What types of knowledge do teachers use to engage learners in "doing science"?

Rethinking the continuum of preparation and professional development for secondary science educators

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Accomplished musicians and master science teachers have something in common— they can both make complex performances look effortless. The great jazz pianist, Thelonious Monk, would take song requests from the audience then reinvent the piece as he played it by changing the key, tempo, and mood of the tune. At the right time he would back off the melody to let another player in his ensemble take charge, then listen for subtle rhythmic cues that it was his turn again to take the lead; his fingers would dance over five octaves on the keyboard while he gazed out at the crowd, smiling.

Monk had a deep understanding of the fundamental structure of the music, but knew how to improvise and shape the experience for the audience as well as share the production with others in his band.

The experienced science educator is no less an artist. Consider a "simple" high school laboratory activity that begins with the teacher placing a mass on a scale at the front of the classroom. The scale reads "10 kilograms." He then produces a large bell jar which he places over the entire scale and attaches the jar to a vacuum pump. "Can anyone tell me what the scale will read if I pump all the air out?" he asks the class. Over the next 20 minutes he orchestrates a flow of discourse with his students that compels them to hypothesize, suggest thought experiments, make reasoned connections, to try out and justify explanations with one another...in other words, to think. He poses questions that probe the mental models his students are beginning with, assessing how elaborate these models are, how generalizable, whether they refer to observations or to theory. During this time the teacher constantly judges whether the discussion is moving the students toward a scientific way of thinking about the phenomena. He must decide who has "pieces" of the scientific explanation and how to help students put these together for themselves. He is strategically scaffolding the thinking of the students and assessing group progress on a moment-by-moment basis. In addition to all this, he monitors whether students are following the classrooms norms for civil conversation and the degree of involvement, puzzlement, or frustration of individual students.

This is a brief but intense performance for this teacher—one of hundreds of interactions with students and the materials of science during the course of the school year. From this relatively common slice of classroom life we can see that many types of teacher knowledge are crucial to the success of inquiry-based instruction, especially when the aim is for students to do the intellectual work. More involved forms of laboratory work (student-designed investigations for example) call for an even greater range of teacher skills.

Where do teachers develop the knowledge and expertise for this type of instruction? The areas of undergraduate preparation, pre-service teacher education, and in-service professional development seem to be the primary influences, but the knowledge outcomes of these three phases of teacher growth have been under-examined, especially with respect to the articulations between them. To understand better how teachers develop and deploy certain types of knowledge necessary for laboratory work, this paper addresses the following questions:

Q1. What kinds of teacher knowledge and skills are required to design and guide students through different forms of laboratory activity?

Q2. Do teachers' current preparation and professional development provide them with these knowledge and skills?

Q3. How should teachers' preparation and professional development be changed to foster the knowledge and skills necessary for effective laboratory instruction?

Question 1. What kinds of teacher knowledge and skills are required to design and guide students through different forms of laboratory activity?

A framework for thinking about "laboratory work"

To understand the types of teacher knowledge used for guiding laboratory work, we must first identify the characteristics and boundaries of this type of instruction. *Laboratory work* (or *practical work*) has been described as any teaching and learning activity which involves, at some point, the students observing or manipulating real objects and materials (Millar, 2004, p. 3).

In practice, however, "laboratory work" is becoming harder to identify as a definable genus of practices distinct from other forms of instruction— it is no longer a set of prescribed exercises for students that happen in a place and time separate from the rest of science learning. Students now can be involved in the processes of science in a broader range of circumstances. Computer technology, for example, allows new kinds of interactions with tools, data, and simulated environments, and learners can use many of these technologies in settings other than the classroom. Another reason laboratory work is hard to characterize is that much of it is more aptly described as "field work" in which students conduct studies outdoors rather than in the classroom. Definitions of laboratory work are elusive also because some teachers move seamlessly between lab work and other forms of instruction, often hybridizing these activity structures (e.g. demonstration-based discussions or "just-in-time" mini-lectures during student inquiries). Despite the ambiguities of definition, if we are to identify different types of teacher knowledge necessary for particular forms of instruction, a reasonable attempt must be made to create a taxonomy of activities that can fall under the general rubric of "laboratory work."

I describe (in a following section) six different activity structures[1] commonly used in classrooms that fall under the general category of laboratory work. The first three will be discussed together because they are all relatively short term in duration, focus on a single or limited set of ideas, are generally teacher-directed, and have known outcomes. This grouping is not meant to suggest that certain types of laboratory activities are more or less effective, or more or less important in the broader picture of science instruction. These six activity structures are:

- Demonstrations
- Building skills
- Discovery learning

- Problem solving
- School science inquiry
- Authentic forms of inquiry

Clearly, in any such taxonomy there will be ambiguities, overlap, gaps, and the inevitable baggage of historical terminology. Any framework, however, is defined by the particular purposes it is designed to serve, and this set of activity structures provides a context for thinking about the types of knowledge teachers use to engage learners under a range of circumstances in which real objects and scientific materials are used.

A framework for thinking about teacher knowledge

We now turn to the second dimension of this framework—the types of teacher knowledge necessary to plan and execute these forms of laboratory work. The framework for categorizing teacher knowledge is based on six guidelines:

1) It is grounded in a constructivist approach to teaching and learning.
2) It does not make artificial distinctions between knowledge and skills (knowing and doing are forms of the same intellectual capacity).
3) The types of knowledge needed by teachers to plan and execute laboratory work in its different forms are largely inseparable from the types of knowledge needed to conduct effective science teaching in general.
4) It uses only those categories for teacher knowledge that are potentially responsive to development through undergraduate coursework, pre-service preparation, or professional development.
5) These categories do not include unique forms of knowledge for certain populations of learners such as ELL (English Language Learners) or special education students.
6) Any such framework will always under-specify the knowledge, intuitive understandings, reasoning processes, metacognitive strategies, and other intellectual activities of teachers-in-action because of the inevitable layers of thinking that occur in a social/scientific/educational setting and the contingent nature of teacher cognition in response to changing classroom conditions.

The following framework has four aspects; it is adapted from Shulman's (1986) original conceptualization of teacher knowledge:

General pedagogical knowledge –

- understanding how to moderate discussions, design group work, organize materials for student use, utilize texts and media, etc.

Content knowledge –

- understanding of a domain's concepts, theories, laws, principles, history, classic problems, and explanatory frameworks that organize and connect its major ideas

Pedagogical content knowledge –

- knowledge of how *students* understand the subject matter, what theories of natural phenomena they hold and how these may differ from scientific explanations

- knowledge of the types of ideas appropriate for learners of different ages to explore
- knowledge of ideas that are prerequisites for students' understanding of target concepts
- understanding how to select representations, analogies, and activities that help learners conceptualize science ideas
- knowledge of how to scaffold students' reasoning processes (e.g. problem-posing, distinguishing theory from evidence, adjudicating between rival hypotheses, etc.) and skills of various kinds related to scientific work (e.g. planning investigations, working with data, communicating findings, constructing arguments, etc.)
- understanding of science-specific assessment strategies

Disciplinary knowledge –

- understanding the purposes of science inquiry
- knowledge of domain-specific methods of investigation
- understanding the nature of relationships between scientific models and data
- knowledge of standards for evidence and argument held in various fields of science, etc.
- recognizing reputable sources of information and distinguishing them from pseudo-science, commercial reports, secondary sources, etc.

