Coordinating Physics and Education Instruction

Linking Research, Teaching, and Community Service

Noah D. Finkelstein

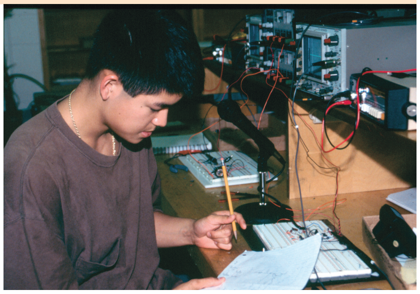
This article describes a university science course that integrates physics, education, and community outreach. The class both improves student mastery of science and teaching as well as addresses the university's mission to pursue research, education, and community service. The structure, implementation, and effectiveness of the course are discussed to present one approach or model for science education.

The explicit mission of many research universities includes the pursuit of excellence in three core elements—research, teaching, and community service. Yet, support for high-quality teaching (at the university or precollege level) and partnerships with local communities are largely treated as separate and often nonessential programs at these institutions. Too often, research is emphasized at the expense of teaching or community partnerships. However, it is possible to integrate each of these goals into a single activity system. Here, I describe the implementation of a new course that unifies the three disparate elements in a single activity system.

Course Structure

Along with colleagues, I developed a program that brings together physics, education, and community partnership in a single course designed to improve undergraduate student mastery of both physics and physics teaching. The focal point and coordinating agent of these three different domains is a class entitled Teaching and Learning Physics, offered within the university's physics department.

Noah D. Finkelstein is an assistant professor in the Department of Physics at the University of Colorado, Boulder, UCB 390, Boulder, CO 80309; e-mail: finkelsn@colorado.edu.



This article describes the structure of the class and its effect on students. Pre- and post-tests of basic physics concepts measure improved student mastery of domain. Analyses of class audiotapes, field notes, course evaluations, and student interviews further demonstrate improvements in student mastery of both physics and the teaching of physics. These data are presented as a case study of one class and its utility for improving student understanding while addressing the university's mission of research teaching and community partnership.

The course is composed of three elements—physics content, theories of teaching and learning physics, and practical experience teaching physics to less-educated (K–12) students. The course is designed for upper-division undergraduate physics majors who have expressed an interest in education. It is described in the course catalog as "A course on how people learn and understand key concepts in introductory physics. Readings in physics and cognitive science plus fieldwork teaching and evaluating precollege students. Useful for students interested in teaching science at any level. Prerequisites: Introductory level courses in electricity and magnetism."

Each of the three curricular components represents roughly one-third of the course. One of the two weekly class sessions focuses predominantly on the study of traditional physics content, and the other emphasizes readings in physics education and cognitive theories of learning. At least once per week, students teach precollege students in a laboratory portion of the course.

Each component is designed to complement the others by explicitly providing varied perspectives from which to view physics. Because the course draws upon and addresses questions from different domains (physics content, education research, and community outreach), it is an interface among these domains and borrows material and methods from each (Star and Greisemer 1989). Figure 1 (page 38) illustrates these overlapping features, depicting the three interacting components of the course as the vertices of a triangle. Each of these components necessarily interacts with the others. That is, the boundaries of these domains and activities are not fixed, nor are the domains mutually exclusive.

In this course structure, the environment is tailored to engage students in activities that engender both broad-based skills (e.g., problem solving, analytical,

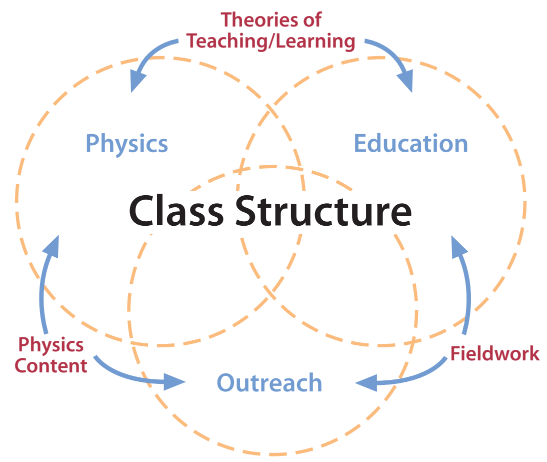
Reprinted with permission from NSTA, copyright 2003 from *The Journal of College Science Teaching,* National Science Teachers Association, 1840 Wilson Boulevard, Arlington, VA 22201-3000.

