Preparing effective and reflective teachers of science: The role of physics education research

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Courses based on *Physics by Inquiry (PbI)* for preservice and inservice teachers have been taught for many years at the University of Washington (UW) and other colleges and universities.[1] Three decades of physics education research have made it possible to set very high standards and to enable the course participants to develop a deep understanding of the science content that they will be required to teach at the precollege level. On many topics, the performance of students in the 400-level *PbI* course far exceeds that of science (even physics) majors who have had only traditional instruction. In addition, these courses serve as a productive setting for in-depth investigation of other important issues that must be addressed in a discipline-based program for the professional preparation of teachers of science.

Introduction

Many teacher preparation programs delegate to the science disciplines the teaching of "content" as a collection of facts and formulas, while education courses teach instructional methods that are divorced from the content being taught. Generic methodologies of educational research may be taught but often without the proper grounding in the specific findings of discipline-based education research. Furthermore, practicing teachers rarely feel that they are a part of the scientific enterprise.

An effective teacher education program must prepare teachers in several (non-orthogonal) dimensions. Research suggests that there are several roles in which teachers have to become skilled. Below is a partial list.

1. *Teacher as content expert*
   A deep subject matter content knowledge is a necessary (but not sufficient) condition for effective teaching.
2. *Teacher as "diagnoser"*
   Teachers must be familiar with prevalent modes of student reasoning (both productive and problematic) and with strategies they can employ to help their students to develop a robust understanding in specific topical areas.
3. *Teacher as classroom researcher*
   Teachers must obtain, to the extent possible, a reproducible description of the level of learning that takes place in their classroom. In so doing they may contribute to the research base on the learning and teaching of the discipline.
4. *Teacher as discipline practitioner*
   It is unlikely that teachers will model science as a human endeavor if they themselves do not share in the practices, ethos, and norms of the discipline.

Physics by Inquiry–a case study

Physics by Inquiry has been available and used widely for many years. This laboratory-based curriculum is primarily intended for the preparation of preservice and inservice K-12 teachers in courses ranging from the 100 to 400 levels.[2] It is also appropriate for use with other students, including non-science majors and undergraduates who are inadequately prepared in science. Given this wide range of populations for which the curriculum is appropriate, the establishment of high standards for performance of preservice or inservice high school teachers in a 400-level *PbI* course has been crucial. In this paper, we use recent examples from such courses to illustrate student performance on two of the many dimensions that a substantive professional preparation program for teachers must possess: the development of subject matter understanding and the immersion in the "doing" of science.

Description of class

The 400-level *PbI* course sequence at UW is required for endorsement in physics or mathematics. The class has about 20-25 students of varying physics background and writing ability. It is co-taught by faculty members of the Physics Education Group and resident K-12 teachers who have extensive experience in providing professional development. It is my experience as a lead instructor in these courses for several years that the contributions by the teachers to the instructional effort are indispensable.

Description of instructional mode

A major goal of instruction is the step-by-step construction by the students of a coherent framework for understanding a class of physical phenomena. The instructional mode used is guided inquiry.

Role of students

Students work in groups of two or three. They perform experiments suggested by the curriculum (as well as ones suggested by their group) and make observations. They record the development of their ideas on the basis of their observations, inferences, and possible discrepancies between their predictions and the outcome of their experiments. Throughout they practice scientific skills (*e.g.,* proportional reasoning, analogical reasoning, control of variables, graphing, *etc.)*. They monitor their own intellectual development very closely through extensive writing in their lab notebook. They extend their evolving understanding through written homework that emphasizes explanations of reasoning. They synthesize their knowledge in exams as well as in two formal papers per quarter.

Role of instructors

The instructors model best practices for the students. There is no lecture. Large group discussions, to the extent that they occur at all, never precede the development of ideas.

The primary interaction between instructors and students takes place in in-depth dialogues between an instructor and a small group of two or three students. The focus is on continuous formative assessment of the evolving intellectual state of each student. The instructor may pose questions or suggest scenarios that require students to transfer their knowledge to different situations. The most challenging part of the instruction is listening intently to students as they try to make sense of the phenomena without correcting them or affirming their success.