Of these four types, content knowledge has perhaps the greatest documentation as to its role in science teaching. We know for example that eachers with limited subject matter preparation tend to emphasize memorization of isolated facts and algorithms; they rely on textbooks without using student understandings as a guide to planning lessons; they use lower-level questioning and rule-constrained classroom activities; furthermore, they employ only limited use of student questions or comments in classroom discourse, which results in marginal student development of conceptual connections and misrepresentations of the nature and the structure of the discipline (Carlsen, 1991; Gess-Newsome, 1999; Talbert, McGlaughlin, & Rowan, 1993). Kennedy (1998) notes that some take a minimalist view of necessary content knowledge by requiring teachers to only know the subject matter actually covered by the curriculum, reasoning that this knowledge is exactly what the teachers will be teaching. Kennedy and others argue, however, that if students can ask questions that push the edges the formal curriculum and if teachers must respond to those questions, they need knowledge that goes far beyond the curriculum being taught (e.g. Hilton, 1990).

With regard to pedagogical content knowledge, Shulman (1987) defines this as a "special amalgam of content and pedagogy that is uniquely the province of teachers, their own form of professional understanding…it represents the blending of content and pedagogy into an understanding of how particular topics, problems, or issues are organized, represented and adapted to the diverse interests and abilities of learners, and presented for instruction" (p.8).

And finally, in the original formulations of teacher knowledge, understanding the discipline was considered part of content knowledge. Content knowledge had a "syntactic structure" which included understanding how knowledge was produced and judged in a particular domain of inquiry. However, because this area of understanding is considered fundamental to reform-based science instruction, it has been treated here as its own category and labeled as "disciplinary knowledge."

It should also be noted that, in considering the knowledge and skills necessary for laboratory work, it may seem intuitive to focus primarily on the abilities of the teacher to design and manage *activities* for students. Recent scholarship, however, has emphasized that meaningful learning is a product not of activity *per se*, but of *sense-making discourse* aimed at developing conceptual understanding and the links between theory and observable phenomena (Bereiter, 1994; Mortimer & Scott, 2003). In this view, learning is not accomplished through the transmission of knowledge from person to person, but rather through an ongoing process of comparing and checking one's own understandings with those that are being rehearsed on the social plane of the classroom. In addition to using dialogue to facilitate conceptual understanding, other researchers have employed classroom discourse as a way to engage learners in the canonical practices of science—that is, "to formulate questions about phenomena that interest them [students], to build and criticize theories, to collect, analyze and interpret data, to evaluate hypotheses through experimentation, observation, measurement, and to communicate findings" (Rosebery, Warren & Conant, 1992, p. 65). Language, in the form of purposeful talk, reading, and writing, mediates all these activities (for examples of teachers reflecting on their own use of discourse in middle school settings see Rosebery, Warren, & Conant, 1992; for high school see van Zee & Minstrell, 1997; for college see Hammer, 1997). This emphasis on sensemaking discourse is echoed in the policy literature aimed at clarifying what it means to get students to "think" in classrooms. Thompson and Zeuli (1999) state that "By think, we mean that students must actively try to solve problems, resolve dissonances between the way they initially understand a phenomena and new evidence that challenges their understanding, put collections of observations or facts together into patterns, make and test conjectures, and build lines of reasoning about why claims are or are not true. Such thinking is generative. It literally creates understanding in the mind of the learner" (p. 346).

The teacher knowledge necessary for demonstrations, skill-building, discovery learning

As previously stated, the following three activity structures are grouped because they are all relatively short term in duration, focus on a single or limited set of ideas, are generally teacher-directed, and have known or predictable outcomes. Each of these activities have analogs in the practices of authentic science. Scientists, especially novices, watch more experienced members of their profession perform demonstrations of new equipment and techniques. These interns also build laboratory skills over time

> Note: One assumption of discovery learning has drawn criticism over the past 20 years. Scholars have noted that it is all but impossible for students to "discover" the theory underlying various phenomena through observation alone (for example, understanding the theoretical basis for electrostatics by rubbing plastic rods with fur and picking up pieces of paper). Driver et al. (1996) point out that scientific ideas, laws, and theories do not simply "emerge" from data. Rather they are conjectures, thought up imaginatively and creatively to account for the data. Discovery learning, as practiced in many classrooms, is based on an empiricist view of science and an inductive view of the "scientific method" (Feyerabend, 1988). Many mainstream philosophers of science have moved away from this towards a more hypothetico-deductive view, which recognizes the distinction between data and explanations (see for example Giere, 1988; 1991). These critiques do not fault discovery learning as a learning activity, but rather they reinforce the necessity for the teacher to 1) help students recognize the differences between observation and theory, 2) encourage deliberations about competing hypotheses, and 3) emphasize the role of creative thinking in science.

(e.g. safety practices, using/adjusting/maintaining equipment, learning specific procedures) and engage in discovery learning when they replicate (perhaps with slight modifications) other scientists' experiments or projects.

Demonstration is characterized here as: teacher-guided illustration, through the use of materials and procedures, of scientific principles (e.g. Bernoulli's), concepts (e.g. osmosis), or laws (e.g. Newton's Law of Cooling).

Discovery learning is characterized here as: students working in structured or semi-structured ways with materials and procedures to "discover" or confirm an idea or set of relations (e.g. using pulleys, ropes, and masses to explore mechanical advantage).

Skill-building is characterized here as: students engaging in manipulative activity (e.g. assembling distillation apparatus), following procedures (e.g. collecting data on cricket behavior), or practicing intellectual skills (e.g. transforming table data into graphical representations).

Figure 1 shows the types of teacher knowledge used in demonstrations, discovery learning, and skill-building.

Figure 1. Teacher knowledge necessary for: demonstrations, skill-building, discovery learning
***General pedagogical knowledge*:**
-Knows how to organize phases of activity. -Knows how to organize and manage material use by students.
***Content knowledge*:**
-Has at least surface level familiarity of target concept or skill. -Preferably has knowledge of phenomena at the theoretical level. -Knows examples and counterexamples of target concepts. -Understands how key ideas are related to others in domain. -Understands nature of observation versus inference. -Knows historical context of development of idea.
***Pedagogical content knowledge*:**
Understands: • how to elicit students' existing conceptions • which type or sequence of interactions with materials most likely to promote unambiguous conceptions of target ideas • which representations/activities will avoid generating alternative conceptions • how to promote sense-making discussions during and after the experience that will result in greater understanding of focal phenomena • how to scaffold students' generalizations of the focal idea to related contexts • how to scaffold students' integration of focal idea with other ideas in domain • how to bring students to proficient performances with important skills • how to recognize limitations in students' thinking about concepts, skills • how to help students recognize under what circumstances these skills should be used • how to combine these forms of instruction with others for the most effective learning experience • how to formatively and summatively assess students' knowledge and skills.
***Disciplinary knowledge*:**
-Has knowledge of how skills and ideas around natural phenomena might fit within larger context of an investigation.