and metacognitive), which span the three domains, as well as specialized domain-specific knowledge and skills (e.g., physics content and knowledge of and practice in theories of teaching). In addition, the course design is flexible enough to capitalize on the emergent nature of the activity; because the participants, locales, and even the content are dynamic in nature, the precise form of the activity changes over time. The arrangement of the components of this activity system (the vertices in Figure 1) may be thought of as skeletal in nature, and the actual subject matter, interaction, and environment form the "flesh" placed upon the structure.

FIGURE 1

Class structure.

The class brings together physics content, theories of teaching and learning, and fieldwork experience in teaching. It borders on the domains of physics, education, and community outreach.



Course Implementation

Teaching and Learning Physics was first offered in the spring quarter of 1999. As a prerequisite for the course, students were required to complete the introductory physics sequence. The 10-week class met for 3 hours per week on campus; in addition, students taught for 2 to 4 hours per week in local community centers and schools. Each component of the course focused on the field of electricity and magnetism (E&M).

As much as possible, each component was integrated with the others; the lines between the activities were purposely blurred. Students reading about theoretical difficulties in understanding the concept of electric fields were encouraged to wrestle with their own understandings of the topic. Furthermore, as much as possible, there was a temporal alignment of activities. The same week students studied electric fields, they read about student difficulties in understanding the concept of fields and attempted to teach the concept to others.

The physics content of the course was approximately two-thirds of that covered in a typical introductory E&M course, using texts such as *Fundamentals of Physics* (Halliday, Resnick, and Walker 1997). Although calculus was used in problem analysis, mathematics and symbol manipulation were not emphasized. Rather, each topic was introduced from a conceptual viewpoint and placed within a broader context of other physics topics. Additionally, the focus of the physics content shifted from symbolic representation and text coverage to active engagement of students in project-oriented lessons; this focus shift fostered active construction of physics models.

Most often these lessons focused on the physical construction of material and its public presentation (Papert 1991). These lessons varied from tutorials (McDermott and Shaffer 1998), to discussion, to group problem solving (Brown 1992), to teaching and materials development. The lessons were designed to force students to confront traditional difficulties in understanding E&M (Posner et al. 1982).

The class encouraged students to learn collaboratively during class hours rather than solely after hours. Homework was assigned and emphasized deep and broad understanding. For example, for traditional textbook-based problems, students reflected on the solution process, critiqued the problem, and derived an answer. Other homework assignments included interviewing or teaching novices about advanced E&M concepts and subsequently writing up the process and results. Each of these practices was designed to foster both mastery of content and improvement of metacognitive skills—reflection, regulation, and epistemological development (Schoenfeld 1986).

The second component, readings in theories of teaching and learning physics, occurred in a seminar once per week. Each session began with brief student presentations followed by discussion. Students supported or refuted ideas presented in the readings, using evidence from the other components of the course. Readings in physics education research fell into several categories—empirical research on learning (McDermott and Shaffer 1992), theoretical underpinnings of learning physics (diSessa 1988), and cognitive science approaches to teaching and learning (Brown, Collins, and Duguid 1989). Students handed in weekly notes with summaries or questions relating to the readings, which were commented on and returned. These informal notes ensured that students read the assigned papers, and they forced some level of reflective analysis.

Student teaching occurred at one of four sites, during and after school hours, at the junior and senior high school level. Students were encouraged to develop and teach their own curriculum (within E&M); in each instance, supervisors oversaw student work both at the university and in local community programs. Consequently, student fieldwork differed from more traditional service learning models, because students were guided and studied the teaching process while engaged in it.

