Physics Education

Opening lab doors to high school students: keys to a successful engagement

To cite this article: Rebecca M Slayton and Keith A Nelson 2005 *Phys. Educ.* **40** 347 www.iop.org/journals/physed

Opening lab doors to high school students: keys to a successful engagement

Rebecca M Slayton and Keith A Nelson

Department of Chemistry, George R Harrison Spectroscopy Laboratory, and Center for Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

E-mail: rslayton@stanford.edu

Abstract

A project to invite high school students into research laboratories to plan and carry out an investigation over several weeks, using the sophisticated equipment available there, can help to break down social barriers and enhance outreach activities.

Introduction

High schools and research institutions may share cities, but their scientists and scientists-to-be usually live in different worlds. High school science teachers, constrained by budgets that preclude the use of modern, expensive equipment for labs, struggle to move beyond written texts and engage students in the *practice* of science. This struggle is especially poignant for teachers who work in low-income areas, and with demographics that tend to be underrepresented in the sciences. Meanwhile, scientists at nearby research institutions spend lavishly on new equipment to remain on the cutting edge of experimental science, often leaving only slightly older equipment sitting on a laboratory shelf unused. These resources, as well as the ongoing activities of research laboratories, could potentially give local students an opportunity to understand the material and social practices of science, but barriers tend to keep active researchers and local students in their separate worlds. While researchers remain too busy or preoccupied to reach out to local high schools, high school students and teachers often view laboratories as mysterious and inaccessible places.

At MIT, we set out to break down these material and social barriers through an outreach program, the Lambda project. This paper is a summary of the lessons learned in the first year of outreach, written in hopes of encouraging similar collaborations between high school educators and researchers. The Lambda project consists of physical resources including an MIT laboratory space and experimental equipment dedicated to teaching, as well as local research laboratories both at MIT and industry that have provided access for outreach students to learn about and use their facilities. Human resources include a Laboratory Director who initially set up experiments and developed pedagogical materials for students, and who currently maintains contacts with high school mentors and supervises and teaches students who participate in the program. In its first year of operation (2003–04) the program saw through eleven students from four different local high schools and one teacher from a fifth. Here we describe the lessons we learned as we invited students into the lab, guided them through it for the first time, helped them turn a complex apparatus into a simple experiment, and finally present their work. Along the way we illustrate the lessons

0031-9120/05/040347+08$30.00

we learned through experience with a wide range of students and schools. We also describe the deliberate steps taken to overcome social barriers in this initiative, and conclude with a reflection on the lessons of our experience for others interested in similar activities.

Inviting students into the lab

To date, we have worked with student groups from four different high schools, with group sizes ranging from 2–5 students. We gained the participation of local schools in a variety of ways—through teachers whom we knew as friends, through other local outreach programs and through website outreach. The diverse set of relationships that we developed demonstrated that students from a wide range of schools and backgrounds could usefully participate in the program. However, we also learned that key elements must be established early on in these relationships in order to ensure that students fully engage with the lab experience. These include:

- Strong teacher involvement to hold students accountable.
- Student commitment to weekly visits following a plan of research.
- Plans for student presentations.

In this section we briefly describe the five very different schools and student groups that participated in the program's first year of operation; subsequent sections will illustrate how these key elements shaped the experience of students as they worked in the lab.

Our first group of students came from Fenway High School, a pilot school in downtown Boston that was founded in 1983 to help students who were struggling to succeed in a large, often impersonal, urban school environment [1]. Fenway has developed a unique program that fosters close student–teacher relationships and encourages creativity and independence in its students. We gained the participation of Fenway through its school principal, a personal friend who recommended us to a science teacher, Garret Virchick. Virchick was responsible for overseeing senior science fair projects—a graduation requirement at Fenway—and he gave his students the option of pursuing a project in our lab. Three senior students—two male and one female—expressed interest, and after visiting the lab once, we established a plan for weekly visits. This arrangement thus included all three of the elements listed above—student–teacher accountability, a long-term student commitment to weekly visits, and plans to present research. This kept two of the three students coming back to learn more after the initial glamour of a laser lab wore off. All of the students were Hispanic and expressed strong interest in the sciences. The two students who persevered in the program included a young man planning to gain engineering training in the Navy upon graduation, and a young woman who planned to go to college and eventually become a doctor. However, neither of these students possessed strong training in maths and physics, and this shaped our pedagogical strategy.