Problem-solving

In problem-solving, students use their understandings of concepts, systems, instruments, materials, and procedures to solve self-defined or teacher-defined problems.

How one defines a "problem" for high school laboratory work gives rise to a wide range of potential projects that vary in purpose and complexity, in intellectual and material resources required, and time. There are three ways to think about problem-solving as a laboratory activity.

The simplest conception of a problem—as a puzzle with a known, discrete answer—forms the basis for short-term, focused, teacher-defined activities along the lines of "Identify the Mystery Chemical." Another way to construe a problem is from an engineering standpoint, which asks, "How can we use scientific knowledge to design solutions?" This involves technological construction such as creating a working circuit system for a set of model traffic lights (note that the first two types of problem-solving activities are not always distinguishable from discovery learning situations). The third type of activity in this category involves solving ill-defined problems in authentic contexts (e.g. How does run-off from agricultural land affect local aquatic ecosystems?). This type of activity can be of such scope that it contains numerous interconnected sub-problems (e.g. How do we develop an index for the health of an ecosystem?) and nested empirical investigations (e.g. determining the effects of a single chemical on one species of macro-invertebrate in a pond ecosystem).

Figure 2 shows the types of teacher knowledge used to support problem-solving by students.

Figure 2. Teacher knowledge necessary for: problem-solving
***General pedagogical knowledge*:**
Understands: • how to strategically improvise sequences of instructional moves based on ill-structured problem-solving contingencies. • how to organize and manage materials.
***Content knowledge*:**
-Has in-depth understanding of phenomena and how it is manifested in various contexts. -Familiar with range of target problem-solving skills, process skills, etc. -Knows how different science ideas within the problem domain interrelate with one another. -Familiar with instrumentation and other technologies. -Has knowledge of materials needed in problem solving activities.
***Pedagogical content knowledge*:**
Understands: • the timescale of potential investigations • what background reading is necessary • how to scaffold the problem-posing and problem-solving activities of students to bring them to proficient performances • how to speak the language of models and modeling with students • how to recognize flaws in students' problem-solving approaches or conceptual thinking • how to get students to monitor their own thinking and regulate their progress in these tasks • how to get students to recognize under what circumstances problem-solving skills should be used • how to promote sense-making discussions during and after the experience that will result in greater understanding of focal phenomena • how to formatively and summatively assess students' knowledge and performances.
***Disciplinary knowledge*:**
-Preferably knows how skills and ideas might fit within larger context of inquiry. -In some cases needs to understand how scientists approach/define certain types of problems and employ standards for "what counts" as a solution to a problem.

Hypothesis testing via empirical investigations: The "School Science" version

As a simplified template of the investigative activity of scientists, "The Scientific Method" was introduced to education in the early 20th century. Despite being criticized repeatedly since its introduction, it remains a durable icon in science education. Its straightforward sequence of activity allows students (and teachers) an accessible entry point into the world of question posing, data collection, and argument about outcomes. This traditional formulation of scientific work, however, is subject to several flaws, some of which are inherent to its structure and some of which arise from how it is applied. With regard to its structure, there are four interrelated problems. First, the method suggests that questions arise from observation and does not acknowledge the role that background content knowledge and theory have in both the way one chooses to "observe" phenomena and in how questions are formulated. Questions, using this popular version of the scientific method, are often based on what is interesting or do-able, but they are not grounded in any theoretical model. As a result, school science investigations are often content-less (e.g. experiments to determine which paper towels hold the most water). Data are analyzed to determine only how outcomes are related to conditions (for example, whether small crystals of sugar will dissolve faster in water than large ones) while underlying theory (molecular kinetics in this case) is not addressed (Chinn & Malhotra, 2002; Driver et al., 1996).

Figure 3 shows the types of teacher knowledge used to support hypothesis testing via empirical investigations: the "School Science" version.

Figure 3. Teacher knowledge necessary for: hypothesis testing via empirical investigations-- The "School Science" version
***General pedagogical knowledge*:**
-Knows how to organize and manage group work. -Knows how to organize and manage materials.
***Content knowledge*:**
-Understands focal phenomena at the level of observation, and preferably at the theoretical level.
Pedagogical content knowledge:
-Understands: • what background reading is necessary • the timescale of potential investigations • how to organize sequences of events based on ill-structured tasks for learners (listed as PCK rather than general ped. knowledge because teacher decisions are content dependent) • what investigative approaches by students are likely to result in "dead-ends" • how to scaffold those students who are learning to pose questions based on observations, design control group experiments, analyze data, represent data appropriately, draw conclusions • how to get students to monitor their own thinking and regulate their progress in these tasks • how to get students to recognize under what circumstances inquiry skills should be used • how to promote sense-making discussions during and after the experience that will result in greater understanding of relevant phenomena • how to formatively and summatively assess whether students understand these skills and how to execute these skills in appropriate contexts
***Disciplinary knowledge*:**
-Understands principles of randomized control group experimental design. -In some cases needs to understand how scientists approach/define certain types of problems and employ standards for "what counts" as a solution to a problem. -Has competence with scientific information (distinguishes primary and reputable sources from less reputable information).

With regard to how the scientific method is used in classrooms, there are various levels of structure that teachers may apply. For novice learners, teachers may determine the question to be asked in the investigation, prescribe what and how data will be collected, and make known what the intended "outcomes" should be. This amounts to a confirmatory exercise (cookbook lab). Alternatively, teachers may prescribe the question and methods of investigation, but let the students interpret the outcomes (structured inquiry); or they may determine only the question and let students decide on the methods and conclusions (guided inquiry); or finally, they may allow students the freedom to self-direct all phases of the investigation (independent inquiry). Used judiciously, the more structured forms of inquiry can encourage novice learners to "talk science" and participate peripherally in many valuable aspects of scientific work. The problem is that many instructors, even at the undergraduate level, engage their students in only the most prescribed and predetermined exercises, labeling these as "inquiry" or "investigations." This situation notwithstanding, the knowledge required by teachers for these types of investigations is varied and substantial, especially for guided and independent inquiries.

Hypothesis testing via empirical investigation: more authentic versions

The challenge of describing the work of scientists with the intent of emulating these activities in the classroom is that scientists engage in such a variety of types of investigations. Astronomers, field biologists, and bench chemists ask different types of questions, have unique approaches to collecting data, and have their own standards for "what counts" as a satisfying explanation. The following is a partial list of characteristics of authentic investigations. These serve to differentiate "school science" derived from the Scientific Method from more authentic forms of inquiry.

