Preparing Teachers to Teach Physics and Physical Science by Inquiry

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Introduction

The Physics Education Group at the University of Washington is deeply involved in preparing K–12 teachers to teach physics and physical science by inquiry. During the academic year, the Department offers special courses for preservice (prospective) teachers. During the summer, the group conducts a six-week, intensive NSF Summer Institute for Inservice Teachers. The group also designs and helps conduct local short-term workshops for teachers. This paper is a distillation of more than 25 years of experience in working with K–12 teachers.[1]

Teacher preparation has been an integral part of our group's comprehensive program in research, curriculum development, and instruction. Research by our group focuses on investigations of student understanding in physics. The results are used to guide the design of instructional materials for various student populations at the introductory level and beyond. We have drawn on our research findings and teaching experience in developing *Physics by Inquiry*.[2] This self-contained, laboratory-based curriculum is designed for use in university courses to prepare K–12 teachers to teach physics and physical science effectively. Ongoing assesment of the instructional materials takes place both at our university and at pilot sites.

Need for Special Physics Courses for Teachers

Most science departments, including physics, do not take into account the needs of prospective elementary and middle school teachers. These students often lack the prerequisites for even the standard introductory courses, especially in the physical sciences. They are unlikely to pursue the study of any science in depth because the vertical structure of the subject matter requires progression through a prescribed sequence of courses. In physics, in particular, the need for mathematical facility in the standard courses effectively excludes those planning to teach below the high-school level. The only courses generally available are almost entirely descriptive. A great deal of material is presented, for which most preservice and inservice teachers (as well as other students) have neither the background nor the time to absorb. Such courses often reinforce a tendency to perceive physics as an inert body of information to be memorized, not as an active process of inquiry in which teachers and students can participate.

Many university faculty seem to believe that the effectiveness of a high school teacher depends on the number and rigor of courses taken in the discipline. This attitude seems to prevail in most physics departments. Accordingly, the usual practice is to offer the standard department courses to future high school physics teachers (and sometimes to middle school teachers). Although the content of the high school physics curriculum is closely matched to the introductory university course, this course is not adequate preparation for teaching the same material in high school. The breadth of topics covered allows little time for acquiring a sound grasp of the underlying concepts. The routine problem solving that characterizes most introductory courses does not help teachers develop the reasoning ability necessary for handling the unanticipated questions that are likely to arise in a classroom. The laboratory courses offered by most physics departments also do not address the needs of teachers. Often the equipment is not available in high schools, and no provision is made for showing teachers how to plan laboratory experiences that utilize simple apparatus. A more serious shortcoming is that experiments are mostly limited to the verification of known principles. Students have little opportunity to start from their observations and go through the reasoning involved in formulating these principles. As a result, it is possible to complete a laboratory course without confronting conceptual issues or understanding the scientific process.

For those students who progress beyond the first year of university physics, advanced courses are of little direct help in teaching. The abstract formalism that characterizes upper-division courses is not of immediate use in the precollege classroom. Sometimes, in the belief that teachers need to update their knowledge, university faculty may offer courses on contemporary physics for preservice or inservice teachers. Such courses are of limited utility. The information may be motivational but does not help the teachers recognize the distinction between a memorized description and substantive understanding of a topic. Although work beyond the introductory level may help teachers deepen their understanding of physics, no guidance is provided about how to make appropriate use of this knowledge in teaching high school students.

A well-prepared teacher of physics or physical science should have, in addition to a strong command of the subject matter, knowledge of the difficulties it presents to students. Traditional courses in physics do not provide this kind of preparation. They also have another major shortcoming. Teachers tend to teach as they were taught. If they were taught through lecture, they are likely to lecture, even if this type of instruction is inappropriate for their students. Many teachers cannot, on their own, separate the physics they have learned from the way in which it was presented to them.

Development of Physics Courses for Teachers

The emphasis in courses for teachers should be on the development of deep understanding of topics included in the K–12 curriculum. Teachers should study each topic in a way that is consistent with how they are expected to teach that material. The intellectual objectives and instructional approach in courses for teachers should be mutually reinforcing.

Intellectual Objectives

Teachers need the time and guidance to learn basic physics in depth, beyond what is possible in standard courses. They should be given the opportunity to examine the nature of the subject matter, to understand not only what we know, but on what evidence and through what lines of reasoning we have come to this knowledge. A sound conceptual understanding of basic physics and capability in scientific reasoning provide a firmer foundation for effective teaching than superficial learning of more advanced material.