In the spring of 2004, we drew upon the contacts of an outreach program in MIT's Center for Materials Science and Engineering (CMSE), which put us in touch with a physics teacher from Boston Latin High School, Aaron Osowieki. From our perspective, Boston Latin's culture served as a foil to that of Fenway High School. It is a long-established school, antedating Harvard University by one year, and boasts its 'rigorous academic curriculum' rather than emphasizing close student–teacher relationships [2]. Osowieki invited students from his physics class to become involved with our program, promising them some amount of extra credit for the (yet undefined) work that they would do in the lab. Five students responded to his invitation, and visited our lab with their teacher to develop a plan of research. These students—all male, three of Caucasian and two of Asian heritage—were either juniors or seniors, enrolled in high level technical specialty courses, and were planning to take the appropriate AP exams on their way to college majors in science or engineering. Because they had a relatively strong background in maths and engineering, we were able to develop explanations at a somewhat more formal level, as we discuss more below. Here we wish to emphasize that key elements of the relationship we established early on—weekly visits to the lab with the expectation that students would present their work for extra credit—kept four of the five students committed for the spring of 2004.

In an effort to reach out to a broader range of students, we also developed a website. In the spring of 2004, a student from Lynn English High

School found the website and contacted us about becoming involved with the program. This was a highly ambitious young man of Asian heritage, with parents working in technical fields, between his junior and senior years of high school. A fellow student came with him, a much more relaxed young man between his sophomore and junior years, from a Hispanic family that worked in construction. These students were friends but had significantly different temperaments and technical backgrounds. As if these differences were not enough to mix things up, we soon learned of a student from the elite Exeter academy, who was receiving physics tutoring from a graduate student in Professor Nelson's group and was interested in the Lambda project. This group of students—spanning very different levels of technical training in maths and the sciences—worked together in the lab during the summer of 2004. Although working simultaneously with students from a mixed set of backgrounds posed unique challenges, it also provided refreshing benefits. In particular, the least experienced and most relaxed student was willing to admit his confusion. The other two often turned out to be equally confused, but they were either so eager to impress that they would not admit it, or felt so overconfident that they did not know they were confused! But the most significant problem in working with this group of students was not the wide range of students' technical backgrounds, but rather a lack of teacher involvement and a corresponding structure for presenting research results. As we discuss further below, this became problematic after the first few weeks in the lab.

As this summary should demonstrate, students came from a wide range of backgrounds. Although the details of our pedagogy varied considerably, we developed a common pattern for working with each of these groups. We worked with each group of students for approximately two months, which included spending about 2–3 weeks introducing students to the lab environment and developing an experimental plan, 2–3 weeks taking and analysing measurements, and a final couple of weeks preparing to present results. Below we briefly summarize the primary apparatus used in the Lambda project, before turning to a discussion of how we turned this complex apparatus into a science project for high school students.

Guiding students: from a complex apparatus to a simple experiment

The Lambda project was built around an experiment that uses pulsed lasers to make measurements in thin film samples, and is of special interest to the semiconductor industry. In these experiments, illustrated schematically in figure 1, two pulsed (~1 ns duration) excitation laser beams of wavelength λ_E are crossed at an angle θ_E at the surface of a thin film sample. The crossed beams form an optical interference pattern of alternating light and dark fringes. Absorption of light in regions of constructive interference produces sudden, spatially periodic heating and thermal expansion, launching acoustic waves that propagate in the plane of the thin film. The effect is similar to the generation of acoustic waves at the surface of a pond through sudden, brief contact made by a coarse comb-like structure. The acoustic wavelength in the film, Λ_f, is given by the fringe spacing of the optical interference pattern, $\Lambda_\mathrm{f} = \lambda_\mathrm{E}/(2\sin(\theta_\mathrm{E}/2))$. The ultrasonic wave is monitored through diffraction of a probe laser beam off the resulting periodic surface 'ripple', and the diffracted signal reveals time-dependent oscillations corresponding directly to the acoustic frequency, f. These results can be used to determine the speed of sound v in the sample, using the wave relation, $v = f\Lambda_\mathrm{f}$.