- Investigative questions are grounded in tentative theories or models of natural phenomena.
- Questions and investigative procedures are domain specific (for example, geologists ask unique types of questions that are derived from spatial data via Geographic Information Systems).
- Data collection is not necessarily based on randomized control group experiments (can include correlational, descriptive studies).
- Hypotheses can shift during the investigation (as they do in real science).
- Findings, in terms of differences between groups, correlations, changes over time, or other data patterns, are not "ends-in-themselves" but are used to argue for support or revision of a tentative scientific model.
- Because students work more independently and frame their inquiries around what is currently known about a phenomena (existing models and theories), having competence with scientific information is critical. Students and teachers must be able to distinguish between primary or otherwise reputable science authorities and pseudo-science, commercial reports, or secondary sources of information.

Of all the activity structures, authentic forms of empirical investigation require the *most varied and sophisticated forms of teacher knowledge*. It is important to note when students are engaged in activities that are complex and that have parallels to the kinds of work professionals do outside of the classroom, good teachers take on the role of *mentors* and treat their students as *apprentices*. With activities like complex problem-solving or empirical investigations teachers apprentice their students by initially taking on the most intellectually challenging aspects of the work, and letting their students act as peripheral participants. In subsequent investigations, the students take on more of the responsibility for work until they can become relatively independent inquirers. The apprenticeship model involves different forms of scaffolding (knowledge-in-action) by teachers such as:

- making their own thinking explicit so students have access to how problems are framed and approached,
- moving students from asking everyday questions to posing testable questions,
- responding strategically to different ways students could propose collecting and analyzing data,
- providing a conceptual or procedural framework for using data as evidence in arguing final claims, and,
- helping students reflect on how different phases of the investigation are connected.

Figure 4 shows the types of teacher knowledge needed for hypothesis testing via empirical investigation: more authentic versions.

Figure 4. Teacher knowledge necessary for: hypothesis testing via empirical investigations-- authentic versions
General pedagogical knowledge:
-Knows how to organize and manage group work. -Knows how to organize and manage materials.
Content knowledge:
-Has deep knowledge of phenomena required, how it inter-relates to other key ideas. -Has knowledge in the form of models and theories as well as facts, concepts, principles, etc. -Understands the distinctions between theoretical explanations and empirical/descriptive accounts of the relevant phenomena.
Pedagogical content knowledge:
-Understands: • how to organize sequences of events based on ill-structured tasks for learners • what background reading is necessary • the timescale of potential investigations • what investigative approaches are likely to result in “dead-ends” • how to scaffold those students who cannot: pose questions based on theoretical models, design control group experiments, analyze data, represent data appropriately, or draw conclusions • how to scaffold modeling and argumentation • how to promote sense-making discussions during and after the experience that will result in greater understanding of phenomena • how to formatively and summatively assess whether students understand these skills and how to execute these skills in appropriate contexts • how to get students to monitor their own thinking and regulate their progress in these tasks.
Disciplinary knowledge:
-Has some domain-specific knowledge of how: • scientists design questions from models or theory, • to employ methodological standards for data collection • to use arguments around model-based reasoning to link empirical results with theoretical explanations.

Question 2. Do teachers' current preparation and professional development provide them with these knowledge and skills?

We turn now to the question of where, in the educational trajectory of teachers, they develop the understandings required to enact the various lab-based activity structures. The education of teachers can be viewed as a continuum with three phases. First is undergraduate education, where prospective teachers learn principally about the subject matter of science, including aspects of scientific inquiry. Next is pre-service teacher education where students learn about the psychological, historical, cultural, and philosophical foundations of teaching, and they take coursework in the methods of instruction and assessment (this phase is often folded into the 4th year of an undergraduate teacher education program; alternatively, it can be part of a fifth-year of study or it can be part of a separate post-baccalaureate program of study, usually resulting in a master's degree with certification). During pre-service preparation, prospective educators also begin practice teaching in classrooms under the guidance of a cooperating teacher and a supervisor from the university (some programs do not provide a supervisor). Once teachers complete their preparation programs and become practicing teachers, they ideally receive ongoing professional development to deepen their knowledge in various areas related to instruction. The following three subsections provide an overview of what the literature says about teacher learning associated with each stage of this continuum.

Undergraduate preparation

Undergraduate work for prospective teachers forms the foundations of their subject matter knowledge and their knowledge of the disciplinary activities of science. There is little documentation, however, of the quality of instruction or learning for prospective teachers or other undergraduates. Unlike the K-12 educational system, which is the subject of intense scrutiny with regard to assessment of learning outcomes there is little documentation and critique of teaching in higher education. In a review for the US Department of Education, Wilson et al. (2001) state that "This means we know next to nothing about high quality teaching in subject matter courses that are part of the preparation of teachers" (p. 11).

Much of the data on undergraduate learning comes from research conducted in teacher education programs, where pre-service teachers are asked to use their content and disciplinary knowledge to organize units of instruction and design inquiry activities for students. One theme that emerges from such research is that the content knowledge gained from undergraduate work is often superficial and not well integrated. The traditional didactic pedagogy to which teacher candidates are exposed in university science courses equips learners with only minimal conceptual understandings of their science disciplines (Duschl, 1983; Gallagher, 1991; Pomeroy, 1993). Many pre-service teachers hold serious alternative conceptions about the science content that are similar to those held by their students (Anderson, Sheldon, & Dubay, 1990; Sanders, 1993; Songer & Mintzes, 1994; Westbrook & Marek, 1992).

In a year-long study of prospective biology teachers (Gess-Newsome & Lederman, 1993), the participants reported never having thought about the central ideas of biology or the interrelationships among the topics. The teachers, all biology majors, could only list the courses they had taken as a way to organize their fields. They appeared to have little understanding of the field "writ large." They knew little about how various ideas were related to each other, nor could they readily explain the overall content and character of biology. Over the course of a year's worth of pedagogical preparation and field experiences, the new teachers began to reorganize their knowledge of biology according to how they thought it should be taught. The following quotes characterize two teachers' perceptions of their undergraduate coursework:

> *I've been so used to, in college, you take plant physiology and it's just plant physiology. You take invertebrate zoology and its just invertebrate zoology.*
>
> *I feel like the only pattern…was the pattern I've been fed. And because I've been channeled through the content one way, I'm afraid I'm going to spit it out the same way it was fed to me without actually thinking about why things should be organized in a certain way.*

In another set of case studies of three prospective biology teachers, Lemberger, Hewson, and Park (1999) remarked: "All three individuals came into the program with positivist conceptions of knowledge and science. They all thought of science as being a body of established, reliable information. All three entered with a static and fragmented knowledge of biology" (p. 350). These findings confirm those from a substantial literature on arts and sciences teaching in colleges and universities which has clearly documented that both elementary and secondary teachers lack a deep and connected conceptual understanding of the subject matter they are expected to teach (Kennedy, Ball, McDiarmid, & Schmidt, 1991; McDiarmid, 1994).