The instructor attempts to ask questions to help students identify any holes in the reasoning employed or to suggest other explanatory mechanisms for the student to consider or refute. The instructor uses these so-called "checkouts" as opportunities to challenge unproductive links to a student's previous experience and the inappropriate generalizations about the behavior of physical systems.

Another important goal of the checkout is to expose teachers intentionally to alternate pathways to a deep understanding of the topic, which they are likely to encounter in their classrooms.

The development of deep trust in instructor-student interactions is a prerequisite for the success of such intensive questioning. The checkouts also serve to normalize (to the degree possible) student expectations about the course with the stated goals of the course.

Effectiveness of *PbI* instruction

In this paper, I will use research results on the effectiveness of *Physics by Inquiry* in helping students develop a deep conceptual understanding. These have been published elsewhere. In addition, I will share some preliminary results from an experiment conducted in Autumn 2001 on the efficacy of the program in immersing students in the practice of science.

Teacher as content expert

There is ample (published and unpublished) evidence that *PbI* helps students deepen their subject matter understanding. I will outline the evidence for a topic that is taught at both the precollege and college levels: *electric circuits.* This topic was taught in the first part of the Autumn 2001 *PbI* course.

Why Electric Circuits?

Electric Circuits is a well-investigated area of physics education research.[3,4] Student ideas and modes of reasoning are well characterized. Facility with mathematical formalism is not a prerequisite. Rather, the emphasis is on observations, inferences, predictions, and rule development. The existence of distinct qualitative models that account for the behavior of DC circuits is an added bonus. Finally, *Electric circuits* was chosen in Autumn 2001 because the instructors had extensive background in teaching the topic to elementary, middle, and high school teachers, introductory physics students, and graduate students in physics.

Development of a scientific model for electric circuits

The following is an outline of the powerful model that students develop on the basis of a complex interplay of observations, assumptions, and inferences.

Students first develop an operational definition for a simple closed electric circuit (*i.e.,* they determine the conditions that an arrangement of a battery, wire, and bulb must satisfy for the bulb to light). They then categorize objects as *conductors* or *insulators* on the basis of the objects' effect on the brightness of the bulb when they are placed in the circuit.

A paperclip connected directly across a battery becomes uniformly warm (as does the battery). Students are asked to consider the implications of this observation together with their previous work on a circuit as a continuous path of conducting material from one side of the battery to the other. Two assumptions that are consistent with the experimental results obtained thus far are suggested to students: (1) there is a continuous flow in the circuit. (The term *current* is given to this (unknown) flow.) (2) The brightness of identical bulbs is an indicator of the current through them. Students use these two assumptions as the foundation for the development of rules that allow them to predict the relative brightness of bulbs.

Two bulbs are placed in series. The observed equality of brightness suggests equality of currents through the bulbs (and by extension through the battery). The lesser brightness of each bulb (compared to that of a single-bulb circuit) suggests a smaller current through the battery in a two-bulb circuit than through the battery in a single-bulb circuit. Additional bulbs in series result in equally bright but even dimmer bulbs. This suggests a rule for series circuits: Adding bulbs in series increases the obstacle to the flow (which is termed *resistance)* and therefore the current through the battery decreases (and vice versa).

Two bulbs are placed in parallel to the battery. The observed equality of brightness suggests equality of currents through the bulbs. Equality of brightness of each bulb with that of a single-bulb circuit suggests a larger current through the battery in this two-bulb circuit than through the battery in a single-bulb circuit. Students are led to recognize that, if they want to use a similar rule for series and parallel circuits, they are forced to conclude that the increased current through the battery in the two-bulbs-in-parallel circuit suggests that the resistance in this circuit is smaller than the resistance in a single-bulb circuit.

Students enrich their emerging model by determining the conditions that must hold for networks of bulbs to be (un)affected by changes in other networks. In addition, they explore short circuits and they refine their model to accommodate this behavior. Throughout the curriculum, students are guided to revisit problematic modes of reasoning, namely that current is used up or that a battery is a constant current source.

Students are led to realize that the model, powerful as it is, cannot predict the behavior of all circuits that are analyzable into series and parallel networks. For instance, students try to predict the change in brightness in a three-bulb circuit (bulb A in series with the parallel network of bulbs B and C), after bulb B is removed. The model developed thus far is adequate to predict the change in brightness of bulb A (it gets dimmer) but not of bulb C (it gets all of less current as opposed to one-half of more current). The provisional nature of scientific models is therefore driven home. To be able to predict the fate of bulb C, a brand new concept needs to be introduced (voltage).