Unlike the case of bulk materials, in which the speed of sound hardly varies with the acoustic wavelength, in films the speed of a surface acoustic wave (or SAW) depends strongly on the ratio of the acoustic wavelength to the film thickness. This occurs because the surface acoustic wave actually extends into the sample by a distance roughly equal to its wavelength. For a film that

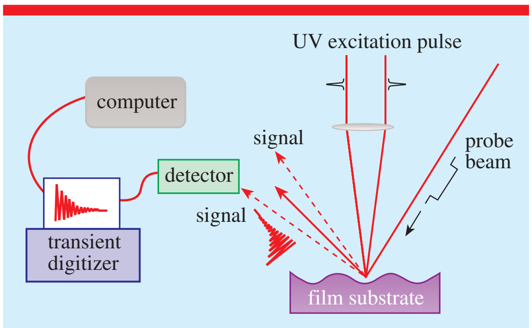

Figure 1. Schematic diagram of the transient grating measurement in a thin film.

is thick compared with the acoustic wavelength, the surface acoustic wave is entirely within the film and the sound velocity is given by the film properties. However, as the film is made thinner, more of the wave extends into the substrate, and so the sound velocity approaches that of the substrate. Velocity measurements can thus be used to determine film properties such as thickness, stiffness and delamination of the film from its substrate. This measurement has been commercialized for the microelectronics fabrication industry, where it is uniquely suited for fast, non-contact and nondestructive sample monitoring [3].

As this short summary suggests, the thin film experiment is filled with potential physics lessons, including laser operation, optical wave interference and diffraction, basic acoustic principles, advanced material structure and function, and much more. We developed a lab manual that explained each of these concepts in relatively simple terms, and provided additional references for curious students. This was an essential tool for working with the students—both for explaining individual concepts and for helping structure their presentations, as we discuss more below. However, most of the instruction took place through interactive demonstrations and lectures, and the lab manual was most useful as a ready reference. We typically used the first few weeks in the lab to help students understand what was going on in the experiment, helping them trace beams through the apparatus with infrared viewers (see figure 2), demonstrating physical phenomena and explaining concepts through chalkboard discussions and diagrams in the lab manual. For example, students were able to directly image constructive and destructive wave interference by crossing the excitation beams in the plane of a CCD camera. We explained the basic principles of interference and asked them to explain why interference effects disappeared when one beam was blocked. Supplemental materials in the lab manual helped students envision how the interference pattern changed with angle and wavelength. Students could also determine the interference fringe spacing (and check their calculations) using a CCD camera image. This is just one of many of the physical phenomena that students learned about through direct observation of and interaction with the apparatus.

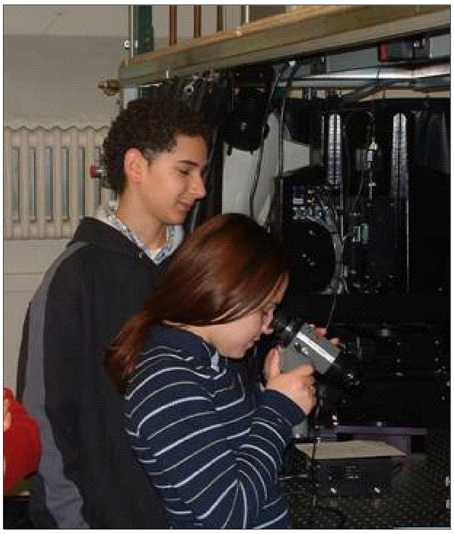

Figure 2. Fenway High School students learning to use an infrared viewer in the lab.

We felt that it was important for students to experience more than an exotic tour of the lab, however educational an excursion it was. To ensure that they gained a sense of competence and confidence with the apparatus, we wanted them to be able to take measurements of their own, analyse the results and present them to others. Here the challenge lay in helping them develop a relatively simple experiment from a potentially very complex apparatus—a challenge that was easier to overcome than it might initially seem. Students were able to use the thin film measurement to develop a variety of possible experiments, simply by defining independent and dependent variables in the apparatus, developing a hypothesis about how they ought to be related and then attempting to verify or disprove the hypothesis. For example, in the thin film metrology experiment, we can 'hypothesize' that as the acoustic wavelength increases, the frequency should decrease to keep the sound velocity constant. A test of the wave relationship would then require students to change the interference fringe spacing and record different measurements of frequency in the same thin film. With some help from the Laboratory Director, students were able to formulate a variety of similar hypotheses, such as those listed in order of increasing complexity of analysis in table 1.