With regard to prospective teachers' exposure to science as a knowledge-building enterprise, much of what new teachers learn about inquiry comes from their experiences as undergraduates, which are not unlike the confirmatory laboratory experiences found in high school (Trumbull & Kerr, 1993). In addition to the problem of being subjected to models of highly-structured inquiry, pre-service teachers are *rarely exposed to ideas about science as a discipline* at the college level and *do not participate in discussions of how new knowledge is evaluated* (Bowen & Roth, 1998; Wenk & Smith, 2004). Not surprisingly, the studies that have been done on inquiry in teacher education programs indicate that pre-service teachers lack basic knowledge of methodology and do not think in terms of theory as they attempt scientific investigations (Roth, 1999; Shapiro, 1996). Lemberger et al. (1999) said of three biology majors they were studying: "Coming into our [teacher education] program the prospective teachers had precious little exposure to the methods of inquiry used within the discipline of biology. This was most crucial because it left them without an understanding of the role of theory in biology, and how scientists use theory to pose problems and construct new understandings" (p. 351).

In a multi-case study of 14 pre-service secondary science teachers' understanding of authentic inquiry practices during a science methods course (as they engaged in their own independent science investigations over three months), results showed that most of the participants subscribed to a "folk theory" about scientific inquiry (Windschitl, 2004). Some facets of this folk theory were congruent with authentic science inquiry (e.g.

empirical inquiries involve developing questions, designing studies, and collecting and analyzing data; set-backs are to be expected; etc.). Other facets seemed to represent a limited view of scientific inquiry (e.g. there is a standard scientific method, although it is not linear; the ultimate goal of inquiry is to determine whether a relationship exists between two variables; etc.). More problematically, several facets of this folk theory were misrepresentations of some of the most fundamental aspects of scientific inquiry:

- hypotheses function as "guesses about outcomes", but are not necessarily part of a larger explanatory framework;
- background knowledge may be used to suggest ideas about what to study, but this knowledge is not in the form of a theory, explanation, or model;
- empirically testing relationships and drawing conclusions about these relationships are epistemological "ends-in-themselves"; and
- models or theories are optional tools you might use at the end of a study to help explain results.

Almost entirely absent from written artifacts and interviews were references to the epistemological bases of inquiry—talk of claims and arguments, alternative explanations, the development of models of natural phenomena, etc. Most of the participants, for example, based their inquiry questions not on a hypothesized model or theory, but on what seemed interesting, do-able, and novel (e.g. bubbling car exhaust through water to see how acidic it becomes, comparing plant growth with and without exposure to music). During the study, participants kept extensive journals of their experiences. An analysis of these journals showed that the idea of "theory" or "model" in association with their research questions or data collection was almost non-existent.

In a follow up study with 21 pre-service teachers, Windschitl & Thompson (2004) focused on participants' understanding of the roles of models and theory in science inquiry. They found: 1) although most of the pre-service teachers had a modest familiarity with scientific models, at least half did not have the depth of understanding necessary to engage others in discourse about the nature and function of models; 2) most pre-service teachers could talk about models in relatively sophisticated ways when provided with examples and prompting questions, but most could not generate coherent theoretical models themselves, nor were they adept at incorporating models and model-based reasoning into inquiry; 3) domain subject expertise and past research experiences influenced not only what was recognized as a model, but the way models were incorporated into inquiry; and; 4) for most pre-service teachers, the "scientific method" remains the dominant conceptual framework for inquiry— to the exclusion of considering scientific models as the fundamental grounding for investigateable questions and the object of inquiry's pursuits. A quote from one of the participants typifies how prospective teachers struggle to reconcile their undergraduate lab experiences with their responsibilities to teach their own students in a reform-oriented way:

> *At the end of the course, Sinda reflected on her inquiry experiences, claiming that she "was less than a novice at completing full inquiries" and that she "had always been given the question to start with." She said her previous studies had never included assumptions, predictions, argumentation, or initial theories, none required supporting one's claims, presenting to peers, or looking up other studies. She said she had now*

> *changed her mental model of inquiry which previously she had "considered as step-by-step, very orderly", where "one step had to be finished before the next step started."*

Despite this imperfect picture of undergraduate preparation, there are many efforts underway to reform college instruction. In one such case, Adamson et al. (2003) developed month-long workshops for university professors to learn about reform-based science instruction based on the AAAS standards. They later found that pre-service teachers who attended courses taught by the professor participants demonstrated significantly higher scores on measures of reformed instruction when they began their own teaching (as compared with a group of teachers who had not taken the reformed undergraduate science course) and their secondary students later demonstrated significantly higher achievement in terms of scientific reasoning, the nature of science, and biology concepts. The grasp of content for the experimental group teachers *was not negatively affected by the reform-based "less is more" approach to curriculum*. The results confirm that "teachers teach the way they have been taught."

In their study of preservice biology teachers, Hewson, et al. (1999) conclude that there is a need for significant changes in the curriculum and instruction of content courses, ideally arising from a dialogue between science educators and their colleagues in arts and sciences. Courses that could serve as models have been described by Monk and Osborne (1997), Shapiro, (1996), Stofflet (1994), and Zuzovsky (1994).

A nationally distributed effort to improve undergraduate STEM teaching, Project Kaleidoscope (PKAL), works to equip teams of faculty and administrators to engage in reform. PKAL integrates changes in programs, faculty, and facilities to realize systemic changes at the institutional level. Three dimensions are emphasized: 1) Learning is experiential and steeped in investigation from the very first courses for students through capstone courses; 2) learning is personally meaningful for students and faculty, by making connections to other fields of inquiry, by embedding ideas in the context of their own history, and by suggesting practical applications related to the experiences of the students; and 3) learning takes place in a community where faculty are committed equally to undergraduate teaching and to their own intellectual vitality, where faculty see students as partners in learning, where students collaborate with one another, and where institutions support such communities of learners. For more on improving undergraduate education see *Improving Undergraduate Instruction in Science, Technology, Engineering, and Mathematics* (National Research Council, 2003).

Teacher preparation

Teacher preparation is a time when prospective educators begin to acquire general pedagogical knowledge and pedagogical content knowledge. Determining the influence of teacher education is complicated by two factors. First, there is no single phenomenon called "teacher preparation." Teacher preparation means many different things across the country and the same is true for alternative preparation programs which vary in their content, complexity, length, and structure. Second, as Anderson and Mitchener (1994) note, there is only a small amount of research on pre-service education and what does exist "is rather limited in scope and usefulness" (p. 28). In their review of 57 studies on teacher preparation, Wilson, Floden, and Ferrini-Mundy (2001) add that "[t]here is no research that directly assesses what teachers learn in their pedagogical preparation and then evaluates the relationship of that pedagogical knowledge to student learning or teacher behavior" (p. 12).[2]

In their study of new secondary science educators, Adams and Krockover (1997) found that teachers attributed their knowledge of a range of instructional strategies, classroom discipline, classroom routines, and management to their educational coursework. The authors also identified cases where new teachers failed to use the constructivist forms of instruction they had been taught in pre-service education, until two years after they had become practicing teachers. They noted that the key influence for these changes was a professional development experience that provided these individuals time to reflect on their own teaching and consider how it compared with what they had learned in their pre-service experience. Other studies confirm that ideas presented in pre-service education are subsumed into the knowledge structures of practicing teachers (Craig, 1992; Cunliffe, 1994; Greenwood, 1992).

