

#### 4. NATURE, SOURCES, AND DEVELOPMENT OF PEDAGOGICAL CONTENT KNOWLEDGE FOR SCIENCE TEACHING

##### INTRODUCTION

"What shall I do with my students to help them understand this science concept? What materials are there to help me? What are my students likely to already know and what will be difficult for them? How best shall I evaluate what my students have learned?" These questions are common for every teacher, and central to describing the knowledge that distinguishes a teacher from a subject matter specialist. In this paper, we argue that such knowledge is described by the concept known as pedagogical content knowledge, and that this concept is critical to understanding effective science teaching. We describe pedagogical content knowledge as the *transformation* of several types of knowledge for teaching (including subject matter knowledge), and that as such it represents a unique domain of teacher knowledge. This chapter presents our conceptualization of pedagogical content knowledge and illustrates how this concept applies to understanding science education from the perspective of the teacher, the science teacher educator, and the science education researcher.

##### THEORETICAL FOUNDATIONS

Planning and teaching any subject is a highly complex cognitive activity in which the teacher must apply knowledge from multiple domains (Resnick 1987; Leinhardt & Greeno, 1986; Wilson, Shulman, & Richert, 1988). Teachers with differentiated and integrated knowledge will have greater ability than those whose knowledge is limited and fragmented, to plan and enact lessons that help students develop deep and integrated understandings. Effective science teachers know how to best design and guide learning experiences, under particular conditions and constraints, to help diverse groups of students develop scientific knowledge and an understanding of the scientific enterprise.

These statements about the role of knowledge in teaching is supported by a body of research documenting that science teachers' knowledge and beliefs have a profound effect on all aspects of their teaching (e.g., Carlsen, 1991a 1993; Dobey & Schafer, 1984; Hashweh, 1987; Nespor, 1987; Smith & Neale, 1991), as well as on how and what their students learn (Bellamy, 1990; Magnusson, 1991). Some of this research was framed by conceptualizations developed by Shulman and his

colleagues of the diverse knowledge domains that teachers use when planning and teaching (Grossman, 1990; Shulman 1986, 1987; Wilson, Shulman & Richert, 1988). A major contribution of this formulation of the knowledge base for teaching was its acknowledgment of the importance of subject-specific knowledge in effective teaching. A revolutionary feature of this work was the identification of a type of knowledge that was viewed as unique to the profession of teachers: pedagogical content knowledge.<sup>1</sup> Pedagogical content knowledge is a teacher's understanding of how to help students understand specific subject matter. It includes knowledge of how particular subject matter topics, problems, and issues can be organized, represented, and adapted to the diverse interests and abilities of learners, and then presented for instruction. We argue that pedagogical content knowledge, also known as content-specific or subject-specific pedagogical knowledge (e.g., McDiarmid, Ball, & Anderson, 1989), is integral to effective science teaching. Further, an understanding of this domain of knowledge and its influence on teachers' practice is necessary to foster the improvement of science teaching and science teacher education.

#### DEFINING PEDAGOGICAL CONTENT KNOWLEDGE

In our view, the defining feature of pedagogical content knowledge is its conceptualization as the result of a *transformation* of knowledge from other domains (Wilson, Shulman, & Richert, 1988). This idea is depicted graphically in Figure 1, which presents a model of the relationships among the domains of teacher knowledge that primarily has been informed by the work of Grossman (1990). The shaded boxes in the figure designate the major domains of knowledge for teaching.<sup>2</sup> The lines that link the domains of knowledge illustrate the relationship between pedagogical content knowledge and the other domains of knowledge for teaching. The terms on the lines and the arrows at the ends of lines describe the nature and direction of each relationship. Arrows at each end of a line indicate a reciprocal relationship between domains. The figure is intended to depict that pedagogical content knowledge is the result of a transformation of knowledge of subject matter, pedagogy, and context, but that the resulting knowledge can spur development of the base knowledge domains in turn. Grossman conceptualized pedagogical content knowledge as consisting of four components (shown in the figure to the sides of the box representing pedagogical content knowledge). Our conceptualization is very similar, with some modification and the addition of one component. We begin our discussion of the concept of pedagogical content knowledge for science teaching by defining and describing these components.

#### *Components of Pedagogical Content Knowledge for Science Teaching*

Building upon the work of Grossman (1990) and Tamir (1988), we conceptualize pedagogical content knowledge for science teaching as consisting of five compo-

nents: (a) orientations toward science teaching, (b) knowledge and beliefs about science curriculum, (c) knowledge and beliefs about students' understanding of specific science topics, (d) knowledge and beliefs about assessment in science, and (e) knowledge and beliefs about instructional strategies for teaching science. These components are shown in Figure 2.<sup>3</sup> In this section, we provide conceptual descriptions and illustrative examples to define the specific knowledge that is represented by each component. In addition, we synthesize findings from research that has assessed teachers' pedagogical content knowledge and, where it has been examined, the impact of that knowledge on science teaching and learning.

### *Orientations Toward Teaching Science*

This component of pedagogical content knowledge refers to teachers' knowledge and beliefs about the purposes and goals for teaching science at a particular grade level. Grossman designated this component as consisting of knowledge of the purposes for teaching a subject at a particular grade level or the "overarching conceptions" of teaching a particular subject. Research in science education has referred to this component as "orientations toward science teaching and learning," (Anderson & Smith, 1987),<sup>4</sup> which we prefer to Grossman's term. An orientation represents a general way of viewing or conceptualizing science teaching. The significance of this component is that these knowledge and beliefs serve as a "conceptual map" that guides instructional decisions about issues such as daily objectives, the content of student assignments, the use of textbooks and other curricular materials, and the evaluation of student learning (Borko & Putnam, 1996).

Orientations toward teaching science that have been identified in the literature are shown in Tables I and II.<sup>5</sup> The orientations are generally organized according to the emphasis of the instruction, from purely process or content to those that emphasize both and fit the national standard of being inquiry-based. Each orientation has then been described with respect to two elements that are useful in defining and differentiating them: the goals of teaching science that a teacher with a particular orientation would have (Table I), and the typical characteristics of the instruction that would be conducted by a teacher with a particular orientation (Table II).

A comparison of the characteristics of instruction that follow from particular orientations reveals that some teaching strategies, such as the use of investigations, are characteristic of more than one orientation. This similarity indicates that it is not the use of a particular strategy but the *purpose* of employing it that distinguishes a teacher's orientation to teaching science. For example, teachers with a discovery, conceptual change, or guided inquiry orientation might each choose to have students investigate series and parallel circuits, but their planning and enactment of teaching relative to that goal would differ. The teacher with a "discovery" orientation might begin by giving his students batteries, bulbs, and wires, and proceed by having them follow their own ideas as the students find out what they can make

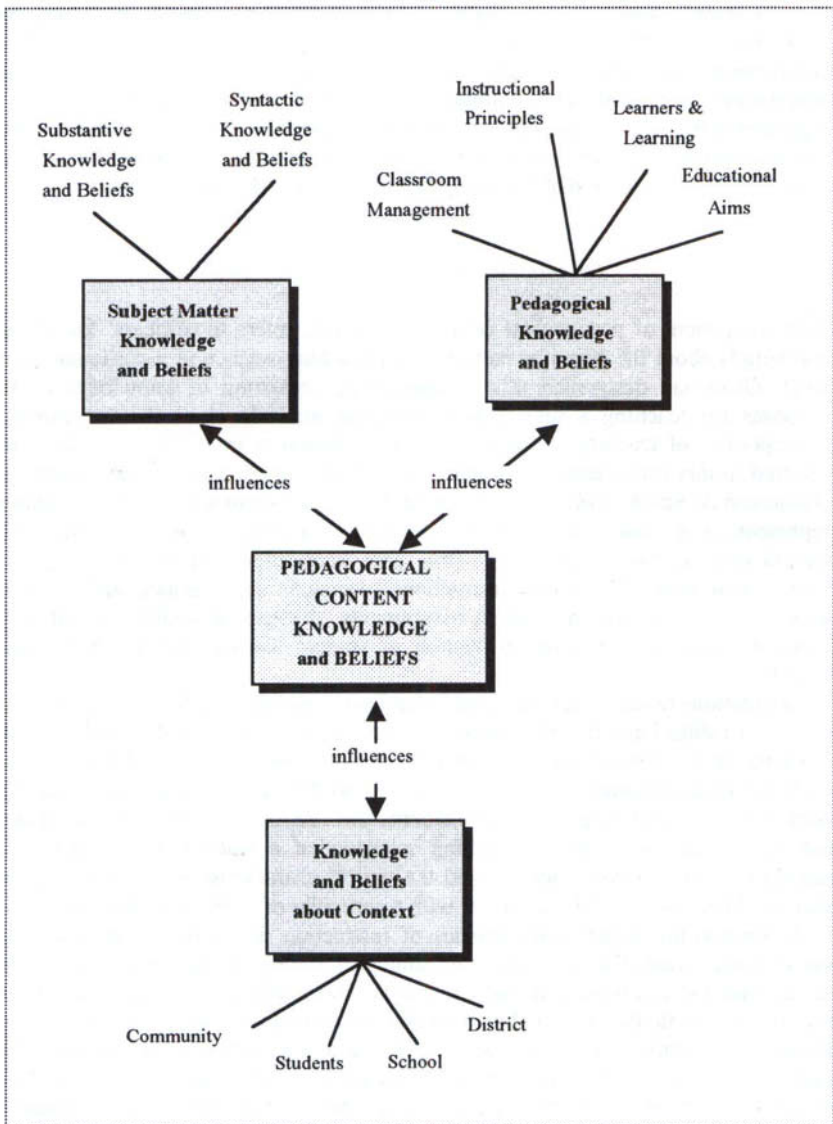


Figure 1. A model of the relationships among the domains of teacher knowledge. modified from Grossman (1990)]