It is critical that teachers be able to do the qualitative and quantitative reasoning that underlie the development and application of concepts. Instruction for teachers should cultivate scientific reasoning skills, which tend to be overlooked in traditional courses. It has been demonstrated, for example, that university students enrolled in standard physics courses often cannot reason with ratios and proportions.[3] Proportional reasoning is obviously a critically important skill for high school science teachers, but it is also essential for elementary and middle school teachers who are expected to teach science units that involve concepts such as density and speed.

Although high school teachers must be able to solve textbook problems, the emphasis in a course for teachers should not be on mathematical manipulation. As necessary as quantitative skills are, ability in qualitative reasoning is even more critical. Teachers need to recognize that success on numerical problems is not a reliable measure of conceptual development. They should be given a great deal of experience with questions that require careful reasoning and explanations.

It is also necessary for teachers to develop skill in using and interpreting formal representations, such as graphs, diagrams and equations. To be able to make the formalism of physics meaningful to students, teachers must be adept at relating different representations to one another, to physical concepts and to real-world phenomena.

An understanding of the nature of science should be an important objective in a course for teachers. Teachers at all grade levels must be able to distinguish observations from inferences and to do the reasoning necessary to proceed from observations and assumptions to logically valid conclusions. They must understand what is considered evidence in science, what is meant by an explanation and what the difference is between naming and explaining. The scientific process can only be taught through direct experience. An effective way of providing such experience is to give teachers the opportunity to construct a conceptual model from their own observations. They should go step-by-step through the process of making observations, drawing inferences, identifying assumptions, formulating, testing and modifying hypotheses. The intellectual challenge of applying a model that they themselves have built (albeit with guidance) to predict and explain progressively more complex phenomena can help teachers deepen their own understanding of the evolving nature, use and limitations of a scientific model. We have also found that successfully constructing a model through their own efforts helps convince teachers (and other university students) that reasoning based on a coherent conceptual framework is a far more powerful approach to problem solving than rote substitution of numbers in memorized formulas.

The instructional objectives discussed above are, in principle, equally appropriate for the general student population. However, teachers have additional requirements that special physics courses should address. For example, teachers need to develop skill in formulating and applying operational definitions. To be able to help students distinguish between related but different concepts (e.g., velocity and acceleration), teachers must be able to describe precisely and unambiguously how the concepts differ and how they are related. Teachers also need to be given the opportunity to confront and resolve their conceptual and reasoning difficulties, not only to improve their own learning but to become aware of the difficulties that their students will have.

Courses for teachers should help develop the critical judgment necessary for making sound choices on issues that can indirectly affect the quality of instruction in the schools. For example, teachers must learn to discriminate between meaningful and trivial learning objectives. When instruction is driven by a list of objectives that are easy to achieve and measure, there is danger that only shallow learning, such as memorization of factual information, will take place. Teachers also need to develop criteria for evaluating instructional materials, such as science kits, textbooks, laboratory equipment and computer software. They should be able to identify strengths and weaknesses in school science programs. Through service on district committees, individual teachers can often have an impact that extends beyond their own classrooms. Aggressive advertising and an attractive presentation often interfere with objective appraisal of the intellectual content of printed materials or computer software. Teachers should learn to resist the temptation of an appealing program format when there are serious flaws in physics. A poor curriculum decision can easily deplete the small budget most school districts have for science without resulting in an improvement in instruction.

Instructional Approach

If the ability to teach by inquiry is a goal of instruction, teachers need to work through a substantial amount of content in a way that reflects this spirit. The instructional approach in our courses for teachers can be characterized as guided inquiry.

Science instruction for young students is known to be more effective when concrete experience establishes the basis for the construction of scientific concepts.[4] We and others have found that the same is true for adults, especially when they encounter a new topic or a different treatment of a familiar topic. Therefore, instruction for prospective and practicing teachers should be laboratory-based. However, “hands-on” is not enough. Unstructured activities do not help students construct a coherent conceptual framework. Carefully sequenced questions are needed to help them think critically about what they observe and what they can infer. When students work together in small groups, guided by well-organized instructional materials, they can also learn from one another.