Gess-Newsome and Lederman (1993) state that "It is within content-specific education courses that the greatest gains in subject matter reflection and the translation of such reflection into practice may be achieved (p. 39). They add this caution however, "Despite the apparent ability of specific education courses to develop coherent subject matter structures, these structures do not appear to transfer immediately into classroom practice."

The importance of subject matter knowledge does not obviate the need for developing the pedagogical knowledge and pedagogical content knowledge necessary for effective laboratory instruction. Geddis (1993), for example, observes that novice teachers, whose classroom confidence is located primarily in their knowledge of the subject matter, tend to have simplistic views of teaching and learning, which pre-dispose them to didactic methods. Their pre-occupations with presenting "good science", getting through a crowded syllabus, and meeting the demands of external examinations lead them to provide copious notes, utilize a heavy diet of worksheet-driven practical activities, and drill their students in algorithmic procedures for solving standard problems.

One problem regarding PCK in teacher education is that some individuals never get training in pedagogical methods and strategies that are *particular to science instruction*. It is estimated that only 75% of high school teachers have taken a science-specific methods course as part of their teacher preparation (Weiss, Banilower, McMahon & Smith; 2001). Almost a quarter of secondary science teachers then, do not have the opportunity in teacher education to develop knowledge around science-specific modes of classroom discourse, inquiry, assessment, etc. The idea of science-specific methods courses for prospective teachers is supported by current literature in the learning sciences and adult learning. Adults learn best when the material is directly relevant to their perceived needs and taught in a context similar to that in which the knowledge will be used (Bransford, Brown, & Cocking, 2000). General methods courses assume that pedagogical skills are generic and may be applied similarly across a range of subject matter contexts (how to hold a discussion, conduct an assessment, plan lessons, etc.). Science teaching, however, requires knowledge and skills that are uniquely tied to the subject matter and the nature of the discipline. Eliciting and dealing with alternative conceptions is different in science classrooms than in mathematics classrooms and may not even be a part of language arts and social studies pedagogy. Inquiry in science has some similarities with that in the social studies but issues of evidence, argument, safety, and use of natural materials and equipment in the classroom are not only unique to science, but critical to have personal experience with in a subject-specific methods course.

Using data from 2,800 students, Monk (1994) found that education courses in subject matter methods for their teachers had a positive impact at all grade levels and concluded that “ a good grasp of one’s subject is a necessity but not a sufficient condition for effective teaching” (p. 142). Wenglinsky (2000) found that students whose teachers majored in science or science education, had more training is how to develop laboratory skills and engaged in more hands-on learning performed better on NAEP assessments.

There are some exemplary courses that combine methods with specific content. One is the on-line course *Teaching Evolution* (http://scied.fullerton.edu/biol409) which models the types of instruction that participants would use with their own students and attempts to shift participants from a focus on content delivery to a focus on student learning. Features of the instruction congruent with reform efforts are that: participants examine how young learners’ alternative conceptions about evolution can be raised and addressed; participants explore how assessment strategies can be integrated into inquiry-based lessons; and they examine how questioning can facilitate student thinking and discussions about science. In addition, participants engage in reflection on their own learning. A significant feature of the course is the curricular focus on a *limited number of important ideas* in biology.

Another aspect of teacher preparation is dealing with the often counter-productive understandings about knowing and learning that candidates bring into the program. In their study of six pre-service science teachers, Tabachnick and Zeichner (1999) describe how faculty in a constructivist program of teacher education had difficulty influencing the beliefs about learning held by participants. The authors noted that the prospective teachers’ understanding of the nature of knowledge was a critical factor in their instruction. Most began the program believing that true knowledge exists, that it is independent of individuals, and that it can be transmitted or passed on to another person by using good explanations and demonstrations of scientific principles. Additional difficulties arose when the program could not find school placements that modeled constructivist teaching. The study demonstrated that it is crucial to have field placements where prospective teachers can observe and be apprenticed by master teachers who have deep content knowledge and who use constructivist approaches to instruction; the authors state that the field experiences were made even more problematic by the fact that the pre-service teachers were pressured to move rapidly through a substantial curriculum. The authors concluded that: “The cooperating teacher is a powerful role model, whether positive or negative, his or her beliefs and teaching approaches can significantly influence the direction of a prospective teacher’s development… As was the case here, cooperating teachers rarely modeled the kind of teaching that we were seeking to encourage, prospective teachers are caught in a dilemma of how to accommodate competing demands” (p. 380).

Erickson et al. (1994) documented similar problems with field experiences. In their study of how collaborative and constructivist approaches to teaching science could be established in association with cooperating teachers and their student teachers, it became clear that social issues (trust, power, school culture) and institutional issues (curriculum demands, time constraints, university expectations, pupil ability) worked against these goals. Some cooperating teachers found constructivist teaching to be too time-consuming, unmanageable, or without purpose that was apparent to them. They believed that a constructivist approach was unrealistic in terms of the demands to cover the content-laden high school curriculum and manage student behavior (see also Rodriguez, 1993; 1995).

Recurring in the teacher education literature cited above and in studies of teachers attempting reform-based teaching is the pervasive and pernicious effect of the pressure to "cover the curriculum" (see Schmidt, McKnight, & Raizen, 1997 for an analysis of the bloated American science curriculum). The problem is pervasive because this ethos encourages a frantic pace of instruction throughout the educational system, from middle school classrooms to undergraduate survey courses—with teachers at each level made to worry that students won't have the breadth of knowledge to move on in their careers. The problem is pernicious because, as Jerome Bruner (1996) observed, the "breakneck pace" is wholly antithetical to teaching for understanding. It results in "teaching as telling' and a disregard for student thinking. *This cult of coverage looms as one of the most formidable obstacles to moving both new and experienced teachers towards reform-based inquiry instruction and meaningful laboratory work*.

And finally with regard to teacher preparation, the institution itself has recently been subjected to scrutiny. Two issues have arisen. One is the contention by some that verbal ability and content knowledge should be the primary qualifications for becoming a classroom teacher (labeling education course work and student teaching as "bureaucratic hurdles": see US Department of Education, 2002, p. 19). The other issue is the efficacy of alternative certification programs (ACP's).

Concerning this first issue, there are a number of peer-reviewed studies that demonstrate a relationship between teacher education certification measures and teacher effectiveness, as measured by student performance. This includes a review of 57 studies meeting rigorous research criteria (Wilson, Floden, & Ferrini-Mundy, 2001). One study in particular (Goldhaber & Brewer, 2000) found strong influences of teacher certification on student achievement in high school science and math, above and beyond the effects of teachers' subject matter degrees. The effect of certified teachers on student achievement was larger in both math and science than the effect of degrees in the subject matter specialties. This suggests that what certified teachers learn about teaching adds to what they gain from a strong subject matter background. Monk (1994) found that teachers' content preparation, as measured by coursework in the field, was positively, though rarely significantly, related to student achievement in mathematics and science.