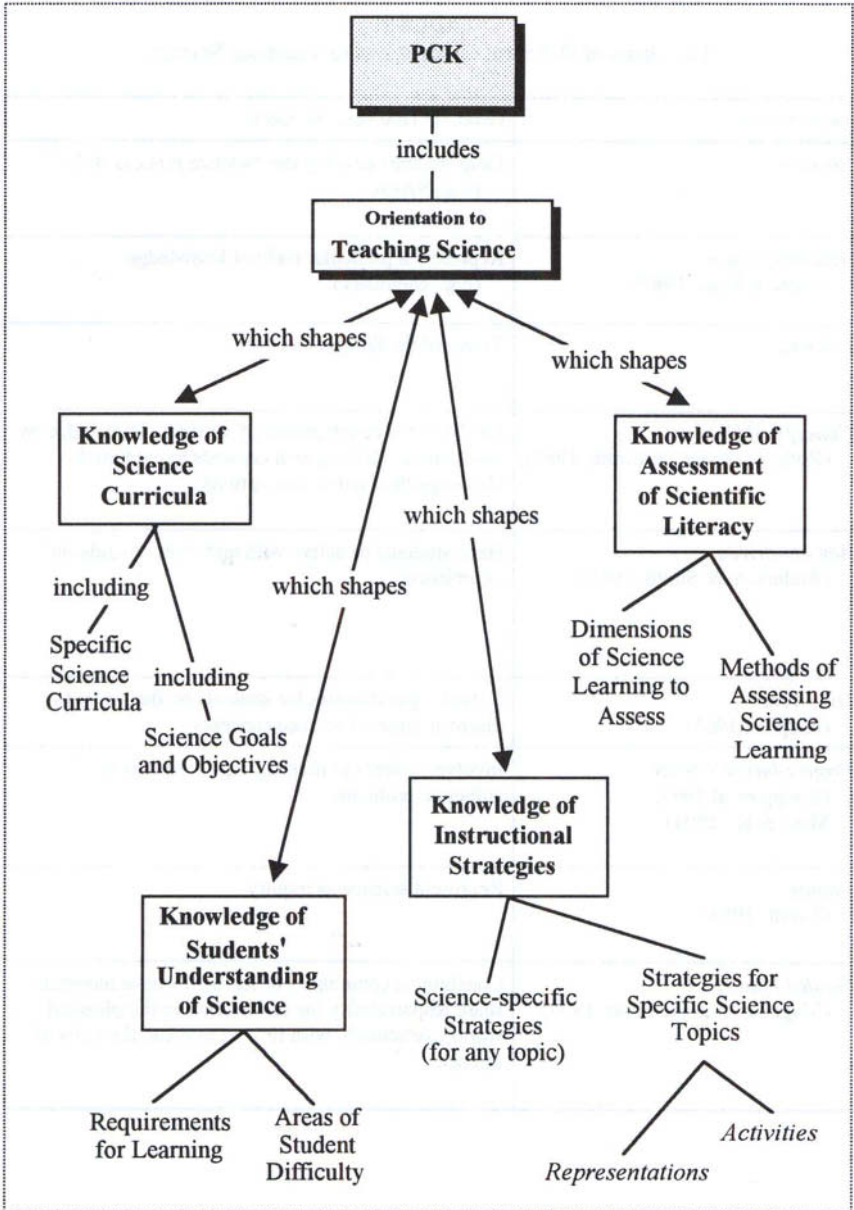


Figure 2. Components of pedagogical content knowledge for science teaching.

TABLE I  
The Goals of Different Orientations to Teaching Science

<i>ORIENTATION</i>	GOAL OF TEACHING SCIENCE
<i>Process</i>	Help students develop the “science process skills.” (e.g., SAPA)
<i>Academic Rigor</i> (Lantz & Kass, 1987)	Represent a particular body of knowledge (e.g., chemistry).
<i>Didactic</i>	Transmit the facts of science.
<i>Conceptual Change</i> (Roth, Anderson, & Smith, 1987)	Facilitate the development of scientific knowledge by confronting students with contexts to explain that challenge their naive conceptions.
<i>Activity-driven</i> (Anderson, & Smith, 1987)	Have students be active with materials; “hands-on” experiences.
<i>Discovery</i> (Karplus, 1963)	Provide opportunities for students on their own to discover targeted science concepts
<i>Project-based Science</i> (Ruopp et. al 1993; Marx et al., 1994)	Involve students in investigating solutions to authentic problems.
<i>Inquiry</i> (Tarnir, 1983)	Represent science as inquiry
<i>Guided Inquiry</i> (Magnusson & Palinesar, 1995)	Constitute a community of learners whose members share responsibility for understanding the physical world, particularly with respect to using the tools of science.

TABLE II  
The Nature of Instruction Associated with Different Orientations to  
Teaching Science

ORIENTATION	CHARACTERISTICS OF INSTRUCTION
<i>Process</i>	Teacher introduces students to the thinking processes employed by scientists to acquire new knowledge. Students engage in activities to develop thinking process and integrated thinking skills.
<i>Academic Rigor</i>	Students are challenged with difficult problems and activities. Laboratory work and demonstrations are used to verify science concepts by demonstrating the relationship between particular concepts and phenomena.
<i>Didactic</i>	The teacher presents information, generally through lecture or discussion, and questions directed to students are to hold them accountable for knowing the facts produced by science.
<i>Conceptual Change</i>	Students are pressed for their views about the world and consider the adequacy of alternative explanations. The teacher facilitates discussion and debate necessary to establish valid knowledge claims.
<i>Activity-driven</i>	Students participate in “hands-on” activities used for verification or discovery. The chosen activities may not be conceptually coherent if teachers do not understand the purpose of particular activities and as a consequence omit or inappropriately modify critical aspects of them.
<i>Discovery</i>	<i>Student-centered.</i> Students explore the natural world following their own interests and discover patterns of how the world works during their explorations.
<i>Project-based Science</i>	<i>Project-centered.</i> Teacher and student activity centers around a “driving” question that organizes concepts and principles and drives activities within a topic of study. Through investigation, students develop a series of artifacts (products) that reflect their emerging understandings.
<i>Inquiry</i>	<i>Investigation-centered.</i> The teacher supports students in defining and investigating problems, drawing conclusions, and assessing the validity of knowledge from their conclusions.
<i>Guided Inquiry</i>	<i>Learning community-centered.</i> The teacher and students participate in defining and investigating problems, determining patterns, inventing and testing explanations, and evaluating the utility and validity of their data and the adequacy of their conclusions. The teacher scaffolds students’ efforts to use the material and intellectual tools of science, toward their independent use of them.

happen with the materials. He would expect his students to discover that there are different types of circuits and he would supply the appropriate name for the different types as students discovered them. The purpose of the instructional activity would be for students to discover what they can about electrical phenomena through pursuing their own questions. In contrast, the teacher with a “conceptual change” orientation might begin by having her students talk about their ideas about electricity to have them become aware of their own ideas and differences between their ideas and others, and to give her some sense of some of the misconceptions they have about electricity. She might have them proceed by working with a particular circuit that she shows them how to make, expecting that it would challenge their misconceptions, and she would press the students to generate explanations to account for their observations of the circuit. She would expect the students to compare the explanations of one another to identify differences among them, and she might provide the view of scientists for them compare as well with their own explanations. The hope is that students would be persuaded by the greater explanatory power of the scientific view to adopt that view following opportunities to test out and apply their understanding of it.

Finally, in contrast yet again, the teacher with a “guided inquiry” orientation might begin by engaging her class in the task to establish a question or problem related to exploring electricity. For example, if she proposed that her students undertake the task of “lighting” scale models of buildings that they design and build, they would discuss what they would need to know and be able to do to accomplish that task, such as generating light and being able to control it (e.g., turning on and off, one light working independently of another).<sup>6</sup> That conversation would lead to determining and conducting investigations to understand electrical behavior in circuits, and determining patterns that distinguish different types of circuits. The teacher would have the students report their ideas about the behavior of electricity to the class during each cycle of exploration so that, as a learning community, they could determine the best ideas to go forward with to proceed to the next cycle of investigation. This reporting might lead to cycles of investigation in which students seek information about how scientists think about electricity. At some point she would engage her students in inventing explanations or models to account for the relationship they have identified,<sup>7</sup> and the views of scientists might be sought at this point again as an additional resource of information with which to build their understanding of electricity.

These scenarios illustrate the hypothesized central role of this component of PCK in decision-making relative to planning, enacting, and reflecting upon teaching. Few studies have been conducted, however, that directly assess teachers’ orientations to teaching science in order to put that claim to an empirical test. Research that has been conducted includes the work of Hewson and Hewson (1989) who developed a specific approach for identifying teachers’ conceptions of teaching science. These researchers were reluctant, however, to use their scheme to categorize a group of teachers they studied because they claimed it would “[wash] out the interesting nuances between [them]” (p. 207). In other research that has discussed teachers’ orientations, researchers have labeled teachers as having particular



orientations, but attempts have not been made to more specifically determine the teachers' knowledge relative to those designations. Nevertheless, one interesting finding from this research is that teachers can hold multiple orientations, including ones such as didactic and discovery that have incompatible goals for teaching science (Smith & Neale, 1989).

### *Knowledge of Science Curriculum*

This component of pedagogical content knowledge consists of two categories: mandated goals and objectives, and specific curricular programs and materials. Shulman and colleagues originally considered curricular knowledge to be a separate domain of the knowledge base for teaching (Wilson, Shulman, & Richert, 1988). Following the lead of Grossman (1990), we have included it as part of pedagogical content knowledge because it represents knowledge that distinguishes the content specialist from the pedagogue—a hallmark of pedagogical content knowledge.