Students next develop an independent model for voltage (and discover Kirchhoff's rules in the process) and finally integrate the two models. They quantify their qualitative rules using voltmeters and ammeters, discover Ohm's law and study the Ohmic behavior of nichrome wire as well as the non-Ohmic behavior of light bulbs, and develop rules for combining resistances. Some students explore the behavior of real batteries (including internal resistance). Fast groups even study energy and power in circuits.

Improvement of student performance

An ungraded question was given to students prior to their study of electric circuits. The question involves three circuits, each with an ideal battery. The first circuit has a single bulb; the second, two bulbs in series; the third, two bulbs in parallel. Students are asked to rank the brightness of the five identical bulbs and to explain their reasoning. To be counted as correct, a student would have to reason that the two bulbs in parallel are equally bright to each other and to the single bulb (because, for instance, all three have the same voltage across them, which is equal to the battery voltage), whereas the two bulbs in series are equally bright and dimmer than the other three (because, for instance, their voltages are equal to one-half the voltage of the battery).

Results from administrations of this question to different populations are given in Ref. 4. In our Autumn 2001 class, about 45% of the students responded correctly. The remaining students used variations of the canonical modes of incorrect reasoning. Their responses were consistent with a belief that the current is used up or that the battery drives the same current in all three circuits.

By the final examination, almost all students were able to rank bulb brightnesses in complex multi-bulb, multi-battery circuits; recognize circuits for which the model for current could not make unambiguous predictions; and be successful in performance-based tasks. It is clear that, like other student groups before them, these students had become content experts in this topic.

A study at the University of Cyprus showed that the high learning gains in their *PbI* classes remained undiminished after one year. The same study showed that open inquiry (in contrast to *PbI* directed inquiry) did not lead to satisfactory results even at the end of the course.

Teacher as practitioner of discipline

It is clear that students in a *PbI* class achieve mastery of the subject matter by *doing* science. What was not so clear to us was the degree to which, if at all, students acquire the habits of mind that characterize the work of scientists. In Autumn 2001, we infused the construction of the specific scientific model for electric circuits with an additional layer: the study of scientific models. In particular, we wanted to find out if students could extract the generalizable features that underlie the development of a model.

The first homework (HW1) included an essay question that elicited student ideas on scientific models. Students were asked to reflect on what they thought constitutes a scientific model, how a model is developed, and what role a model plays in helping an investigator come to an understanding of scientific concepts.

After students had completed the construction of a model for current, they produced a paper outlining the crucial intellectual steps that they had taken in developing the model. Toward the end of the unit on electric circuits (in HW14), students were asked to revisit their answers to HW1 in light of their direct model-building experience. In addition, students studied Critical Thinking by Arnold Arons and were asked to critique the guided inquiry approach of their *PbI* curriculum in allowing them to pursue alternate models of electric current.

What is a scientific model? – HW1

The following student response to the HW1 assignment was typical. "In order to conduct an experiment, the scientist must develop or design a sort of scientific model, which would allow her to test her hypothesis. This model becomes a **physical representation** of a scientific concept necessary to prove, disprove, or explain the concept. Usually a scientific model is constructed from various **apparatus** with all the parts labeled with their name and function. Scientists use models or **drawings of models** to communicate their ideas … to other scientists."

What is a scientific model? – HW14

The same student changed drastically her ideas on scientific models. "… I thought of a model as a physical representation of a scientific concept. … but a model is different than just an apparatus used in experiments … A model represents an explanation as to how something works, happens, or behaves… We are often testing a model for **consistency**, asking ourselves, "Is this conclusion consistent with my model? Do I need to **revise** my model in order to explain this observation?" … The model is based on **observation** and is an **evolving** work in progress… As we encounter new situations, we **refine** our model, making it as simple and as explicit as possible …."

Discussion

Science teachers have several needs. Physics education research can set high standards for the professional preparation of prospective and practicing teachers.

References

[†] S. Vokos was a member of the Physics Education Group at the University of Washington from 1995 to 2002.

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