Concerning the issue of alternative certification programs, there is some ambiguity about the classification itself. ACP's range from university-based 5-year bachelor's plus master's degree models or pre-service master's degree programs (which are labeled "alternative" because they are not undergraduate pathways) to district–run models that place teachers in classrooms after a summer of training. On the latter end of the spectrum (least preparation) the attrition rate is high. This is a concern because the knowledge and skills to teach reform-based inquiry in science takes years to develop. Darling-Hammond and Youngs (2002) describe the drop-out rates of some large scale ACP's. An evaluation of the Los Angeles Teacher Trainee Program, California's largest district-run internship program, found that only 80% completed the 1st year of training and only 65% completed the second year and received a clear credential the year after (Wright, McKibbin, & Walton, 1987). Another analysis of the same program revealed that 53% of the recruits had left the district within the first 5 years of program operation (Stoddart, 1992). Comparable attrition rates were found for an ACP in Dallas, Texas, in which only about 54% of the recruits progressed from 1st year to second year status without "deficiencies" and only 40% planned to remain in teaching (Lutz & Hutton, 1989) and one in New York City (the Teaching Fellows Program), which lost more than 15% of its first class by Thanksgiving and more than 30% by the end of the initial year (Goodnough, 2000). A study of Teach for America (ACP) recruits in Houston (Raymond, Fletcher, & Luque, 2001) shows that TFA recruits were about as effective as other inexperienced teachers, but over the three years of the study from 60 to 100% had left after their second year of teaching. These attrition rates are far higher than those in high quality teacher education programs; the University of Washington teacher education program, for example has an 80% retention rate for teacher graduates after *eight years* in the profession.

Despite the high attrition rates of many ACP's, there are some strong programs in existence. In a review of the literature, Darling-Hammond and Youngs (2002) conclude that among ACP's, those with the most capable graduates were those that 1) offered university coursework (including methods) before entering the classroom, 2) provided student teaching that included intensive supervision and assistance by both school-based mentors and university supervisors while they completed additional coursework needed to meet full standard state certification requirements, and 3) conducted regular in-service classes for continued development (Darling-Hammond, Hudson, & Kirby, 1989; Snyder, 1999). They also, however, caution that programs and entry pathways that skirt the core features of teacher preparation produce recruits who consider themselves underprepared, are viewed as less competent by principals, are less effective with students, and have high rates of attrition.

Professional development

A national survey of over 5,700 mathematics and science teachers nationwide by Weiss, Banilower, McMahon and Smith (2001) provides a context for examining the issues of advanced study and professional development (PD) for teachers. They found that 81% of all high school science teachers had an undergraduate degree in science, but for those teachers with up to 20 years of experience, less than half had earned masters degrees. Approximately 55% of high school science teachers in the Weiss et al. study (2001) reported spending less than 35 hours total over the past 3 years on professional development activities. The most common form of professional development was attending a workshop (70% of respondents). On average, less than a third of teachers said that professional development experiences "caused them to change their teaching practices." In another national survey, teachers ranked in-service training as their *least effective* source of learning (Smylie, 1989).

Most professional development has proven ineffective for a number of reasons (Desimone, et al., 2002). PD usually takes the form of one-day "workshops." These often are focused on "how to" activities which do nothing to challenge fundamental knowledge and beliefs about teaching and learning. This form of PD is typically a generic, one-sizefits-all experience, rather than being grounded in experiences of the teachers, their curriculum, and local context. Furthermore, these types of PD do not use students' thinking as a basis for planning, evaluating, and revising instruction. At best, the prevalent forms of PD lead only to "additive" learning, that is, grafting "tips and tricks" onto an existing repertoire of pedagogical strategies. These forms of PD rarely stimulate "transformative learning", where teachers critically analyze their own practice and fundamentally restructure existing knowledge and beliefs (Thompson & Zeuli, 1999).

In a study of NSF's Local Systemic Change Initiatives, Supovitz and Turner (2000) found that teacher participation in high-quality professional development positively influenced both inquiry-based teaching and an investigative classroom culture. They found that content preparation was the most powerful individual teacher factor in their predictive models. It appeared that it was somewhat more difficult to change classroom culture than teaching practices; significant changes in teaching practice came after approximately 80 hours of professional development, while the changes in classroom culture came only after 160 hours.

In a similar study conducted of Ohio's Statewide Systemic Initiative in science and mathematics, Supovitz, Mayer, and Kahle, (2000) found that a highly intensive (160 hour) inquiry-based professional development effort changed teachers' attitudes towards reform, their preparation to use reform-based practices, and their use of inquiry-based teaching practices. Furthermore, they found that these changes persisted several years after the teachers concluded their professional development experiences.

In a study of 1,027 science and mathematics teachers, Garet et al. (2001) found the core features of professional development that have significant effects on teachers' self-reported increases in knowledge and skills and changes in classroom practices are: a) focus on content knowledge; b) opportunities for active learning; and c) coherence with other learning activities. It is primarily through these core features that the following structural features significantly affect learning a) the form of the activity (e.g. workshop versus study group); b) collective participation of teachers from the same school, grade, or subject, and; c) duration of the activity.

In a longitudinal study of 207 science and mathematics teachers from 30 schools, Desimone et al. (2002) found that professional development is more effective (likely to change teacher practice) when it has: a) the collective participation of teachers from the same school, department, or grade; b) active learning opportunities such as reviewing student work or obtaining feedback on teaching; and c) coherence, for example, linking to other activities or building on teachers' previous knowledge. Reform-type professional development also had a positive effect. Surprisingly, the duration of the professional development had no effect on outcomes. It may be that the factor of time is important only to permit the experiences of collective participation, coherence, and experimentation with new practices to unfold in meaningful ways.

These results suggest not only that schools provide more coherence in professional development offerings but also that teachers' PD experiences take place in community settings rather than as individual endeavors. Seceda and Williams (in press) describe the significant uncertainty that reform-based teachers face as they attempt new practices in their classrooms. They refer to a larger research effort by Gamoran et al. (2003) of six school sites where science and mathematics teachers were collaborating with university researchers to teach for understanding. Two hypotheses were confirmed in that study: 1) the shift from conventional teaching to teaching for understanding makes teachers' uncertainty more salient in all areas of teaching: curriculum, instruction, assessment, and teacher knowledge about student reasoning; 2) professional communities of teachers provide the social mechanisms through which uncertainty can be managed, allowing teachers to respond to one another's affect, beliefs, and ideas, to provide support and encouragement to try out new ideas in the classroom, and help each other to maintain the practices that resonate with newly developing ideas about how to teach for understanding. The authors suggest that social interaction among teachers, in a professional community, plays a critical role in their growth. Several other PD efforts successfully utilize the dynamics of community to initiate and sustain reform efforts among teachers. Among these are Looking at Student Work (LASW), Japanese Lesson Study, Coalition of Essential Schools, and the SACNAS biography project.

Question 3. How should teachers' preparation and professional development be changed?

Undergraduate work

The following are recommendations for re-thinking and taking steps to modify undergraduate experiences.