#### *Knowledge of Goals and Objectives*

This category of the curricular knowledge component of pedagogical content knowledge includes teachers' knowledge of the goals and objectives for students in the subject(s) they are teaching, as well as the articulation of those guidelines across topics addressed during the school year. It also includes the knowledge teachers have about the vertical curriculum in their subject(s); that is, what students have learned in previous years and what they are expected to learn in later years. (Grossman, 1990)

Examples of sources for knowledge of goals and objectives include national- or state-level documents that outline frameworks for guiding decision-making with respect to science curriculum and instruction (e.g., AAAS, 1989; California State Board of Education, 1990; Michigan State Board of Education, 1991). Schools and districts may also have documents that indicate, for specific courses or programs, what concepts are to be addressed to meet mandated goals. Effective science teachers are knowledgeable about these documents.

#### *Knowledge of Specific Curricular Program*

This category of teachers' knowledge of science curriculum consists of knowledge of the programs and materials that are relevant to teaching a particular domain of science and specific topics within that domain. Substantial curriculum development in science education has occurred for each level of schooling over the past 30 years. As a result, there are typically several programs at each grade level and for each subject area, about which teachers should be knowledgeable. For example, a chemistry teacher might be expected to be knowledgeable about curricula for teaching chemistry, including programs such as CHEM Study and CBA (Chemical Bond Approach) which were developed in the 1960s, IAC (Interdisciplinary

Approaches to Chemistry) which was developed in the 1970s. and CHEMCOM (Chemistry in the Community) which was developed in the 1980s. Similarly, an elementary school teacher might be expected to be knowledgeable about FSS (Elementary Science Study) and SCIIS (Science Curriculum Improvement Study) which were developed in the 1960s, and GEMS (Great Explorations in Math and Science) and Insights which were developed in the 1980s. Teachers' knowledge of curricula such as these would include knowledge of the general learning goals of the curriculum as well as the activities and materials to be used in meeting those goals.

Several studies that provide a picture of the general state of science education (e.g., Helgeson, Blosser & Howe, 1977; Stake & Easley, 1978; Weiss, 1978, 1987) have reported that the vast majority of teachers surveyed were not knowledgeable about nationally-funded curriculum projects relevant to their teaching. There is also evidence that teachers who are knowledgeable about programs may not agree with their learning goals and as a result may substantially modify them or reject important parts of materials (Cronin-Jones, 1991; Mitchener & Anderson, 1989; Welch, 1981). This finding provides some evidence of the issue of coherence with respect to the components of PCK, in this case the lack of coherence of teachers' orientations toward science teaching and the focus of the curricular materials.

#### *Knowledge of Students' Understanding of Science*

This component of pedagogical content knowledge refers to the knowledge teachers must have about students in order to help them develop specific scientific knowledge. It includes two categories of knowledge: requirements for learning specific science concepts, and areas of science that students find difficult.

#### *Knowledge of Requirements For Learning*

This category consists of teachers' knowledge and beliefs about prerequisite knowledge for learning specific scientific knowledge, as well as their understanding of variations in students' approaches to learning as they relate to the development of knowledge within specific topic areas. Teacher knowledge of prerequisite knowledge required for students to learn specific concepts includes knowledge of the abilities and skills that students might need. For example, if a teacher's goal is to help students learn about temperature by investigating phenomena undergoing thermodynamic changes, she must know how to help students develop the understandings and skills necessary to collect and interpret temperature data, such as reading a thermometer. Teachers' knowledge of variations in approaches to learning includes knowing how students of differing developmental or ability levels or different learning styles may vary in their approaches to learning as they relate to developing specific understandings. One illustration of this aspect of teacher pedagogical content knowledge concerns helping students to understand molecular-level phenomena in chemistry. A variety of representations can be used to illustrate

molecular structure; however, a particular representation may be more readily understood by some students than others. Some students may be able to envision a three-dimensional structure from a chemical formula whereas others require a drawing or model of the molecule. Effective teachers are aware of students' differing needs and can respond appropriately.

### *Knowledge of Areas of Student Difficulty*

This category refers to teachers' knowledge of the science concepts or topics that students find difficult to learn. There are several reasons why students find learning difficult in science, and teachers should be knowledgeable about each type of difficulty.

For some science topics, learning is difficult because the concepts are very abstract and/or they lack any connection to the students' common experiences (e.g., the mole, protein synthesis, quantum mechanics, cellular respiration). Teachers need to know which topics fall into this category and what aspects of these topics students find most inaccessible.

Other topics are difficult because instruction centers on problem solving and students do not know how to think effectively about problems and plan strategies to find solutions. In these cases, it is important for teachers to be knowledgeable about the kinds of errors that students commonly make, and the types of "real-world experiential knowledge" that they need to comprehend novel problems (Stevens & Collins, 1980). There has been a substantial amount of research examining problem solving within specific science topics (see Part III in Gabel, 1994); hence, there is substantial information to help teachers develop pedagogical content knowledge about students' difficulties with problem solving. With respect to the topic of motion, for example, an effective science teacher would know that students often have difficulty solving kinematics problems because they attend to surface features of the problems. Research has found, for example, that if a problem involves an inclined plane, it is common for students to think that certain equations are used to solve inclined plane problems and they search for the equations they previously used to solve problems involving inclined planes. They do not think to begin solving the problem by considering what underlying principles (e.g., conservation laws) might be applicable to a particular situation and should be used to set up the problem (Champagne, Klopfer, & Gunstone, 1982).

A third type of difficulty students encounter when learning science involves topic areas in which their prior knowledge is *contrary* to the targeted scientific concepts. Knowledge of this type is typically referred to as misconceptions,<sup>8</sup> and misconceptions are a common feature of science learning (e.g., Driver & Easley, 1978; Confrey, 1990; Wandersee, Mintzes, & Novak, 1994). Scientific concepts for which students have misconceptions can be difficult to learn because misconceptions are typically favored over scientific knowledge because they are sensible and coherent and have utility for the student in everyday life. In contrast, the targeted scientific concepts may seem incoherent and useless to the learner. Wandersee, Mintzes, & Novak (1994) caution that attributing students' lack of development of

scientific knowledge to interference from misconceptions is misleading in that there is evidence that misconceptions are not equally resistant to change. As a result they suggest that "it is important to differentiate between the concepts that might require high-powered conceptual change strategies and those that are equally likely to yield to well-planned conventional methods," (p. 186). Furthermore, others argue that the view of misconceptions as interfering agents that must be removed and replaced ignores the constructivist basis of learning (eg., Magnusson, Boyle, & Templin, 1994; Magnusson, Templin, & Boyle, 1997; Smith, DiSessa, & Roschelle, 1993). These researchers argue that misconceptions are the product of reasonable, personal sense-making, and that they can continue to evolve and change and result in desired scientific knowledge.

Regardless of one's view of the role of misconceptions in learning, this is student knowledge about which teachers should be knowledgeable with respect to the topics they teach because it will help them interpret students' actions and ideas. Numerous studies have documented students' misconceptions at various levels of schooling and in various scientific domains. The majority of studies have focused on physical science concepts, particularly in the area of physics; nevertheless, there is substantial information about students' misconceptions for many topics (Driver, Guesne, & Tiberghien, 1985; Driver, Squires, Rushworth, & Wood-Robinson, 1994; Pfundt and Duit, 1991). An example of desired pedagogical content knowledge with respect to students' understanding about motion is that students think that objects stay in motion because a force continually acts upon them and cease to move when no force is acting, and that this interpretation is a reasonable deduction from students' experiences in the friction-filled world in which we live. Other topics areas in which students have difficulty, and common misconceptions that lead to students' difficulties include the following: (a) light - *color is an intrinsic property of a substance* (Guesne, 1985), (b) lunar phases - *the phases of the moon are due to the shadow of the earth on the moon* (Keuthe, 1963), (c) nature of matter - *spaces between atoms or molecules of gas are filled with air* (Nussbaum, 1985), (d) plant nutrition - *plants get their food from the soil* (Bell, 1985), and (e) human systems - *a separate system from the circulatory system carries air to the heart and other structures in the body* (Arnaudin & Mintzes, 1985).

Research about science teachers' pedagogical content knowledge of students' understandings has not been widespread, but the studies that exist report similar findings and provide some indication of the knowledge that teachers typically have. One study, a survey of secondary school teachers, listed the 15 topics that biology, chemistry, physics, and earth science teachers rated as most as difficult for their students (Finley, Stewart, & Yarroch, 1982). The study did not provide information about why some topics were rated as more difficult than others, so it is not known whether the ratings indicated teachers' knowledge and concerns about students' misconceptions, their difficulties with problem solving, or other issues.