Whether intended or not, teaching methods are learned by example. The common tendency to teach physics from the top down, and to teach by telling, runs counter to the way precollege (and many university) students learn best. The instructor in a course for teachers should not transmit information by lecturing, but neither should he or she take a passive role. The instructor should assume responsibility for student learning at a level that exceeds delivery of content and evaluation of performance. Active leadership is essential, but in ways that differ markedly from the traditional mode. This approach, which can be greatly facilitated by a well-designed curriculum, is characterized below in general terms and illustrated in the next section in the context of specific subject matter. Other examples are given in published articles.[5]

The instructional materials used in a course for teachers should be consistent with those used in K–12 science programs, but the curriculum should not be identical. Teachers must have a deeper conceptual understanding than their students are expected to achieve. They need to be able to set learning objectives that are both intellectually meaningful for the topic under study and developmentally appropriate for the students.

The study of a new topic should begin with open-ended investigation in the laboratory, through which students can become familiar with the phenomena of interest. Instead of introducing new concepts or principles by definitions and assertions, the instructor should set up situations that suggest the need for new concepts or the utility of new principles. By providing such motivation, the instructor can begin to demonstrate that concept formation requires students to become mentally engaged. Generalization and abstraction should follow, not precede, specific instances in which the concept or principle may apply. Once a concept has been developed, the instructor should present new situations in which the concept is applicable but may need to be modified. This process of gradually refining a concept can help develop an appreciation of the successive stages that are involved in developing a sound conceptual understanding.

As students work through the curriculum, the instructor should pose questions designed to help them to think critically about the subject matter and to ask questions on their own. The appropriate response of the instructor to most questions is not a direct answer but another question that can help guide the students through the reasoning necessary to arrive at their own answers. Questions and comments by the instructor should be followed by long pauses in which the temptation for additional remarks is consciously resisted. Findings from research indicate that the quality of student response to questions increases significantly with an increase in "wait time," the time the instructor waits without comment after asking a question.[6]

As mentioned earlier, a course for teachers should develop an awareness of common student difficulties. Some are at such a fundamental level that, unless they are effectively addressed, meaningful learning of related content is not possible. Serious difficulties cannot be overcome through listening to lectures, reading textbooks, participating in class discussions, or consulting references. Like all students, teachers need to work through the material and have the opportunity to make their own mistakes. When difficulties are described in words, teachers may perceive them as trivial. Yet we know that often these same teachers, when confronted with unanticipated situations, will make the same errors as students. As the opportunity arises during the course, the instructor should illustrate instructional strategies that have proved effective in addressing specific difficulties. If possible, the discussion of a specific strategy should occur only after it has been used in response to an error. Teachers are much more likely to appreciate important nuances through an actual example than through a hypothetical discussion. Without specific illustrations, it is difficult for teachers to envision how to translate a general pedagogical approach into a specific strategy that they can use in the classroom.

The experience of working through a body of material step-by-step can help teachers identify the difficulties their students may have. A considerable amount of research has been done on difficulties common to students at all levels (K–20) of physics education. Faculty who teach teachers should be familiar with this resource and be able to refer them to relevant articles. Teachers who understand both the subject matter and the difficulties it poses for students are likely to be more effective than those who know only the content.

Because it is critical that teachers be able to communicate clearly, group discussions and writing assignments should play an important role in a physics course for teachers. Providing multiple opportunities for teachers to reflect upon and to describe their own conceptual development can enhance both their knowledge of physics and their ability to formulate the kinds of questions that can help their students deepen their understanding.

Illustrative Example: Electric Circuits

We can illustrate the research basis and instructional approach that guide the development of our courses for teachers with a specific example. The topic of electric circuits is included in almost all K–12 standards–based science curricula.

1. Investigation of conceptual understanding

Research by our group on student understanding of electric circuits has extended over a period of many years.[8] Since the results are well known by now, only a brief discussion is presented here. The question shown in Figure 1 has been given to many different groups of students and teachers. The question asks for a ranking by brightness of the five identical bulbs in the circuits shown and to explain their reasoning. The batteries are ideal. The correct response is A = D = E > B = C.