In practice, we found it best to keep the independent variable simple and well controlled.

Table 1. Designing a simple experiment for high school students.

Hypothesis	Independent variable	Dependent variable
The frequency of sound increases as the wavelength decreases	Wavelength	Frequency of sound
Sound travels faster through ‘stiffer’ and less dense materials (more formally, the speed of sound increases with the acoustic modulus and decreases with density)	Film material (of known acoustic modulus)	Speed of sound
As a thin film gets thinner, the speed of sound travelling through it becomes closer to the speed of sound in the layer underneath it	Film thickness	Speed of sound
Films deposited on wafers tend to be thicker in the middle and thinner on the edge.	Position on the wafer	Thickness of the material

This was a problem in the fall of 2003, when the Fenway High School students recorded measurements from three samples with different film materials and thicknesses. Typical data collected by students, and an analysis yielding the acoustic frequency, are shown in figure 3. Because of the limited sample selection, students had no choice but to vary three key parameters at once—density, modulus and thickness (i.e. they needed to make reference to hypotheses 2 and 3 in table 1). In contrast, the Boston Latin students chose to take a series of acoustic velocity measurements across the plane of a film. This allowed them to observe how changes in a single parameter—the film thickness—changed the acoustic velocity. A typical plot from this series of measurements is shown in figure 4. In the following summer, we further enhanced experimental control by fabricating standardized samples containing steps of different thicknesses.

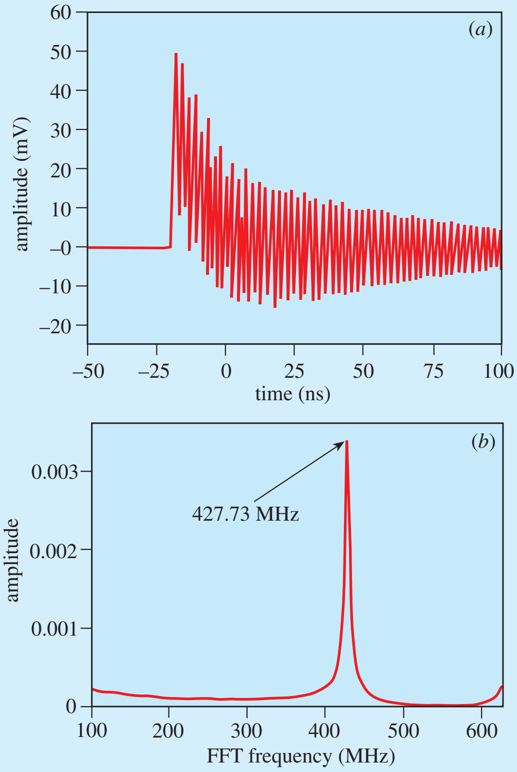

Figure 3. Student-collected data from a thin copper film showing (*a*) time-dependent acoustic vibrational oscillations and (*b*) computer-based Fourier transfom analysis giving the oscillation frequency. From this value the speed of the surface acoustic wave can be determined.

Helping students analyse and present research

We discovered several key benefits to insisting that students develop a plan for conducting and presenting their research within the first few visits to the lab. First, it was very common for students to indicate that they understood the experiment but to struggle when asked to explain it in their own words. As they worked to explain the experiment and their results, we encountered opportunities to correct misunderstandings. Second, a tangible presentation gave the students a sense of achievement and competence with the material. Third, it provided a powerful incentive for students to move beyond the ‘wow’ factor and try to understand what was going on—especially if their teacher could provide a forum that included their peers, and offer students tangible incentives. Finally, simply planning to present work became

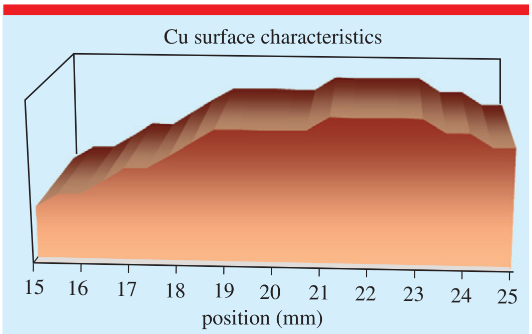

Figure 4. Depth profile of a copper thin film on silicon, compiled from student data.