Other studies have directly assessed teachers' knowledge of students' understanding. The pattern of findings from this type of study is that although teachers have some knowledge about students' difficulties, they commonly lack important knowledge necessary to help students overcome those difficulties. For example, an

investigation of physics teachers' knowledge of students' understandings about force and gravity found that, as a group, the teachers identified nearly all of the common misconceptions that had been identified by the researchers; however, individually, they tended to be aware of only a few common misconceptions and were not aware of all of the misconceptions held by their own students. Moreover, one-third of the teachers (7 of 20) held common misconceptions themselves (Berg & Brouwer, 1991)! A study of elementary school teachers who participated in a project introducing them to conceptual change strategies for teaching about light similarly reported that students' misconceptions about which the teachers were not knowledgeable were ones that they themselves held (Smith & Neale, 1989).<sup>9</sup>

Research examining experienced middle school teachers' knowledge of students' understanding about temperature and heat energy also reported that teachers lacked crucial knowledge to promote student learning. This research was conducted as part of the University of Maryland's Middle School Probeware Project (UMMPP), a teacher enhancement project designed to help teachers use microcomputer-based laboratories for teaching about heat energy and temperature. At the beginning of the project, 92% (n=13) of the teachers who participated in the research exhibited misconceptions about heat energy and temperature (Krajcik & Layman, 1989). Of those who remained in the project for two years (n=8), half of them still exhibited some misconceptions. In addition, after two years in the project, teachers were not equally aware of the prevalence of errors in student reasoning about heat energy phenomena, and the explanations that they provided to account for students' reasoning errors differed (Magnusson, Borko, & Krajcik, 1994). This finding was considered important by the researchers because differences in the teachers' explanations implied differences in the instructional responses they would use to help students reason more accurately about heat energy phenomena. Furthermore, assessment of the *students'* knowledge indicated that only the teachers who thought that particular errors were uncommon had students who exhibited those reasoning errors after instruction in the topic area (Magnusson, Borko, Krajcik, & Layman, 1994; Magnusson, 1991). The researchers reasoned that this result may have been a consequence of the teachers' lack of pedagogical content knowledge because they were not aware of the likelihood of students' errors or the need to address them.

The UMMPP research, and that conducted by Smith and Neale (1989, 1991), both indicate that with appropriate in-service experiences, teachers can become more knowledgeable about common misconceptions. However, Smith and Neale reported that increased knowledge of students' understandings did not ensure that teachers could respond in appropriate ways when students exhibited misconceptions. They described that even though increased knowledge led the project teachers to pay more attention to their students' thinking than in their previous teaching, and even though some teachers exhibited some successful instances of recognizing and addressing students' misconceptions, in the majority of cases the teachers ignored students' misconceptions or struggled for ways to respond to them. Some undesirable responses by the teachers were to correct the misconception and supply a more detailed explanation rather than probing for the student's reasoning. From this

pattern of findings, Smith and Neale concluded that acquiring pedagogical content knowledge does not guarantee the ability to respond effectively during instruction. Their findings may also illustrate the independence of the components of pedagogical content knowledge in that changes in teachers' knowledge of one component may not be accompanied by changes in other components that are also required for effective teaching.

### *Knowledge of Assessment in Science*

We conceptualize this component of pedagogical content knowledge, which was originally proposed by Tamir (1988), as consisting of two categories: knowledge of the dimensions of science learning that are important to assess, and knowledge of the methods by which that learning can be assessed.

### *Knowledge of Dimensions of Science Learning to Assess*

This category refers to teachers' knowledge of the aspects of students' learning that are important to assess within a particular unit of study. In keeping with a major goal of school science, which is to produce a scientifically literate citizenry (Hurd, 1989), the dimensions upon which teacher knowledge in this category is based are those of scientific literacy. One example of a recent view of the possible dimensions of scientific literacy is the framework for the science component of the 1990 National Assessment of Educational Progress (NAEP). It identifies conceptual understanding, interdisciplinary themes, nature of science, scientific investigation, and practical reasoning as important dimensions of science learning to assess (Champagne, 1989). At this time of continuing national-level development of perspectives regarding science teaching and learning \_ such as exemplified by the national science education standards (National Research Council, 1994)\_ we do not describe a particular framework of scientific literacy to define teacher knowledge relative to this category. Rather, we simply argue is that it is important for teachers to be knowledgeable about some conceptualization of scientific literacy to inform their decision-making relative to classroom assessment of science learning for specific topics.

Whatever the dimensions of scientific literacy, it is likely that some dimensions will be more easily addressed than others for a particular topic of study and, hence, might be considered important to consider in planning and enacting teaching on that topic. Thus, effective teachers should know what dimensions or aspect of a dimension of scientific literacy should be assessed in a particular unit. As an example, it is more difficult to empirically investigate the solar system than weather. As a result, an effective teacher would plan to assess students' understandings regarding the planning and conduct of empirical investigations during the study of weather by having them actually carry out such investigations, and she would plan to utilize a different method of assessment during the study of the solar

system. This illustration brings us to the other category of teacher knowledge of assessment: knowledge of methods of assessment.

### *KnowLedge of Methods of Aesement*

This category of pedagogical content knowledge refers to teachers' knowledge of the ways that might be employed to assess the specific aspects of student learning that are important to a particular unit of study. There are a number of methods of assessment, some of which are more appropriate for assessing some aspects of student learning than others. For example, students' conceptual understanding may be adequately assessed by written tests whereas their understanding of scientific investigation may require assessment through a laboratory practical examination (e.g., Lunetta, Hofstein, & Giddings, 1981; Tamir, 1974) or laboratory notebook.

Considerable attention is being given to assessment within the science education community at this time, including attention to changing assessment practices and the development of new methods such as performance-based assessments and portfolios (e.g., Duschl & Gitomer, 1991; Kulm & Malcom, 1991). These methods highlight that student-generated products provide important opportunities for assessment. whether evaluated at the end of a unit of study or during the course of study. Examples of *student-generated products* that have been used to assess student learning include journal entries, written laboratory reports, and artifacts such as drawings, working models, or multi-media documents (see appendix in Kulm & Malcom, 1991).

Teachers' knowledge of methods of assessment includes knowledge of specific instruments or procedures, approaches or activities that can be used during a particular unit of study to assess important dimensions of science learning, as well as the advantages and disadvantages associated with employing a particular assessment device or technique. Research examining science teachers' use of assessment indicates that teachers at all levels of schooling largely depend upon teacher-constructed or curriculum-embedded objective tests that evaluate the conceptual understanding dimension of scientific literacy (Doran, Lawrenz, Helgeson, 1994). These findings do not indicate whether that practice results from a lack of knowledge of other methods, a lack of knowledge of the need to evaluate other dimensions of scientific literacy, or other issues. As efforts to define scientific literacy at all grade levels continue, and as new instruments and procedures continue to be developed and become more prominent in this "decade of reform in student assessment" in science education (Tamir, 1993, p. 535), pedagogical content knowledge in this area is likely to change substantially over the next 10 years.

### *Knowledge of Instructional Strategies*

Teachers' knowledge of the instructional strategies component of pedagogical content knowledge is comprised of two categories: knowledge of *subject-specific*

strategies, and knowledge of *topic*-specific strategies. Strategies in these categories differ with respect to their scope. Subject-specific strategies are broadly applicable; they are specific to teaching *science* as opposed to other subjects. Topic-specific strategies are much narrower in scope; they apply to teaching particular *topics* within a domain of science.

### *Knowledge of Subject-specific Strategies*

Strategies included in this category represent general approaches to or overall schemes for enacting science instruction. Teachers' knowledge of subject-specific strategies is related to the "orientations to teaching science" component of pedagogical content knowledge in that there are general approaches to science instruction that are consistent with the goals of particular orientations.

A number of subject-specific strategies have been developed in science education, many of them consisting of a three- or four-phase instructional sequence. Perhaps the best known of the subject-specific strategies is the "learning cycle," a three-phase instructional strategy consisting of *exploration*, *term introduction*, and *concept application* (Karplus & Thier, 1967; Lawson, Abraham, & Renner, 1989). The learning cycle has been used for discovery and inquiry-oriented instruction, as well as conceptual change-oriented instruction (see Tobin, Tippins, & Gallard, 1994, pp. 76-79). Strategies that have been developed more recently (e& the Generative Learning Model, conceptual change strategies, Guided Inquiry) have typically added phases designed to support conceptual change, such as eliciting students' pre-instructional conceptions (e& Osborne & Freyberg, 1985), presenting anomalous data to create cognitive conflict (e.g., Nussbaum & Novick, 1982), distinguishing between real world patterns that can be "discovered" and explanations for them that must be invented (e.g., Magnusson & Palinesar, 1995), emphasizing public presentation and discussion of patterns and explanations (ibid), or scaffolding student debate about the adequacy of alternative explanations (e.g., Anderson & Smith, 1987). Teachers' knowledge of subject-specific strategies for science teaching consists of the ability to describe and demonstrate a strategy and its phases.

We surmise, based on the fact that there is a substantial body of research literature describing efforts to help teachers become knowledgeable about such strategies (see reviews by Anderson & Mitchener, 1994; Tobin, Tippins, & Gallard, 1994), that teacher knowledge of strategies for teaching science is limited. Supporting that assertion is evidence from studies examining the impact of the inquiry-based science curriculum development in the 1960s and 1970s, which reported that teachers perceived themselves as ill-prepared to teach inquiry-oriented instruction (e.g., Helgeson, Blosser, & Howe, 1977; Stake & Easley, 1978; Weiss, 1978).

Research focused on teachers who participated in program to help them adopt new strategies for teaching science provides evidence that a teacher's ability to use a subject-specific strategy may be dependent upon knowledge from other domains. Anderson and Smith (1987) described instances of teachers changing from "didactic or discovery teaching to the use of conceptual change teaching strategies" without



any explicit instruction in the new strategies that they were observed using (p. 104). The teachers attributed their change to increased knowledge of subject matter and the understandings of their students (one component of pedagogical content knowledge). In a similar vein, a lack of subject matter knowledge (e.g., Smith & Neale, 1989) and a lack of pedagogical knowledge (Marek, Eubanks, & Gallaher, 1990) have both been linked to the ineffective use of subject-specific strategies, suggesting that the development of pedagogical content knowledge relative to this component requires drawing upon knowledge from each of the three base domains of teacher knowledge: subject matter, pedagogy, and context.