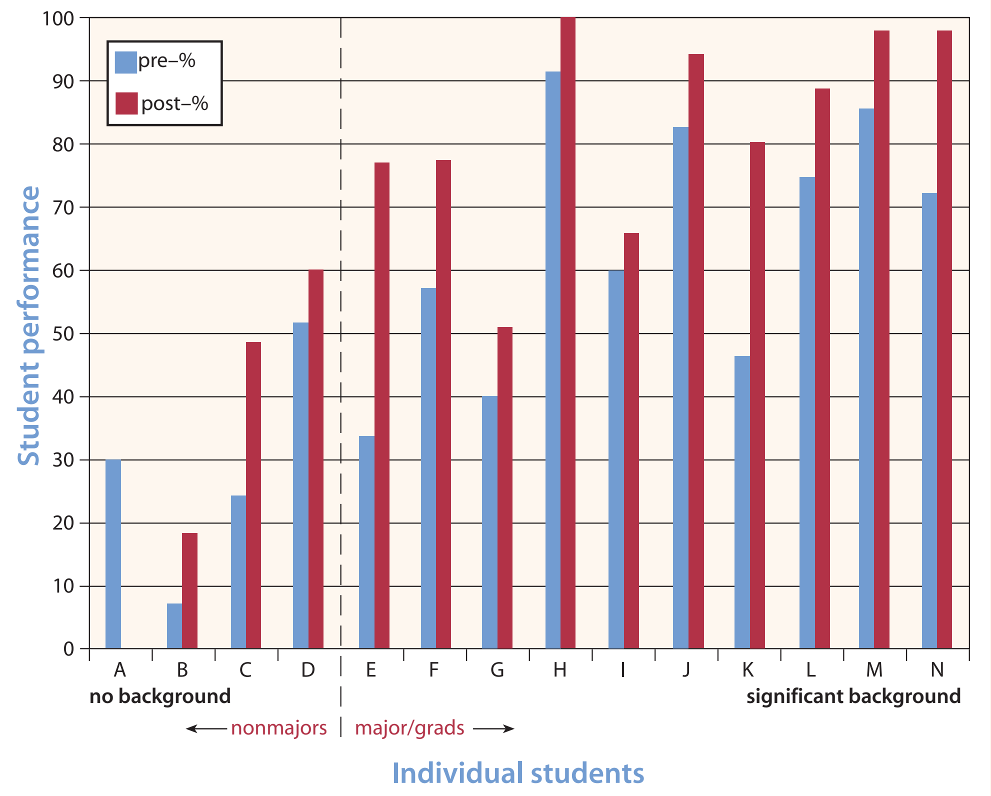
Each week, students and supervisors wrote detailed field notes describing their experiences, curriculum, interactions, and reflections. Students used the sites as resources for research for their final projects and papers, which served as mechanisms for students to reflect back on the quarter's activities. Although not a goal made explicit to students, the teaching experience was designed to help the university students master physics content as well.

The course was assessed at the level of student learning, as a research venue, and as an organizing tool for institutional coordination enabling outreach. The data are presented as a proof-of-concept. Here, I focus on evaluation at the student level. However, no less significant is the analysis of this coordinated set of activities as a venue for conducting research (for example, what about teaching makes it an effective practice for learning?) or as a means for coordinating various institutions.

FIGURE 2

Student performance.

Student performance on pre- and post-test assessment of conceptual understanding of physics. Student A has had no formal physics education. Student N is a fifth-year graduate student in physics. Mean pre-test = 54% (σ = 25%); mean post-test = 74% (σ = 24%); $N = 13$.



Physics Expertise

Students generally did not enroll in this course to remediate their physics understanding; all had passed between one and three E&M classes. Nonetheless, students demonstrated improved understanding of E&M after taking this course. Evaluation of student performance included pre- and post-tests of basic concepts in E&M, audio recordings of class sessions, student evaluations of the course, and in-class observations. All students ($N = 13$) participated in all forms of evaluation.