Figure 5. A student from Fenway High School presents her work at her senior science fair.

a crucial part of keeping students focused and engaged in the laboratory.

These reasons for presenting research become especially clear when we compare our experiences in working with the three groups of students described here. As mentioned above, the students from Fenway High School were motivated to present lab work by a requirement that each student conduct a science project and present results at a senior science fair. These students were required to design an experiment, formulate their project report and present their work according to a carefully constructed format. Although the prescribed format was somewhat artificial at times—for example, requiring a list of materials used where a ray-tracing diagram was more appropriate—the student-teacher relationship and the reality of a hard deadline for presenting the work motivated the students to invest in understanding the principles behind the experiment and presenting their results.

Plans to present evolved more organically with the students from Boston Latin High School, and this experience illustrates the value of such presentations for keeping students focused. Since these students did not begin work in the lab with a definite objective in mind, they began searching for some more definite direction after their initial introduction to the lab. We responded by helping them define an experiment of interest—measuring the ‘profile’ of a thin film sample—and making plans for them to present their results to their class. We split the presentation among the four students, giving each responsibility for presenting the purpose, theory, methods or results section of the experiment, and requiring all four to collaborate on a conclusion. At this time we reorganized the lab manual to include a separate section on each of these aspects of the experiment. This helped guide the students through the process of formulating and presenting scientific work, and also provided each individual student with a well-bounded set of concepts to master for the presentation. Because their teacher was able to arrange for them to present their work to their peers, and because he provided a tangible incentive in the form of extra credit, most of the students became fairly motivated to invest significant time in understanding the experiment.

In contrast to students from Boston Latin and Fenway, who eventually learned to explain their work to others in formal presentations (see figures 5 and 6), the students from Exeter Academy and Lynn English High School never formally presented their work. Having learned about the importance of presenting work, after their first couple of visits to the lab we began to encourage these students to develop an experiment and present the results publicly—at a science fair or for a future science project in the classroom. However, without the structuring influences of student–teacher accountability, the students were little motivated to present their findings publicly. They took measurements and we discussed the physics behind the experiment in some detail, but they did not construct a purposeful program of experimentation or present a coherent summary of what they had done. These experiences suggest that active partnership with a teacher may be the most effective way to channel students’ work. All

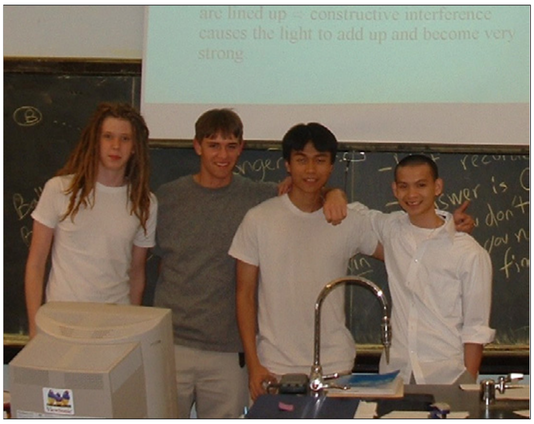

Figure 6. Four students at Boston Latin take a photo-op after presenting their research to their classmates.

but the most dedicated students are likely to need some tangible incentive to complete the detailed analysis and presentation through which much of the learning is consolidated. Presentation of the results also offers the possibility that some of the students' peers will become interested in expanding their own exposure to science through this program or other opportunities.

Overcoming barriers

Educational outreach projects often focus upon the development of intellectual resources to help students learn about science. However, relatively few of these projects address the social and material barriers that prevent high school students from assessing what a career in science would be like. Many of the high school students who worked with the Lambda project in its first year were particularly interested in talking with the scientists and learning more about what a career in science would be like. In this respect it was helpful that the outreach lab was not situated in a special teaching area but rather in a basement filled with laser research labs. The Laboratory Director was a member of one of the research groups, so informal contact with other group members was frequent.

The students who worked with the Lambda project were given an opportunity to talk with local graduate students, see their experiments and ask them questions about what it was like to be a graduate student at MIT. Finally, an industrial R&D laboratory, Philips Advanced Metrology Systems, partnered with us by giving the students a tour of their facility, where students were able to see once again the experiment they had worked with in the lab—but this time to see it as a commercially viable instrument, developed and under constant refinement in an industrial research facility. They were also able to talk with the scientists, engineers and managers there about how the experiment they worked with in a laboratory setting was applied in the 'real world'. Many of the students who participated in our program did not know scientists in their ordinary lives, and hence found these interactions particularly valuable and emboldening.