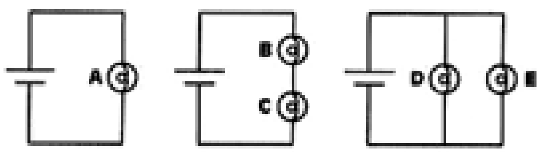

Figure 1. The five bulbs are identical and the batteries are identical and ideal. Rank the five bulbs from brightest to dimmest. Explain your reasoning.

This question has been administered to more than 1,000 students in introductory calculus-based physics. Whether before or after standard instruction in lecture and laboratory, student performance has been essentially the same. Only about 15% of the students have responded correctly. The same question has produced similar results when administered to high school physics teachers and to university faculty in other sciences and mathematics. Analysis of the responses revealed the lack of a conceptual model for a simple electric circuit. Reliance on the rote use of inappropriate formulas was common.

We have also had opportunities to pose this question to graduate students in our Department's Physics PhD program. Approximately 70% have given the correct response. Since these students are Teaching Assistants in our introductory physics courses, we have felt it important to help them develop a coherent conceptual model through an abbreviated version of the approach that we use in our courses for teachers.

2. Instruction by guided inquiry

To prepare teachers to teach the topic of electric circuits by inquiry, we engage them in the step-by-step process of constructing a qualitative model that they can use to predict and explain the behavior of simple circuits that consist of batteries and bulbs.[9] Mathematics is not necessary. Qualitative reasoning is sufficient. Specific difficulties that have been identified through research are addressed during the development of the model. Two of the most common are the apparent belief that the battery is a constant current source and that current is "used up" in a circuit.

Students are guided through carefully sequenced activities and questions to make observations that they can use as the basis for their model. The students begin the process of model-building by trying to light a small bulb with a battery and a single wire. They develop an operational definition for the concept of a complete circuit. Exploring the effect of adding additional bulbs and wires to the circuit, they find that their observations are consistent with the assumptions that a current exists in a complete circuit and the relative brightness of identical bulbs indicates the relative magnitude of the current. As the students conduct further experiments—some suggested, some of their own devising—they find that the brightness of individual bulbs depends both on how many are in the circuit and on how they are connected to the battery and to one another. The students are led to construct the concept of electrical resistance and find that they can predict the behavior of many, but not all, circuits of identical bulbs. They recognize the need to extend their model beyond the concepts of current and resistance to include the concept of voltage (which will later be refined to potential difference). As bulbs of different resistance and additional batteries are added, the students find that they need additional concepts to account for the behavior of more complicated circuits. They are guided in developing more complex concepts, such as electrical power and energy. Through deductive and inductive reasoning, the students construct a model that can account for relative brightness in any circuit consisting of batteries and bulbs.

It is important that teachers be asked to synthesize what they have learned, to reflect on how their understanding of a particular topic has evolved and to try to identify the critical issues that need to be addressed for meaningful learning to occur. As they progress in their investigation of electric circuits, the teachers are given many opportunities to express their ideas in writing.

The instructional approach that has been illustrated in the context of electric circuits has proved effective with teachers at all levels from elementary through high school. The process of hypothesizing, testing, extending and refining a conceptual model to the point that it can be used to predict and explain a range of phenomena is the heart of the scientific method. It is a process that must be experienced to be understood.

3. Assessment of effectiveness

Although many of the teachers in our preservice and inservice courses have had considerably less preparation in physics than those in the standard introductory courses, their performance on qualitative questions has been consistently better. The question shown in Figure 2 provides a good example of what elementary teachers without a strong mathematical background, but with a good conceptual understanding, can do. The students are asked to rank the five bulbs in the circuit according to brightness. Reasoning on the basis of a model based on the concepts of current and resistance, most of the elementary and middle school teachers who have been through our courses for teachers predict correctly that E > A = B > C =

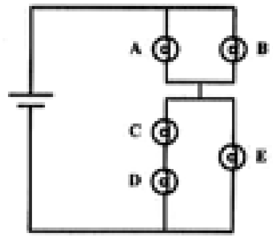

Figure 2. The five bulbs are identical and the batteries are identical and ideal. Rank the five bulbs from brightest to dimmest. Explain your reasoning.