The diagnostic test was a mix of 35 free-response and multiple-choice questions drawn from the Conceptual Survey of Electricity and Magnetism (Hieggelke et al. 2001) and the Electric Circuit Conceptual Assessment (Sokoloff 1999). In addition to selecting answers for each question, students provided confidence levels for their answers on a three-point Likert-like scale (guessing, somewhat sure, or certain).

The results of the pre- and post-tests are shown in Figure 2, above. The independent axis plots scores of individual students. The leftmost student, A, had never formally studied the material; the rightmost student, N, is a fifth-year graduate student in physics. The dashed line indicates a division between physics majors and nonmajors. The dependent axis plots student performance. The mean pre- and post-test scores are, respectively, 54 percent (σ = 25 percent) and 74 percent (σ = 24 percent). The average of individual student gains is 51 percent (σ = 30 percent; $N = 13$; $P < 0.001$).

The audiotapes of classes and observational notes written immediately after each class were complementary tools for qualitatively evaluating changes in student understanding. These observations corroborate the pre-test data showing that students did not begin the course with the expected grasp of material.

The use of audiotape discussions and observational notes help detail when and why students make conceptual shifts. For example, in a discussion about one of the course readings on the use of analogies for teaching electric circuits (Gentner and Gentner 1983), a student reflected on the utility of a water reservoir analogy:

> F: Can we just talk about … like if you have the uhhh two batteries in series. You get twice the current.
> NF: Right.
> F: I thought the batteries in parallel gave you [reference to an equation for batteries in series, which produces twice the current] [discussion of the water analogy and two batteries in series produce twice the current of a single battery for a fixed load].
> F: Okay but see, I thought it was the opposite of that [referring to the effect of having batteries in series or parallel in simple circuit]. Because I think I was using the wrong model. *[Audiotape transcription of class, -week 3]*

After class, I made observational notes: "Student F made an interesting revelation, with which student J also identified: Total lack of conceptual understanding of series and parallel batteries and bulbs. Student F made the comment that he had thought batteries worked differently until he read the article. Still, throughout the class he and student J would make little mistakes about relative brightness, voltage, etc.

When asked to think about it in terms of the article and the analogies presented, [however], they would get the right answer. It required conscious effort and thought." *-week 3*

A comparison of the pre- and post-test responses for students F and J confirms that, after the course was over, both students better understood how elements behave in series and parallel and that they had greater confidence in their answers. On the series and parallel circuit questions in the conceptual survey, student F improved 33 percent from pre- to post-test (70 to 80 percent correct) and his confidence in his answers rose (from 1.8 to 1.1; where 1 is certain and 3 is a guess). Student J improved 75 percent (60 to 90 percent) with confidence rising from 1.7 to 1.1.

Understanding and learning physics is intertwined with students' attitudes. At the quarter's end, students reported on their own understanding of the material; they said they had greater comfort and interest in the subject area. In an open-ended "comments" section of the course evaluation, students wrote the following:

- "I'm finally enjoying this material. Overall, I've learned (understand finally) so much about E&M and I'm learning about techniques to teach it." - *week 5*
- "I learned a lot about teaching, and even found a new interest in the subject of physics through this course." - *week 9*

My goal for students in this course was not simply to improve their conceptual understanding of and attitude toward physics but also to develop their epistemological understanding (what it means to do or *know* physics) as well as their awareness of their own understanding. In this class, students became more aware of their own knowledge. For example, in a discussion about current conservation, student F said, "I don't know some of these things. I have the same misconceptions that kids and undergraduates [have] that we're reading about. I'm a physics major, and I don't know these things. I can do the advanced stuff (calculations, etc.) but not the conceptual side." - *week 4*

