teachers in Arizona, Colorado, Iowa, Missouri, Virginia, and Wisconsin. Teachers, scientists, and PREP staff mentor about 2,000 students annually and more than 12,000 students to date (19% Hispanic or Latino, 12% African American, 5% Asian, 3% Native American).

PREP's website (see "On the web") provides information about *Arabidopsis* and experimental protocols, as well as opportunities for dynamic interactions among partners. Although dissemination sites are located only in the states already noted, guidelines are available for teachers and scientists to initiate local collaborations (Figure 1). Online mechanisms are being pilot-tested to involve students and teachers in rural schools located far from any research institution or participating scientist. The ultimate goal is for teachers to be able to choose from a menu of communication strategies, including virtual meetings and web-mediated discussion forums, and tailor them to fit the needs and interests of their students and the technical capacity of their schools. (**Note:** Please contact the first or second author to get involved in the pilot.) Anyone visiting the site can find information, advice, and video demonstrations on how to sow and grow the plant, what it looks like at different developmental stages, and how to go about studying plants' responses to the stresses they typically encounter in their environment (Figure 2). Although seeds can be ordered for free or at low cost from the *Arabidopsis* Biological Resource Center (see "On the web"), mutant and wild-type seeds are best obtained from partner scientists who can verify the genotypes, steer students in scientifically productive directions, and help with proper disposal of materials at the end of the investigations.

Because teachers can integrate PREP into their curricula to teach concepts in genetics, plant biology, ecology, environmental science, or scientific inquiry, there is no single set of instructional guidelines or a uniform approach to its use in the classroom. However, teachers and scientists are prepared to participate through introductory workshops, annual meetings, ongoing conversations with each other and PREP staff, and review of curricular materials available through the website. During the workshops, teachers become familiar with PREP through an introductory dialogue with PREP staff, which is structured in the same way students learn about the program. The website and logistics of plant care are also discussed. The annual meeting brings together teachers and scientists for more in-depth discussion of critical points during the investigation, when students make decisions that involve scientific reasoning (e.g., when considering what research question to pose and the rationale for doing so, what observations to make and the rationale for doing so, and what variables to control).

Teachers and scientists can find and contribute vetted lessons for teaching concepts in biology and scientific inquiry and other useful resources via the Flash-animated PREP *Arabidopsis* Timeline (Figure 1, p. 40), which depicts the plant's growth over time. Partners can also discuss investigations and share documents (e.g., images and spreadsheets) through password-protected blogs. This protection helps maintain the integrity of the uploaded information and keeps students' discoveries confidential for their partner scientists.

How PREP works

PREP partners high school students and their teachers with scientists who are studying the genes of *Arabidopsis thaliana*. The program helps students design their own experiments to examine the effects of environmental changes on *Arabidopsis* plants in which scientists have disabled a gene that they are studying. Students might discover something about that gene that no one else in the world knows and those discoveries may ultimately contribute to advances in medicine, agriculture, and industry. In this program:

1. Scientists contribute seeds from the model plant *Arabidopsis thaliana* in which the gene that they are studying has been disabled (mutants).
2. Students grow the mutant plants alongside unaltered plants (wild-type) under experimental conditions of their own design aimed at discovering the function of the gene.
3. Students observe the plants as they grow, and then share their findings with the scientists via the PREP Online Notebook.

(**Note:** The information here is provided by PREP.)

Collaboration takes root

The scientific content of PREP is broad, integrating concepts in genetics, natural selection, plant biology, and ecology, as well as the processes and nature of science. Teachers take advantage of this flexibility by highlighting diverse ideas, teaching a variety of standards, and emphasizing the development of different skills, from plant growth to scientific problem solving.

PREP starts with a dialogue in the classroom, during which the project staff explains to students that their assistance is needed in characterizing the functions of genes in the model plant, *Arabidopsis*. Students are intrigued, because it is rare that scientists are looking for their help. The discussion continues as students consider the usefulness of model organisms, as well as the insights that can be gleaned through genetic studies. Students are familiar with the idea that genes help determine characteristics, but usually only visible characteristics such as height, color, and leaf number. Students are challenged to generate ideas about why a plant may look completely normal, even if it has a disabled gene. Following additional questioning, brainstorming, and discussion, students are introduced to the idea that phenotypes may be revealed through interactions between genes and environment, such that the impact of disabling a gene may be observable only when the plant must respond to changes in its surroundings.

The discussion continues, alternating between small and large group conversations, now cofacilitated by the teacher and PREP staff. Students consider environmental factors that might influence a plant’s growth. Specifically, students are challenged to design and conduct their own experiments to compare how wild-type and mutant plants differ in their response to an environmental change. The only boundaries to an otherwise limitless collection of experimental paths are that students’ investigations must be relevant to plants, feasible and safe in the classroom, and not intentionally lethal to the plants.