A second valuable consequence of inviting students into the domain of a major research institute is that it offers prospects for expansion of outreach opportunities with only minor additional commitment of personnel or physical resources. In our case, film deposition facilities at the MIT Center for Materials Science and Engineering (CMSE) will be made available so that students can design and fabricate their own samples, characterize them with CMSE instrumentation such as a profilometer (which is reliable but which requires physical contact and damage to the sample) and then conduct non-contact optical characterization in the outreach lab. This will broaden the students' exposure to advanced materials technology and deepen their appreciation of the purpose of the outreach measurement. Another research group has made a modern Raman spectroscopy system available to outreach participants. Since the Raman spectroscopy lab is engaged in biomedical analysis, including collaborative work with local hospitals on *in situ* Raman diagnostics of the human body, students also will see an entirely distinct area of application. At present this is expected to be a brief 'extra' excursion, but separate outreach experiences based around measurements of this kind may emerge.

Conclusion

By inviting high school students into the physical and social spaces of a research lab, this project has focused upon breaking down unique barriers to groups of students who are typically underrepresented in science. Research laboratories are typically full of equipment that high school students can use to conduct relatively simple experiments, ranging from home-built, labour-intensive experimental systems to black-boxed scientific instruments. We believe that the approach taken here—teaching students about the functioning of a research instrument, helping them use it to conduct their own measurements and giving them the opportunity to engage with local scientists—may prove feasible in other, pre-existing laboratory settings, so long as a researcher or other qualified technical personnel is willing to devote a few hours a week to engaging with students. We would close with a few cautionary notes, however.

First, this approach is only practical with relatively small groups of students. We managed to largely avoid working with more than three students at a time, splitting up even the group of five students from Boston Latin High School and asking them to come in on separate days of the week. We took this approach because it was the only way to ensure that all of the students were engaging with fairly complex material. Because most of the students did not have a strong formal background in maths and science, discussions took place largely on an intuitive level, and we found it important to tailor the discussions taking place in the lab to the backgrounds and interests of the individual students. For example, students with backgrounds in music were especially facile with the notion of a Fourier transformation, while others needed more help. Second, given the limited number of students that can reasonably become involved at this level, we advocate a more targeted approach to recruiting students who are typically underrepresented in the sciences. Our experience suggests a special need to encourage the involvement of female students who may not otherwise feel confident in their ability to become involved in such an excursion. We regret that we have yet to see more than one young woman through the program. Finally, we emphasize that a long term commitment to the project was key to ensuring that students really engaged with the experiment, and we reiterate the importance of giving students the opportunity to present their work formally. A quick tour of the lab does little to give students a sense of competence and empowerment in the world of scientific research.

An outreach project in which participants are invited to the academic laboratory environment offers an opportunity to overcome social and material barriers that may otherwise prevent some pre-college students from considering career options in science and technology. We have illustrated through the example of our experience some of the elements that contribute to the success of such a project. We have found that, once up and running, a program of this kind can attract the interest of others within our community, leading to additional opportunities for participants. We hope that more teachers and researchers will undertake similar endeavours in the future.

Acknowledgments

This project was made possible in part through support from the MIT George R Harrison Spectroscopy Laboratory, the MIT School of Science, the MIT Department of Chemistry Paul M Cook Innovation Award and the National Science Foundation grant no CHE-0212375 and MRSEC award no DMR-0213282. We thank Philips Advanced Metrology Systems for their participation in the program. We also thank Somerville High School teacher Michael Maloney for contributing figures to this paper.

Received 12 October 2004, in final form 25 February 2005
doi:10.1088/0031-9120/40/4/001

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Keith Nelson is a Professor of Chemistry and Director of the Lambda Project at MIT. He uses ultrashort laser pulses to study and control collective modes of motion and collective structural rearrangements in condensed matter. He continues to integrate the outreach program with his ongoing research.

Rebecca Slayton was an NSF Pre-Doctoral Fellow in Professor Nelson's research group, and developed and directed the outreach laboratory as an NSF Postdoctoral Fellow at MIT. Beginning in fall 2005, she will be a lecturer and researcher in the Science, Technology and Society Program at Stanford University.