The observational field notes document corroboration by another student. The notes say, "Student J detailed his experience of not believing in current conservation. He also identified where this belief arises from. Ironically, such thought hasn't been countered by any formal training. He was a little [upset] about this." - *week 4*

In terms of Schoenfeld's definition of metacognition, which schematizes student thinking into three fundamental categories (epistemological development, self-assessment, and self-regulation), students are self-assessing, which is a necessary precursor to regulating their knowledge of physics (Schoenfeld 1986). To summarize briefly, students develop greater expertise in physics broadly conceived. Students demonstrate gains in conceptual mastery, attitudes, beliefs of what constitutes physics, and the ability to monitor and potentially modify their own level of physics understanding.

Teaching Expertise

The course structure was motivated by the belief that physics expertise is strongly influenced by students engaging in teaching experiences. In line with this hypothesis, students reported improved ability and interest in teaching. In the "comments" section of course evaluations, students wrote:

- "I thought I had a pretty good grasp on how to teach physics, but I've learned enough to revamp my whole style." *-week 9*
- "I loved fieldwork b/c I actually was able to observe the teaching theories involved in class and even put them into practice." *-week 10*

Students also reported that their conceptions of teaching changed. During the first and last weeks of class, students turned in statements of teaching in which they wrote a paragraph or two on their teaching approach. One typical example of a student reflection on the process of teaching is as follows:

- *Student L (week 1)* "There seems to be two ways of going about [getting people to learn]. One school of thought is that repetition is how one learns, and the teacher should focus on the most important ideas and go over them repeatedly. The other method is to saturate the students with information. I have no opinion on which method works better."
- *Student L (week 10)* "I believe that teaching is less telling and more leading through interactive experiences. It is important for a teacher to know the subject material and be able to convey it clearly, but it is equally important for a teacher to be able to prompt students into learning experiences through which students learn on their own, and in the process own the knowledge themselves. Another important duty of a teacher is to provide an environment for the student that is conducive to learning. This may include providing groups of students for interaction and making sure the students are learning and not just memorizing by getting involved in the learning process."

The class had a constructivist bent (Papert 1991), which seemed to seep into students' consciousness. A significant effort was made, however, to ensure that students wrestled with the theoretical underpinnings of their convictions and teaching experiences. Some of these theories and tools for understanding the teaching/learning process cycled through communication in the course, as demonstrated by an increased use of technical language from the course readings in student field notes. For example, student H wrote of precollege students' failure to grasp a lesson, "This might be a consequence of the fact that they were not forced to confront many of their preconceptions, come upon a conflict, and resolve it."

This sentiment parallels Posner et al.'s (1982) comments on developing a theory of accommodation, which argues that the process by which one accommodates new knowledge (knowledge not close to that which we already know) is by eliciting contradictory information, confronting this conflict, and resolving it. The student field note continues, "knowledge never really became integrated as a system," which, in this context, appears to refer to diSessa's (1988) notion of knowledge in pieces (that knowledge does not sit in static full-blown theories, but rather is assembled, depending upon the context for which it is invoked or needed, from smaller pieces) and Reif's (1986) discussion of knowledge structures (that knowledge does not sit in chaotic morass but is rationally connected in a hierarchical structure). Students adopt strategies from the readings and reflect on their own success and failure to implement these strategies in the teaching environment.

Students constantly evaluated their own practices (and each other's). For example, student F's field notes reflect on the effectiveness of two teaching approaches. He says, "[The high school] students seemed to respond fairly well to the light bulb/resistor box experiment, but seemed bored when [the theory was] explained to them on the white board. After the explanation, many students were not able to guess [correctly] about the change in brightness of the bulb as the resistance in the series with the bulbs changed. Only after they were able to play with this themselves were the students able to make theories." *-week 7*

Approximately half of the final student projects were directed at assessing student performance and determining how performance correlated with such variables as teaching style, learning environment, representational form of the material, or gender. These studies confirmed or refuted others' theories of student learning and evaluated which strategies work best for students in their educational environments.