D. This question is beyond the capability of most students who have had standard instruction.

In Figure 3 is a circuit that has been used as a post-test in our NSF Summer Institute for Inservice Teachers. After working through a significant portion of the module on electric circuits in *Physics by Inquiry*, virtually all of the teachers (N = 100) were able to predict and to explain, on the basis of the qualitative model that

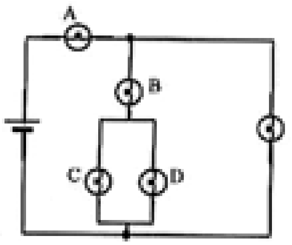

Figure 3. The five bulbs are identical and the batteries are identical and ideal. Rank the five bulbs from brightest to dimmest. Explain your reasoning.

they had developed, that A > E > B > C = D. This represents an improvement over their performance of 15% correct on the pretest in Figure 1.

Other evidence about the effectiveness of the approach taken in *Physics by Inquiry* comes from a colleague at the University of Cyprus.[10] (A Greek translation of *Physics by Inquiry* was used.) The performance of two main groups of prospective elementary school teachers was compared. Both groups were taught by instructors who understood the material well. One of the groups (N = 189) had studied electric circuits in the way that has been described. This group consisted of two classes: one had just completed study of the material (N = 102); the other had completed study the previous year (N = 87). The second main group (N = 101) consisted of teachers who had just completed the topic in a course in which constructivist pedagogy was strictly followed (*i.e.*, the students were actively involved in the construction of concepts.) However, instruction in this course was not guided by findings from the type of discipline-based research that has been described. Specific difficulties were not explicitly addressed nor was there the same degree of emphasis on the development of a coherent conceptual model. Two types of post-tests were given: one consisted of free-response questions that asked for explanations of reasoning; the other contained multiple-choice questions taken from DIRECT, a test developed at North Carolina State University.[11]

As can be seen in Figure 4, both classes of students who had studied the material in *Physics by Inquiry* had mean scores greater than 80% on both tests (a result that indicates that retention was very good). In the other main group, performance on the multiple-choice test was slightly above the 40% level. On the free-response test, the mean score was less than 20%. Courses in which educational methodol-

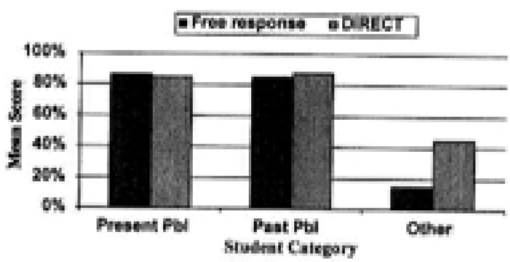

Figure 4. Student performance on free response and on multiple-choice questions on a post-instruction survey on electric circuits. The survey was administered to preservice elementary school teachers at the University of Cyprus. Two main groups of students were included in the survey: those who had used Physics by Inquiry (PbI) and those who had not. Some of the students had studied PbI one year before taking the test (Past PbI). All the others (Present PbI and Other) had just completed their study of this topic.

ogy is emphasized without sufficient emphasis on concept development seem to be no more effective than standard physics instruction.

Inadequacy of Teacher's Guides for Preparation in Content

Teachers who do not acquire the necessary background for teaching science in appropriate preservice or inservice courses are forced to rely on short workshops conducted by school districts and on the teacher's guides that come with the student materials. Even in instances when these materials are good, the accompanying information for teachers is usually grossly inadequate. A few quotes from two well-known elementary-school programs can serve as illustrations.

From one K–6 program:[12]

- "It is not necessary to have studied electricity to teach this module."
- "A battery is said to have so many volts; the more volts, the bigger the push to make current flow. The current itself is measured in amperes. For a given circuit (e.g., a battery, wire, and one bulb) the more volts (push) the more amperes (current)."
- "A given battery exerts a certain amount of push to send electrons around a circuit. …The heat comes from the electrons of the current bouncing against the stationary atoms of the metal as they flow. …even though the metal is solid, most of the space in its atoms is empty and the electrons can move very easily."

From another K–6 program:

- "How does electricity flow along a circuit? Like many things in nature, electricity is invisible, but we can see and measure the results of the flow. The battery, or energy source, gives electricity its 'push' through a circuit. This push, or voltage, can be thought of as electrical pressure, and is analogous to water pressure. Electrical pressure is measured in volts."
- "The actual flow of electricity through a circuit is analogous to the flow of water through a hose. The flow of electrical current is measured in amperes."