There is also evidence that teachers' use of strategies is influenced by their beliefs. Research has documented that some teachers resisted changing their practices to match those of an innovative approach because their beliefs differed from the premises of the new approach (Cronin-Jones, 1991; Mitchener & Anderson, 1989; Olson, 1981). Interestingly, a common area of difference in each of these studies concerned beliefs about the teacher's role, which is a dimension of teaching that several components of pedagogical content knowledge would impact. We think these findings indicate that the transformation of general knowledge into pedagogical content knowledge is not a straightforward matter of having knowledge; it is also an intentional act in which teachers choose to reconstruct their understanding to fit a situation. Thus, the content of a teacher's pedagogical content knowledge may reflect a selection of knowledge from the base domains.

### *Knowledge of Topic-specific Strategies*

This category of pedagogical content knowledge refers to teachers' knowledge of specific strategies that are useful for helping students comprehend specific science concepts. There are two categories of this type of knowledge—representations and activities. Although they are not mutually exclusive (e.g., specific activities may involve particular representations of a concept or relationship) it is conceptually useful to consider them as distinct categories.

*Topic-specific representations.* This category refers to teachers' knowledge of ways to represent specific concepts or principles in order to facilitate student learning, as well as knowledge of the relative strengths and weaknesses of particular representations. We also include in this category a teacher's ability to invent representations to aid students in developing understanding of specific concepts or relationships.

Representations can be illustrations, examples, models, or analogies. Using an example from electricity, there are multiple analogies for representing the concept of an electric circuit: water flowing through pipes in a closed system with a pump, a bicycle chain or a train, or "teeming crowds" (Hewitt, 1993). Each analogy has conceptual advantages and disadvantages with respect to the others. For example, the popular water flow model reinforces a source-receiver model of electricity and implies that electrons move rapidly in the same direction; a bicycle chain model similarly implies that electrons move in the same direction but does not suggest a source-receiver model; and teeming crowds make it possible to conceive of electron

flow in an electric circuit as occurring slowly and randomly, albeit drifting in a common direction. The water flow and teeming crowds models offer one representation of resistance (narrowing in the pipe through which the water is flowing or in an opening through which the crowd has to pass), whereas a bicycle chain model is limited in representing resistance.

An effective teacher must judge whether and when a representation will be useful to support and extend the comprehension of students in a particular teaching situation. An example of the pedagogical content knowledge of one teacher in this respect is presented by Berg and Brouwer (1991). They discuss the teaching of a physics teacher who stated that his most powerful strategy for helping students believe that the path of an object in circular motion (e.g., a ball on a string being whirled about one's head) will become a straight line if the force exerted perpendicular to the motion of the ball is removed (the string is cut), is an anecdote about his personal experience on a merry-go-round. The teacher's anecdote relates how he was riding on the edge of the merry-go-round and when he let go, to his surprise he landed in a bush that he had seen straight in front of him when he let go. In the teacher's words, "it's only anecdotal, but it seems to convince students better than a demo or doing the mathematical derivation." (p. 15)

In the research of which we are aware, teachers generally have not been asked directly about the representations they use in science teaching; rather, information about teachers' knowledge has been inferred from their practice. For example, from examination of teachers' use of analogies, Dagher & Cossinan (1992) described 10 types of analogies used by teachers for the purpose of explaining science concepts, and they reported substantial variations in the number and variety of explanations given by the teachers they studied ( $n=20$ ). They did not discuss the strengths or limitations of any particular explanations used by the teachers they studied, but they did report that 25% of the statements identified as explanations were scientifically inaccurate, and that 25% of the teachers in their sample utilized such explanations.

Some researchers have reported that limited knowledge of topic-specific representations can negatively impact science instruction. Sanders and colleagues intensively studied three secondary science teachers and reported that teachers had difficulty sustaining momentum in a lesson, sometimes confusing themselves and their students when they struggled to respond to student questions requiring more detailed or different representations (Sanders, Borko, & Lockard, 1993). These findings led to the conclusion that this type of pedagogical content knowledge may be particularly dependent on subject matter knowledge because the participating teachers were more likely to exhibit these problems when teaching outside of their area of expertise. This conclusion is not unexpected given the nature of this category: knowing or inventing representations of science concepts to help students comprehend them seems necessarily dependent upon having subject matter knowledge relative to the concepts.

Despite this claim of the dependence of the development of this aspect of pedagogical content knowledge on subject matter knowledge, we caution against an inference that teachers will necessarily develop desired pedagogical content knowledge if they have sufficient subject matter knowledge. In other words, having

subject matter knowledge does not guarantee that it will become transformed into representations that will help students comprehend targeted concepts or that teachers will be adept at deciding when it is pedagogically best to use particular representations. For example, Linn and colleagues describe a heat flow model that they advocate for use to help middle school students understanding thermodynamic phenomena. This model is similar to the caloric theory popular in the mid-1800s, but it includes the provision that heat energy does not have mass. From a scientific perspective, this model is inaccurate because it implies that heat energy is contained in a body; however, they argue that it is more appropriate to use than other models (such as kinetic molecular theory) because it supports accurate qualitative reasoning (Linn & Songer, 1991). In teacher knowledge terms, this model is important pedagogical content knowledge for teaching thermodynamics, but because it is scientifically inaccurate, those with subject matter expertise in this topic area would not likely have this knowledge or know of its pedagogical utility.

In contrast to Linn and Songer, Arons (1991) stresses that (for college students) heat energy should never be referred to as though it is contained in a body, “even in the early stages of development of the concept” because it “raises severe impediments to clear formation of the concept of conservation of energy. even at an elementary level” (p. 120-121). Arons’ contradictory recommendation, compared to Linn and colleagues, illustrates the situation-specific nature of pedagogical content knowledge: Arons’ recommendation concerns the teaching of college students rather than middle school students.

*Topic-specific activities.* This category refers to knowledge of the *activities* that can be used to help students comprehend specific concepts or relationships; for example, problems, demonstrations, simulations, investigations, or experiments. Pedagogical content knowledge of this type also includes teachers’ knowledge of the conceptual power of a particular activity; that is, the extent to which an activity presents, signals, or clarifies important information about a specific concept or relationship. Consider, for example, the question of how to decide what activities to use with middle school students to help them understand the distinction between temperature and heat energy. Important tools that students can use to investigate thermodynamic phenomena include two microcomputer-based devices: a temperature probe and a heat pulser.<sup>10</sup> A heat pulser makes it possible to “control” the amount of heat energy transferred into a system, allowing students to transfer measurable quantities of heat energy in the form of “pulses” that they can count. A temperature probe can record temperature data which can be graphically presented on a computer monitor as it is collected. Used together, students can examine the temperature history” at particular places in a system as heat energy is transferred into and out of it. With this technology, one possible activity that can help students understand the distinction between heat energy and temperature is to have them determine the amount of energy it takes to raise the temperature of two quantities of water by the same amount. By counting the “pulses” of heat energy, students can determine that it takes much more energy to raise the temperature of a large volume of water the same amount as a small volume. Because the temperature change for both volumes is the same but the amount of heat energy transferred is different, this

activity clearly signals that heat is a different entity than temperature, which is contrary to the thinking of many students.

One finding from research about teacher knowledge of topic-specific activities is that it more likely for a teacher who has taught a particular subject for a long period of time to have knowledge of this type than it is for a novice to have such knowledge. Clermont and colleagues, for example, compared the knowledge of experienced and novice teachers of chemistry. They reported that the experienced teachers knew more variations of a demonstration for teaching specific chemistry concepts than did novice teachers (Clermont, Borko, & Krajcik, 1994). The experienced teachers were also better at detecting errors and misleading statements when shown someone conducting a typical demonstration for a specific chemistry concept. And, they were more cognizant of the complexity of a demonstration and could suggest ways to make it simpler in order to aid student understanding.

On the other hand, being an experienced teacher does not guarantee that one will know conceptually strong or powerful activities. Findings from the UMMP Project indicated that at the end of the project, teachers differed markedly in their knowledge of activities that were conceptually strong for helping students understand the distinction between heat energy and temperature (Magnusson, Borko, & Krajcik, 1994). This was true despite the fact that many of the teachers taught the same curriculum. Similar findings were reported by Berg and Brouwer (1991) with respect to physics teachers' knowledge of activities that could help students develop desired understandings when they had misconceptions about force and gravity.

Research has shown that teachers' knowledge of topic-specific strategies can increase as a result of involvement in teacher enhancement programs. This was true for the teachers in the UMMP Project and for the novice teachers studied by Clermont and colleagues. Teachers who participated in the UMMP Project typically began with little knowledge of activities for helping students understand the distinction between heat energy and temperature because those concepts had not been prominent in their teaching. Their knowledge increased substantially over the two-year course of the project (Krajcik, Layman, Starr, & Magnusson, 1991). In the study by Clermont and colleagues, increased knowledge was reported for the novice teachers even though their experience lasted only two-weeks (Clermont, Krajcik, & Borko, 1993). They credited the intensity and specific focus of the workshop for its success, but also cautioned that the increased knowledge occurred for only one of the many topics that chemistry teachers commonly address in their teaching.

Smith and Neale (1991) also reported that the elementary school teachers who participated in their four-week summer institute increased their knowledge of activities for teaching about light; however, they also noted that differences occurred among the teachers and that those differences were related to differences in the teachers' subject matter knowledge. For example, only the teacher with strong subject matter knowledge was able to conceive of activities to do with students that were different from those used as part of the summer institute. This dependence upon subject matter knowledge was also described in studies by Hashweh (1987), and Sanders, Borko, and Lockard (1993), both of which investigated teachers in teaching situations within and outside of their areas of expertise.