For example, in a study of the effectiveness of representational forms (white board versus worksheets), student L's field notes describe the benefits of active engagement and discuss why this worked in his classrooms. He wrote, "To see why these two environments [high school and college] yielded such opposite results, one must contrast the situations of the students involved. One can expect that when students learn from a lecture format lesson, they will not be able to apply the concepts as abstractly as when they were involved in the learning. Not only will the students be merely watching and not participating but also they [likely] will not keep interest in the presentation. At the [college] session, the students were actively learning, discussing, and sharing. The [high school students] were instructed to draw diagrams, whereas the [college] students were using diagrams as tools to reach a goal—finding a solution to a problem." *-final paper, week 11*

While teaching, student L studied his students' learning and developed his own theories of and strategies for teaching. Not surprisingly, the experience of teaching and studying student learning correlated with this (and all students') improved mastery of the subject matter.

This model for coordinating physics education, research, and community partnerships may be adopted more broadly within the science education community by substituting different content. There is nothing particular to physics or undergraduates in this model. The focus could equally well have been Newtonian mechanics or physical chemistry. ■

Acknowledgments

This work builds on that of Cole (1996) and others in the sociocultural school of psychology and their rich theoretically motivated environments that foster student learning and support fundamental research on development and culture. Supported by NSF grant number DGE-9809496 under the supervision of M. Cole and A. diSessa. I thank these mentors and my colleagues at the Laboratory of Comparative Human Cognition for intriguing discussions, and support.

References

Brown, A.L. 1992. Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. *Journal of the Learning Sciences* 2(2):141–178.

Brown, J.S., A. Collins, and P. Duguid. 1989. Situated cognition and the culture of learning. *Educational Researcher* 18(Jan/Feb):32–42.

Cole, M. 1996. *Cultural Psychology: A Once and Future Discipline.* Cambridge, Mass.: Harvard University Press.

diSessa, A.A. 1988. Knowledge in pieces, In *Constructivism in the Computer Age*, eds. G. Forman and P. Puffall. Hillsdale N.J.: Lawrence Erlbaum Associates.

Gentner, D., and D.R. Gentner. 1983. Flowing waters for teeming crowds: Mental models of electricity, In *Mental Models*, eds. D. Gentner and A.L. Stevens. Hillsdale, N.J.: Lawrence Earlbaum Associates.

Halliday, D., R. Resnick, and J. Walker. 1997. *Fundamentals of Physics*. New York: John Wiley and Sons.

Hieggelke, C., A. Maloney, D. Van Heuvelen, and T. O'Kuma. 2001. The conceptual survey in electricity and magnetism (CSEM). *American Journal of Physics* 69(S1):S12–S23.

McDermott, L.C., and P.S. Shaffer. 1992. Research as a guide for curriculum development: An example from introductory electricity, parts I and II. *American Journal of Physics* 60(11):994–1011.

McDermott, L.C., and P.S. Shaffer. 1998. *Tutorials in Introductory Physics.* Upper Saddle River, N.J.: Prentice Hall.

Papert, S. 1991. Situating constructionism, In *Constructionism*, eds. I. Harrel and S. Papert. New York: Ablex Publishing Corporation.

Posner, N.J., K.A. Strike, P.W. Hewson, and W.A. Gertzog. 1982. Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education* 66(2):211–227.

Reif, F. 1986. Scientific approaches to science education. *Physics Today* 39(11):48–54.

Schoenfeld, A.H. 1986. What's all the fuss about metacognition? In *Cognitive Science and Mathematics Education*, ed. A.H. Schoenfeld. Hillsdale, N.J.: Lawrence Erlbaum Associates.

Sokoloff, D. 1999. University of Oregon, personal communication.

Star, S.L., and J.R. Greisemer. 1989. Institutional ecology, 'translations' and boundary objects: Amateurs and professionals in Berkeley's museum of vertebrate zoology, 1907–39. *Social Studies of Science* 19:387–420.