Implementation of Physics Courses for Teachers

Like other physics departments, ours offers a number of courses that could be taken by prospective K–12 teachers. As has been discussed, however, such courses provide inadequate preparation for elementary, middle, and high school teachers. At the University of Washington, we have implemented the ideas that have been discussed in this paper in two sets of courses: one for elementary and middle school teachers and the other for high school physics teachers and well-prepared middle school science teachers.

Course Structure

In designing the curriculum for the course for elementary school teachers, we have drawn on the content that is taught in the lower grades. The course does not proceed through the traditional physics sequence (kinematics, dynamics, electricity and magnetism, etc.). The curriculum instead focuses on basic topics (mass, volume, density, temperature, electric circuits, etc.). There is a strong emphasis on proportional reasoning, control of variables and the development of other important scientific reasoning skills.

In the course for prospective high school teachers, the emphasis is on the material covered in a high school physics course, which often covers the same content as the standard introductory university course. The experience of students in the introductory course (and more advanced courses) is often limited to memorization of formulas and numerical problem solving. As in the course for elementary and middle school teachers, the instructional approach in the course for high school teachers is very different. The students go through the reasoning involved in the development of each concept. They are guided in synthesizing what they have learned into a coherent conceptual framework.

Administrative Challenges

A number of challenges must be met in implementing a teacher-preparation program in a physics department, especially at a large, research-oriented university. The argument must be made to the department and higher administrative units that the proposed courses are at an intellectual level worthy of the credit offered. We made this case successfully at our university by demonstrating that the demands on the students matched, or exceeded, those of other physics courses at comparable levels.

Other problems that may need to be addressed relate to enrollment. Mass education does not work for teachers. Laboratory-based instruction is necessary. The classes must be small enough to foster interaction among the students and between the students and the instructor. Sometimes, however, the problem is low total enrollment. It is particularly difficult to reach prospective teachers when there is no undergraduate education major. They are hard to identify since they are unlikely to decide, on their own, to take physics. In the course for prospective elementary and middle school teachers, we have dealt with this issue by encouraging participation of students not planning to major in science.

In the course for prospective high school (and well-prepared middle school) teachers, the enrollment problem has been addressed in a way that has proved to be very effective. We recognized that it would be impossible to fill a class with physics majors who plan to teach. Moreover, most high school physics teachers were not physics majors. At best, they may have majored in chemistry or mathematics. Therefore, we actively encourage participation in the course by students majoring in other sciences and in mathematics. The course is open to all students who have taken the standard introductory physics course. The range of preparation in the class varies from this level to students getting a graduate degree in physics. The system works well because the emphasis is not on quantitative problem-solving but on concept development and reasoning ability. In addition to maintaining a steady enrollment throughout the academic year (20 to 30), we have found that having more non-majors than majors forces students to abandon their dependence on formulas and think more deeply about the physics involved.

Conclusion

The separation of instruction in science (which takes place in science courses) from instruction in methodology (which takes place in education courses) decreases the value of both for teachers. Effective use of a particular instructional strategy is often content specific. If teaching methods are not studied in the context in which they are to be implemented, teachers may be unable to identify the elements that are critical. Thus they may not be able to adapt an instructional strategy that has been presented in general terms to specific subject matter or to new situations. Even detailed directions cannot prevent misuse of excellent instructional materials when teachers do not understand either the content or intended method of presentation. Since the type of preparation that teachers need is not available through the standard physics curriculum, a practical alternative is to offer special courses for teachers. The instructors in such courses must have a sound understanding of the subject matter, of the difficulties that it presents to students and of effective instructional strategies for addressing these difficulties.

It is important for physics faculty to recognize that teachers must be prepared to teach the material at an appropriate level in K–12 classrooms. We have found that teachers often try to implement instructional materials in their classrooms that are very similar to those they have used in their college courses. Through direct experience with the intellectual demands of learning by inquiry, teachers can become better equipped to meet the challenge of matching their instruction to the developmental level of their students.

Our experience indicates that it is not easy to develop good inquiry-oriented instructional materials. Therefore, unless faculty are prepared to devote a great deal of effort over an extended period to the development of a course for teachers, they should take advantage of already existing instructional materials that have been carefully designed and thoroughly tested with teachers. We have found that the sense of empowerment that results when teachers have developed a sound conceptual understanding of the science content that they are expected to teach greatly increases their confidence in their ability to deal with unexpected situations in the classroom.

Acknowledgments

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