Hashweh reported that when teachers were knowledgeable in a content area they were able to modify activities included in reference materials and eliminate ones they judged to be tangential to the targeted conceptual understandings. He also reported that teachers with strong content knowledge could devise student activities or demonstrations not mentioned in the references whereas those who were not knowledgeable could not do so. Sanders and colleagues reported that teachers teaching outside of their area of expertise had difficulty making important judgments about activities described in resource materials, such as judging whether an activity or demonstration would work.

These findings suggest that developing this aspect of pedagogical content knowledge may also be dependent upon subject matter knowledge. As with a similar conclusion regarding the “representations” category of the topic-specific strategy component of pedagogical content knowledge, this result is not surprising, partly because it is natural for teachers to use their own experiences learning science to develop or revise activities for their teaching. Again, however, we caution against the inference that sufficient subject matter knowledge is all that is needed for the development of desired knowledge of this aspect of pedagogical content knowledge. Indeed, some research has demonstrated the lack of validity of that conclusion. In a study of middle school teachers, Hollon, Roth, and Anderson (1991) found that, despite their superior subject matter knowledge, some teachers were not able to effectively use that knowledge to help their students develop scientific knowledge.

### *Summary*

The representation of pedagogical content knowledge shown in Figure 2 signals two important ideas about pedagogical content knowledge. First, the individual components that are shown indicate that there are different types of subject-specific pedagogical knowledge that are used in teaching science. Within each component, teachers have specific knowledge differentiated by topic, although they might not have similarly elaborated knowledge in each topic area. Effective teachers need to develop knowledge with respect to all of the aspects of pedagogical content knowledge, and with respect to all of the topics they teach. Second, by designating these components as part of a single construct - pedagogical content knowledge - we indicate that the components function as parts of a whole. As a result, lack of coherence between components can be problematic in developing and using pedagogical content knowledge, and increased knowledge of a single component may not be sufficient to effect change in practice. Thus, because the components may interact in highly complex ways, a teacher's knowledge of a particular component may not be predictive of her teaching practice, and, while it is useful to understand the particular components of pedagogical knowledge, it is also important to understand how they interact and how their interaction influences teaching.

## THEORETICAL CONSIDERATIONS

Some scholars argue that pedagogical content knowledge is not sufficiently distinct from other types of knowledge to warrant its identification as a separate domain (e.g., Carlsen, 1991b). We consider the question of whether it is or is not a unique domain of knowledge to be a matter of definition that is a function of how one chooses to carve up the knowledge bases of teaching. There is no one right way to do this. A critical consideration in this debate is what we gain and lose in understanding teaching by defining pedagogical content knowledge as a separate construct. Does the construct of pedagogical content knowledge help the teacher educator plan and implement pre-service and in-service preparation programs? Does it help the teacher develop into a more competent teacher? Does the construct of pedagogical content knowledge help the researcher understand teaching and define pedagogical expertise?

*The Value of Pedagogical Content Knowledge as a Construct*

Our position is that there is value, both conceptually and practically, in defining pedagogical content knowledge as a separate domain of knowledge for teaching. Conceptually, we see the construct of pedagogical content knowledge as useful for two reasons. First, its conceptualization as knowledge that results from a transformation of other domains of knowledge signals that it is more than the sum of its parts, more than simply fitting together bits of knowledge from different domains. Second, because this knowledge is conceptualized as being constructed through the processes of planning, reflection, and teaching specific subject matter, it represents knowledge that is “uniquely the province of teachers, their own special form of professional understanding” (Shulman, 1987, p. 8). As such, this construct represents an important tool for defining what it means to be a competent or expert science teacher.

The practical value of pedagogical content knowledge as a construct has to do with its potential to define important dimensions of expertise in science teaching that can guide the focus and design of pre-service and in-service teacher education programs. Many science teachers and science teacher educators have a wealth of knowledge about how to help particular students understand ideas such as force, photosynthesis, or heat energy; they know the best analogies to use, the best demonstrations to include, and the best activities in which to involve students. Our identification of this knowledge as pedagogical content knowledge recognizes its importance as distinguished from subject matter or pedagogical knowledge. Further, our conceptualization of the components of pedagogical content knowledge provides an important conceptual tool for helping teachers of science construct the specific knowledge they need to be effective teachers.

We find it interesting that content specialists and generalists in education seldom consider pedagogical content knowledge to be sufficiently different from their domains of expertise to be important to discuss. A question to pose in considering

that position is whether we have evidence to the contrary. Generalists in education typically address issues that are important to learning regardless of subject matter. Is that sufficient for effective teaching? Research cited earlier in the chapter suggests otherwise. Content specialists typically focus on the extent to which a particular topic is accurately and completely represented. Is that sufficient to help others understand? Again, results cited earlier provide a contrary picture. As an additional example, Bellany (1990) reported that knowledgeable high school teachers were not equally effective in helping their students understand genetics. In particular, she described assessments of the students of teachers who taught different techniques for solving genetics problems. One teacher believed that students should solve genetics problems in the same way that geneticists would. As a consequence, he emphasized the probability method for finding genotypes and de-emphasized use of the Punnett square. His students were not as successful at solving genetics problems as were students of other teachers who used the Punnett square. In addition, some of the teachers using the Punnett square provided visual connections with the underlying biology, and their students were better able to answer genetics questions concerning the process of meiosis.

This and previous examples provide evidence that the domain of pedagogical content knowledge lies outside the expert knowledge of the typical content specialist and the general educator. To ensure that pedagogical content knowledge will receive the attention it warrants in facilitating the development of effective teachers of science, we argue that it is important to designate it as a unique domain within the professional knowledge base. In the final sections of this chapter we describe the implications of pedagogical content knowledge for the design and implementation of teacher education programs that are likely to support and facilitate the development of effective science teachers.

Finally, although we argue for the value of defining pedagogical content knowledge as a separate construct, we do not claim that there are clear distinctions between pedagogical content knowledge and other knowledge domains used in teaching (e.g., subject matter knowledge, general pedagogical knowledge). Rather, the boundaries that exist between domains are “fuzzy” (Marks, 1990). In part, this is due to the fact that pedagogical content knowledge represents an integrated knowledge system, but equally important is the recognition that the distinctions between domains are necessarily arbitrary and ambiguous. Bearing that in mind, we now describe our thinking about how pedagogical content knowledge develops.

#### *A Model of Pedagogical Content Knowledge Development*

There are many ways to think about the interaction of the domains of knowledge in the development of pedagogical content knowledge. Figure 1 is one possible model. In that figure, the lines stemming from the major domains of knowledge (shaded figures) indicate that each knowledge base influences the development of pedagogical content knowledge. We find this model to be useful in depicting the general influence of the domains of knowledge upon one another, but we raise the possibil-

ity that the domains of knowledge may unequally influence the development of pedagogical content knowledge due to differences in the amount of knowledge in each domain. We depict such a situation in Figure 3. In this figure, the amount of knowledge in a domain is indicated by the size of the box representing it, and the thickness of the lines linking the domains indicate their relative influence upon one another. In the case of Teacher A, the figure indicates that this teacher has substantially more subject matter knowledge than the two other types of knowledge that are key to effective teaching. As a result, we hypothesize that the development of her pedagogical content knowledge is influenced primarily by her knowledge of subject matter. In contrast, for Teacher B for whom pedagogical knowledge is dominant, we hypothesize that the transformation of her knowledge into pedagogical content knowledge will be influenced mostly by the nature of her pedagogical knowledge. These differences may mean that if these teachers taught the same topics in the same educational context they would develop different pedagogical content knowledge, but we would expect there to be significant overlap in the knowledge developed by each. Thus, we argue that there are different routes or multiple pathways to developing pedagogical content knowledge for specific topics.

change the problem to that shown in Part B of the figure if she were to give it to her eighth grade students. This version of the problem would be more meaningful to them, and could therefore help them to persist until they reach a solution. Furthermore, her knowledge of subject matter and pedagogy indicates to her that she should change the problem even further to the version shown in Part C because the questions in that version will prompt her students to think in ways that are beneficial for developing scientific knowledge. The questions that are listed serve to signal to students the thinking that they need to do to fully respond to the problem. This transformation from what appears in Part A of the figure illustrates how a teacher might develop pedagogical content knowledge by drawing upon knowledge of subject matter, pedagogy, and context.

Once the teacher has established an appropriate problem, what kinds of experiences should she provide to students to prepare them to solve the problem? A teacher developing pedagogical content knowledge might go through the following thinking process. Let's assume our hypothetical teacher knows that one possible activity to use is to have students set up the situation in the problem and observe what happens. One weakness of the activity represented in Part C of Figure 4, however, is that the phenomenon does not clearly signal that heat energy and temperature are different entities because the change in those quantities is in the same direction (temperature is decreasing and so is the amount of energy in the system as it is transferred in the form of heat). In addition, the difference in the amount of time to cool does not necessarily indicate to students that there is a difference in the amount of energy transferred because some students attribute that difference to be a function of the "ease" with which heat energy can "escape" (Magnusson, 1993). Assuming our teacher was knowledgeable about these weaknesses, she might conclude that this activity is not sufficiently powerful to warrant its use. She considers, however, that the power of the activity could be increased by adding a requirement that students calculate the relative amount of