Throughout the eight weeks of the project, PREP staff, partner scientists, students, and teachers meet in person or keep in touch through e-mail or online video chats. Interactions move from discussing the scientific context of the research to examining the plants to talking about students’ observations. Teachers typically dedicate about 90 minutes each week for the duration of the project for students to take care of the plants, make observations, collect and analyze data, and have informal group meeting–style discussions. Early on in the project, group-meeting conversations center on how students are designing their experiments and their rationale for choosing particular approaches. As they make progress, teachers encourage students to think more about what data to collect and why. As the end of the project nears, teachers urge students to think about what the data are showing and how to analyze and depict the data to help build explanations. Students wrap up by sharing their data, analyses, and conclusions with their partner scientists who, in turn, ask questions about their findings. Scientists also explain their interpretations of students’ findings and how their results fit into what is known in the field at the moment.

Collaboration in full bloom

Students are thrilled that their findings are useful beyond the classroom; they take ownership of their experiments and are excited to share their results, however preliminary. For example, in an e-mail to the partner scientist, one teacher writes:

> “My class started treating their experimental plants today, but we already have something interesting to share. Today we thinned the plants to six per pot. Most of the students noticed that the mutant plants did not seem to have as many seedlings growing, so we decided to collect data on number of plants growing and do a little

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> statistical analysis. According to our analysis, there were significantly fewer mutant plants growing!"

Students also look forward to discussing their work directly with scientists, noting that their visits "make it feel important since they come from the university." One teacher writes:

> "The students were engaged in real scientific research, trying to learn something nobody knows! This was a chance for students to really be involved in research. They saw that the research process is slow and that data are messy. One of [my] students wrote something about being happy that she could help [the scientist's] lab in doing research."

Some students and teachers are concerned about the quality of their data and scantiness of their results given how few plants they are able to study in a classroom setting (Fogleman and Curran 2008). Through PREP, students learn that no scientist, no matter how experienced, collects ample, publication-quality data the first time he or she conducts an experiment, that data often are messy and inconclusive, and interpretations tentative. Students are conducting a critical first-pass analysis, where they may notice something worth pursuing in additional experiments. The creativity students bring to the table and the shear breadth and magnitude of their communal effort makes their work scientifically significant. A number of PREP scientists initally got involved because students tend to ask "outside of the box" questions, taking investigations in creative new directions that scientists may not have considered. Students' findings serve as the basis for generating new hypotheses, as one scientist explains:

> "The students have been addressing questions that my laboratory does not have the time or resources to pursue, sometimes even think to ask! They have initiated some really novel projects that in many cases resulted in very interesting observations."

The harvest

Excitingly, students have observed noteworthy phenotypes in several of the mutant plants. For example, students at Louisa County High School in Virginia made the first observation that a particular mutant differed from the wild-type plant in the way that it accumulated anthocyanins, which are reddish-purple pigments thought to act as antioxidants. The students' work has been acknowledged in a science publication (Owens et al. 2008). Other scientists have noted the value of collaborating with students and teachers (Lally et al. 2007). Several are following up on students' findings and have included students' work as preliminary results in grant proposals, which, if funded, will further support student-teacher-scientist collaborations.

Several aspects of PREP make it unique. PREP is flexible because teachers can integrate it into their curricula to teach concepts in genetics, plant biology, ecology, environmental science, and scientific inquiry. PREP is scalable because it uses inexpensive, classroom-friendly materials. Finally, PREP fits into a larger research effort, both scientifically and pedagogically. Students are conducting investigations of interest to the scientific community, and research and evaluation of PREP is adding to the body of knowledge about science learning.

Acknowledgments

The authors would like to thank PREP students, teachers, and scientists. They would also like to thank Deanna Lankford and John Walker at the University of Missouri–Columbia, Lisa Johansen at University of Colorado–Denver, Adah Leshem-Ackerman and Andrew Foudree at Iowa State University, Terry Woodford-Thomas at the Donald Danforth Plant Science Center, and Kevin Niemi at the University of Wisconsin, all of whom have been instrumental in establishing PREP collaborations across the country. Initial support for PREP was provided by a grant from the National Science Foundation (NSF; DBI-9975808). Continued development of PREP and preparation of this publication was made possible by grant funding from NSF MCB-0418946 and grant number R25 RR08529 from the National Center for Research Resources (NCRR), a component of the National Institutes of Health (NIH). This article's contents are solely the responsibility of the authors and do not necessarily represent the official views of NCRR, NIH, or NSF.

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Wisconsin Fast Plants. www.fastplants.org

Figure 1. PREP website

The main page of the site provides a point-of-entry for interested students, teachers, and scientists, links to resources, and password-protected blogs for partners to discuss particular investigations.

Figure 2. PREP resources

The PREP website offers information, advice, and video demonstrations on how to sow and grow the plant, what the plant looks like at different developmental stages, and how to go about studying plants' responses to different stresses they typically encounter in their environment.