1) It is recommended that rigorous content courses be made available that model reform-based teaching for both prospective and practicing teachers. This is necessary not only to deepen content knowledge in teachers, but to act as a mechanism, through modeling, to reduce the amount of content addressed in a given course. The compulsion to cover content is perhaps the greatest threat to realizing a substantive change in laboratory learning in this country. Policy recommendations at all levels (K-12 to undergraduate) should help re-shape what educators consider a robust curriculum, focusing on the in-depth understanding of selected key ideas, rather than the whirlwind tours of concepts and facts offered in most science courses. These college-level courses should emphasize:

- teaching for understanding of key ideas and how these ideas are related to one another
- a "less is more" approach to content selection that is made evident to participants
- an emphasis on the role of theory, modeling, and hands-on empirical inquiry in the relevant science domain
- transparency about how evidence and argument are used to adjudicate between competing hypotheses
- a variety of forms of assessment used by instructors, some formative, some summative.

Training should be provided for university faculty in reform-based principles of instruction as outlined in the *National Science Education Standards*. Such courses could be co-taught by sciences and school of education faculty.

2) Include authentic inquiry experiences in all undergraduate laboratory classes. Empirical investigations would not have to be the only mode of teaching/learning, but the laboratory course should not be dominated by confirmatory (cookbook) activities. There should be some overarching themes that connect the work within the course in

meaningful ways and connects the laboratory to what is being studied in complementary lecture or recitation sections.

3) Offer undergraduate courses in the history and philosophy of science that explore the methodological and epistemological underpinnings of modern inquiry.

4) Provide multiple opportunities for undergraduates to be mentored by faculty in authentic research (as opposed to acting as only as lab technicians or data collectors). Undergraduate participants should be part of a team of researchers and engage in on-going conversations where all phases of the research are made transparent (i.e. use of background knowledge to develop initial models, how research questions are formed, how decisions are made about collecting data, how data is analyzed and used as evidence in domain-specific forms of argumentation).

5) Undergraduate education should not simply be a sampling of courses whose content has no unifying threads (i.e. not integrated). An undergraduate major should be a coherent, connected experience. This could be accomplished by coordinating key ideas or themes that are presented across courses in the major and by requiring some capstone experience in the major that synthesizes not only the content of the major, but the methodological and epistemological framework that guides inquiry in that domain.

Teacher Education

The following are recommendations for re-thinking and taking steps to modify teacher education experiences.

1) In teacher education programs, all secondary science teachers should participate in a science-specific methods course that includes opportunities to engage in the kinds of laboratory and inquiry work described by the *Inquiry and the National Science Education Standards* (2000*)*.

2) During practice teaching, pre-service teachers should be placed in schools with cooperating teachers who: a) practice reform-based instruction, b) are competent with meaningful laboratory work, and c) are capable of engaging *all* learners in classrooms that are ethnically, racially, and linguistically diverse.

3) Alternative teacher certification programs that "fast track" teachers past courses in methods and related courses that explore the basis of student learning should be avoided. Reform-based laboratory instruction requires teacher skills that can come only from a robust preparation program and only the best prepared teachers stay in the profession long enough to acquire these skills. Well-constructed alternative certification programs have the following characteristics: university coursework (including methods) before entering the classroom, student teaching that includes intensive supervision and assistance by both school-based mentors and university supervisors while they complete additional coursework needed to meet full standard state certification requirements, and having regular in-service classes to continue their development.

Professional development

The following are recommendations for re-thinking and taking steps to modify professional development. It is important that *teachers learn content, as well as pedagogy, through engagement in learning activity that "mirrors" the kinds of experiences that reformers hope teachers would provide their students* (Borko & Putnam, 1996; Loucks-Horsley et al., 2003). Specific recommendations are as follows:

1) Professional development should be ongoing, regular experiences for teachers that are connected and cumulative in their aims. "One-shot" workshops are of little value.

2) In PD opportunities, content knowledge enhancement should go hand-in-hand with fostering inquiry-based teaching.

3) PD should focus not only on the "hands-on" of inquiry (running teachers through the activities in a kit), but meaning behind the activities and how they tie together. Such experiences should engage the teachers in substantive discourse about evidence and explanation.

4) The PD and broader science education community must promote a marketable, intellectually honest idea to replace the constraining cultural icon of "The Scientific Method."

5) PD should help teachers make existing ideas about teaching and learning explicit and provide experiences that challenge these ideas.

6) PD should consist of *strategic combinations* of experiences for teachers. For example, eighteen different PD strategies are outlined in Loucks-Horsley, et al. (2003), but the *combination and sequence* of multiple strategies is important. The sequence could begin with techniques to challenge one's own beliefs and understandings about learning, then move to more high-stakes changes such as altering actual teaching practices:

- beginning with experiences that challenge teachers' thinking about how one learns about concepts and through scientific investigations,
- immersing teachers in authentic scientific inquiries of their own,
- focusing on the processes and products of student thinking (studying written artifacts of their own student's laboratory work, for example),
- and finally, support them in changing their own instruction (using strategies such as curricular adaptation, lesson study, etc).

7) PD should be grounded in the participants' own school context, using the participants' curriculum as a starting point for exploring the use of laboratory activities.

8) PD experiences should take place in the context of some professional community that can support teachers' reform-based efforts in school environments where this type of instruction may meet with indifference or resistance.

9) Considering that only half of science teachers with 20 years or less of experience have master's degrees, incentives should be provided for practicing teachers to obtain these advanced degrees. These could take the form of financial support and time for teachers to complete further study. Incentives could also be offered to higher education institutions to re-configure masters programs that would emphasize reform-based instruction, a focus on student thinking, reflection on teaching practices, and the development of communities of science education professionals.

Final Comments

The real complexity of teaching can only begin to be revealed by the analyses offered in this report. What is clear is that we expect a lot from science teachers in the way of knowledge and skills. We expect them to have some degree of understanding not only of a wide range of content, but of a number of different types of investigative practices. Further, teachers must deal with the myriad ways that young learners think about the natural world and the pursuits of scientists.

Teachers are the fulcrum of educational reform. If we aim to reconceptualize the role and vision of high school laboratories, then teachers must be cultivated as both intellectuals and professionals, rather than as technicians who simply follow instructional scripts. This means providing them with the best possible preparation and supporting life long learning as the norm that characterizes this special group of individuals.

Footnotes

[1] The term “activity structure” is borrowed from the sociocultural theorists meaning a set of classroom activities and interactions that have characteristic roles for participants, rules, patterns of behavior, and recognizable material and discursive practices associated with them. “Taking attendance”, “having a discussion”, and “doing an experiment” could all be considered activity structures. While the term “activities” refers to specific phenomena occurring in classrooms, the structures underlying these are more general and applicable across multiple contexts.

[2] Wilson et al. add:

> *Conducting research about pedagogical preparation is complicated. One complication is that ‘pedagogical preparation’ means many things. Prospective teachers take courses in instructional methods: sometimes those courses are subject specific, sometimes they are generic. They also take courses in learning theories, educational measurement and testing, and in educational psychology, sociology, and history. …course content varies, as does sequencing, so that even when courses share the same title, they can be qualitatively different* (p. 12).

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