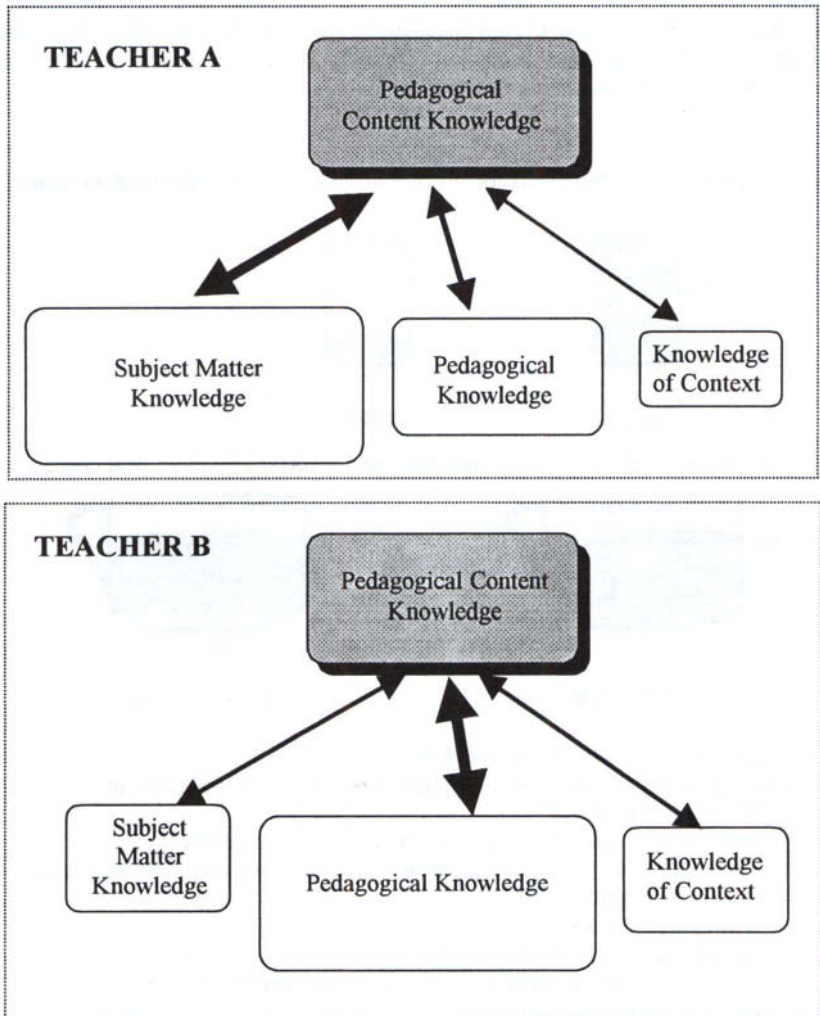
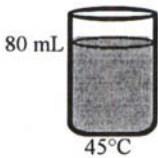


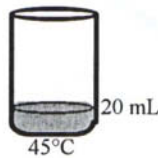
Figure 3. A model illustrating differential influences of the development of PCK for two hypothetical teachers.

heat energy transferred from each cup, but she may also be concerned that this change may not be sufficient to ensure that all of the students will understand the distinction between heat energy and temperature. Knowing about the heat pulser, our teacher might develop the idea that she could have her students create the situation shown in Part C of Figure 4 by using the heat pulser and determining how many pulses it takes to raise the hot chocolate to the desired temperature. Thus, she decides that during the class discussion of how to test their explanations, she will guide students to consider using this strategy.

A) Upon cooling, will these beakers of water lose the same or a different amount of heat energy ?

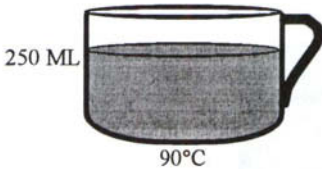


Beaker A

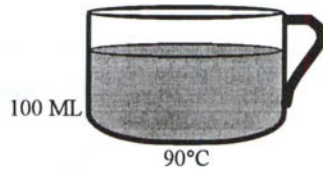


Beaker B

B) Upon cooling, will one of these students' hot chocolate lose more heat energy?



Ramona's Cup



Lekeisha's Cup

C) Cooling Hot Chocolate [with same diagram as B above]

1. Do you think one of these cups of hot chocolate takes longer to cool?  
Why do you think so?  
Describe how you could find out, and check your prediction.
2. After cooling, do you think the amount of heat energy they have lost is the same or different?  
Why do you think so?  
Describe how you could find out, and check your prediction.
3. Provide an explanation that would account for your predictions.
4. Test your predictions and revise your explanation as needed to account for your observations.

Figure 4. Contexts for developing scientific knowledge about the relationship between temperature and heat energy.

This example illustrates the specificity and non-linearity of the thinking that leads to the development of pedagogical content knowledge. It is not necessarily common for teachers to go through the process just described. Further, even if they do, they may not end up with knowing the most powerful strategies for helping students develop desired understandings. In addition, because this type of knowledge is so specific, teachers must develop it for each topic of study they teach. These issues underscore the need for programs to help and support teachers in the development of pedagogical content knowledge.

### IMPLICATIONS FOR TEACHER EDUCATION

In this final section of the chapter we address implications of theory and research on pedagogical content knowledge for teacher education. We begin by setting teacher education efforts in the context of today's reform movement in science education. We then focus on four sets of recommendations for helping teachers learn to teach in new ways:

1. helping teachers examine their pre-existing knowledge and beliefs;
2. addressing the relationship between subject matter knowledge and pedagogical content knowledge;
3. situating learning experiences for teachers in meaningful contexts; and
4. using a model of components of pedagogical content knowledge to guide learning-to-teach experiences.

#### *Science Education Reform*

Current reform rhetoric in science education is asking teachers to teach science in a way that is, for many, fundamentally different from how they were taught. The constructivist views of knowledge and learning upon which the reform recommendations are based differ markedly from the behaviorist view that was dominant when many teachers were prepared and socialized into teaching. Furthermore, for many teachers (both novice and experienced), approaches to teaching science based on constructivist views of knowledge and learning differ from their existing orientations to teaching science and beliefs about science learning and teaching. Given what we know about the role of knowledge and beliefs in teaching and learning to teach, this difference has significant implications for science teacher education—both pre-service and in-service. Moreover, because pedagogical content knowledge results from a transformation of knowledge from other domains, the incompatibility of existing knowledge and beliefs in those domains, with desired knowledge and beliefs, necessarily limits the development of desired pedagogical content knowledge.

*Addressing Pre-existing Knowledge and Beliefs*

Teachers' knowledge and beliefs serve as filters through which they come to understand the components of pedagogical content knowledge. These understandings, in turn determine how specific components of pedagogical content knowledge are utilized in classroom teaching. Just as students' existing knowledge and beliefs serve as the starting point for their learning, teachers' knowledge and beliefs are important resources and constraints on change. Because of the mismatch between the knowledge and beliefs of many teachers and those required to meet the vision of current reform, efforts to help teachers make significant changes in their teaching (e.g., to incorporate new science curricula, instructional strategies and representations into their science teaching) must help them to acquire new knowledge and beliefs (e.g., new conceptions of science teaching). In these situations, the same knowledge and beliefs that function as filters through which change takes place are also critical targets of change. Programs that hope to help novice and experienced teachers think and teach in new ways must challenge their pre-existing beliefs (Cohen & Ball, 1990; Borko & Putnam, 1996).

For example, constructivist models of learning suggest that students can benefit from planning, conducting, and determining their own conclusions from investigations. Guided Inquiry — an attempt to instantiate sociocultural and constructivist theory in classrooms — expects that students will be involved in just such activity, in a collaborative manner as part of a learning community, with the goal of understanding a particular problem or issue using tools reflective of the scientific community. The teacher's role in this type of teaching is very different from that derived from a behaviorist model in which teaching is viewed as transmitting information, and different yet again from cognitive constructivist notions that mainly consider learning from an individual perspective. Teachers must change their underlying assumptions about teaching and learning in order to successfully enact such instruction, but even in cases of teachers having compatible views, it takes time to build and transform the knowledge required to enact instruction as complex and sophisticated as Guided Inquiry (e.g., Magnusson & Palinesar, 1995).

To address this issue, just as it is important for teachers to understand students' conceptions and alternative conceptions in science, it is important for teacher educators to understand teachers' conceptions and alternative conceptions about the teaching of science. That knowledge is critical to building and conducting programs that facilitate the change process. Further, just as it is important for teachers to facilitate conceptual development by providing opportunities for their students to examine, elaborate, and integrate new concepts into their existing conceptual frameworks, teacher educators must provide opportunities for teachers to examine, elaborate, and integrate new knowledge and beliefs about teaching and learning science into their existing systems of knowledge and beliefs. This goal can be addressed through activities such as observing, analyzing, and reflecting upon one's own or another's teaching. Some teacher educators are exploring the use of multimedia technology for facilitating this type of activity. For example, Lampert and Ball (1990) have created a multimedia program from which users can inquire about

teaching by accessing video images of a lesson accompanied by linked information providing the teacher's reflection on the lesson, entries from student journals, and a timeline showing the lessons that proceeded and followed it. Soloway and his colleagues have developed a multimedia tool, structured around video-based teacher cases accompanied by teacher and researcher written and oral commentary, to promote teachers' understanding of project-based science by illustrating instructional possibilities, features, and strategies (Soloway, Krajcik, Blumenfeld, & Max, 1993).

### *Subject Matter Knowledge and Pedagogical Content Knowledge*

In addition to concerns regarding the role of knowledge and beliefs in the development of expertise in science teaching, research evidence that suggests the dependence of subject matter knowledge on the development of pedagogical content knowledge warrants specific attention to teachers' subject matter knowledge. Whereas there is evidence that subject matter knowledge is not sufficient to insure effective teaching or subject matter, some critical amount of subject matter knowledge seems to be necessary to develop the pedagogical content knowledge required to meet current reform recommendations. This circumstance is of particular concern with respect to elementary school teachers because they typically have substantially less subject matter knowledge than persons who teach at higher levels of schooling. However, it is also relevant to middle or high school teachers whose subject matter preparation may be narrow with respect to the topics they are required to teach (e.g., Carlsen, 1993). Just as we now expect students to be able to use their knowledge to explain real world phenomena, teachers must be able to do that as well, and their subject matter preparation may not have adequately prepared them for the task. Many teachers may not have had opportunities to formulate questions from observing real world phenomena, develop investigations to answer their questions, or construct explanations from the data produced by those investigations. Such experiences will help them develop the subject matter knowledge needed for developing desired pedagogical content knowledge.

At the pre-service level, program features consistent with this view include pairing or combining science content courses with science methods courses focused on teaching the same content. These features are characteristic of elementary and middle school science teacher preparation programs at some universities (Rubba, Campbell, & Dana, 1993; Stake et al., 1993). For example, in *Integrating Knowledge Bases: An Upper - Elementary Teacher Preparation Program Emphasizing The Teaching of Science*, Krajcik and his colleagues developed an elementary teacher preparation program that featured an integration of the subject matter and professional education coursework with clinical experiences that provided a context for learning about and practicing science teaching (Krajcik, Blumenfeld, Starr, Palinsar, & Coppola, 1993).

At the in-service level, the influence of subject matter on the development of pedagogical content knowledge means that programs that only address pedagogy

may not provide enough information for teachers to develop effective practices. Further, programs that strictly focus on subject matter are not likely to be as effective as those in which subject matter and subject-specific pedagogy are both addressed.

Another concern arises from the fact that most programs that focus on subject matter along with subject-specific pedagogy can only address a few of the topics teachers are responsible for teaching. Given that teachers' experiences within one topic area may not be sufficient to support them in engaging in desired practices within other topic areas, we must develop ways for teachers and teacher educators to share subject-specific information for teaching science as a support for teachers in extending their new understandings and practices to topic areas beyond those which might have been the focus of particular teacher education programs. The increasing availability of telecommunications in the schools provides one possible strategy for addressing this need. For example, teachers could email one another to share ideas and experiences while teaching similar topics. An electronic database could be formed and indexed so that teachers could easily access a range of representations or activities used by others to facilitate student learning.

#### *Situating Teachers' Learning Experiences in Meaningful Contexts*

Another set of suggestions, strongly supported by research on learning to teach, relates to the importance of situating learning-to-teach experiences in meaningful contexts (Borko & Putnam, 1996). One aspect of this recommendation is that we provide opportunities for teachers to experience, as learners, the instruction they are being prepared to conduct. If teachers are to be successful in creating classroom environments in which science subject matter and learners are treated in new ways, they must experience such learning environments themselves. For example, if science teachers are to support their students in constructing and evaluating their own explanations, then the teachers must participate in similar activities. Similarly, if teachers are to support student learning through the use of technology such as the heat pulser, then they must have learning experiences with technology. Simply telling teachers that they should have their students construct and evaluate explanations or use technology in problem solving activities, does not provide sufficient information or support to enable them to successfully put those ideas into practice.

A second aspect of this recommendation is that teachers must have the opportunity to learn about new instructional strategies and ideas in meaningful and supportive contexts. Meaningful contexts are actual classroom situations. Supportive contexts are ones in which teachers are scaffolded as they take on the challenge of developing new practices. At the pre-service level, teacher education programs should incorporate a substantial classroom-based component in which students have meaningful teaching opportunities. Further, pre-service teachers should be expected to critically reflect upon their teaching, and they should receive support and careful feedback from others who are more experienced and knowledgeable, to aid them in that process. At the in-service level, teachers should have the opportunity to receive

support and feedback from school district staff personnel, university teacher educators and other teachers as they attempt to incorporate new instructional representations and activities into their ongoing classroom practices.

One model of this type of experience is described by Krajcik, Blumenfeld, Marx, and Soloway (1994). It consists of repeating cycles of collaboration, enactment, and reflection. The collaboration occurs through worksessions in which teachers and researchers inform, critique, and support one another. Enactment involves the planning and carrying out of new practices. Finally, reflection involves such activities as writing journals of one's experience and viewing videotape of one's teaching. The knowledge that teachers gain through these types of multi-faceted experiences that acknowledge the complexity and ambiguity of classroom teaching is likely to be accessible and flexible enough to result in future successful teaching experiences and desired student outcomes. In contrast, although intensive out-of-classroom experiences such as university-based methods courses for pre-service teachers and summer institutes for experienced teachers may have an important role to play in teachers' learning, their benefits are unlikely to be realized without complementary classroom-based opportunities. Without integrated experiences, teachers are unlikely to make meaningful or long-term changes in their instructional practices.

We must also recognize that change takes time, and that facilitating change that encompasses beliefs as well as practices can take years. Teachers and teacher educators should consider programs that provide support and encourage critical reflection over a period of years. Models such as Professional Development Schools (Holmes Group, 1990), in which universities and schools collaborate over extended periods of time are examples of such programs.

#### *Guidance Provided by a Model of the Components of PCK*

Our last set of suggestions is specific to pedagogical content knowledge as represented by Figure 2. The figure can serve as a map for planning science teacher education experiences and for specifying desired knowledge outcomes of those experiences. Specifically, the components of pedagogical content knowledge suggest the importance of including the following elements in science teacher education programs:

- the goals of science education and their relationship to purposes for teaching science (knowledge of *orientations to teaching science*, knowledge of *science goals and objectives*).
- Instructional strategies that match particular orientations to teaching science (knowledge of *subject-specific strategies*, knowledge of *specific science curricula*).
- Planning, conducting, and reflection upon teaching specific science topics, guided by considerations of students' understandings (knowledge of *students' understanding*, knowledge of *science assessment*),

- and the appropriateness/value of using particular instructional strategies (knowledge of *topic-specific strategies*).
- Planning and administration of assessments that are compatible with one's orientation to science teaching and targeted goals and objectives (knowledge of *science assessment*).

Ideally, for a science teacher education program to be comprehensive and coherent, all of these areas should be addressed. However, we recognize the difficulty of that undertaking, and we do not suggest that programs which focus on only a subset of the components cannot be successful. Instead, we caution that teacher educators should be aware of the possibility that teachers may not have requisite knowledge of components not addressed by the program that would help them effectively use the knowledge they develop from the program. Further, participants may have pre-existing pedagogical content knowledge and beliefs in areas not addressed by the program that are incompatible with the program's goals, and which might undermine effectiveness of the program in helping teachers develop new practices.

In addition, given that pedagogical content knowledge is transformed as a result of teaching, and that one must develop pedagogical content knowledge for each topic that one teaches, pre-service teachers will only be able to develop a fraction of the pedagogical content knowledge they will need to be effective. Hence, it is critical that pedagogical content knowledge development be the focus of work with practicing teachers as well. Experiences at conferences such as National Science Teachers Association conventions provide one type of opportunity for teachers' continued knowledge development. Many presentations are instances in which pedagogical content knowledge is shared; however, too often the information that is provided is insufficient for teachers in the audience to make optimal use of it when they apply it to their own teaching situation. As a professional community, we can do more to educate presenters to provide more detailed information. We can also encourage different types of sessions in which participating teachers can teach and reflect upon their teaching with the help of those with the necessary expertise. In addition, the science education community can make it a priority to provide other avenues of support for teachers to continue developing and refining their pedagogical content knowledge. This action is particularly needed at this time when the knowledge required for effective science teaching is greater than it has ever been due to the breadth and depth of contemporary goals for science education, and the demands of inquiry-based teaching.

Finally, at this time of focus on national standards to guide the credentialing of teachers, we must recognize that pedagogical content knowledge is at the heart of teaching in ways consistent with the standards. The components of pedagogical content knowledge can help us view those standards in ways that will maximize the development of programs that can support teachers in developing the knowledge required for successful teaching.



## IMPLICATIONS FOR RESEARCH

Despite the utility of pedagogical content knowledge as argued in this chapter and illustrated in the research that was cited, this concept has not received much attention in the field of science education. For example, although the small number of studies examining pedagogical content knowledge that were described in this chapter were only intended to be representative of the research in this area, they comprise a substantial proportion of existing work. One implication that can be drawn from this chapter is that much more research is needed to define desired pedagogical content knowledge for specific science topics, and to examine its influence on teachers' practice in specific teaching situations.

Another recommendation concerns the ways in which researchers examine teachers' pedagogical content knowledge. Because we are (or should be) trying to capture the complexity of changes in teachers' knowledge, beliefs, and practices across components of pedagogical content knowledge (as well as across knowledge domains), it is important to use multiple data sources. Observations of teachers in their classrooms as well as in teacher education settings; interviews with teachers about their knowledge, beliefs and practices; and interviews with other persons central to change efforts are all important sources of information about teaching. Further, because change is a slow process, it is important to study teachers over time - both during and after their participation in teacher education programs.

Finally, although we consider our conceptualization of pedagogical content knowledge to be a powerful tool for understanding science teaching, we think it is important that discussion regarding its conceptualization and utility continues, particularly as new research becomes available. By continuing to challenge and revise our thinking, the science education community is likely to develop sharper and more varied lenses with which to examine and understand science teaching and learning.

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<sup>1</sup>Shulman named this type of knowledge pedagogical content knowledge because he initially conceptualized it as developing from a teacher's knowledge of content and pedagogy.

<sup>2</sup>Notice that the names in each of the shaded boxes describe the domain as consisting of knowledge and beliefs.<sup>2</sup> Our choice to designate the domains a including beliefs signals that when information from any of them is accessed for teaching, that information may be an amalgam of knowledge and beliefs. The designation of knowledge and beliefs should be applied as well to each component of the major domains, even though the term "belief" was not repeated in those boxes in the figure. The remainder of the chapter text uses the term "knowledge" in labeling the domains and their components rather than "knowledge and beliefs" because the knowledge dimension has received the most attention from science educators. Nevertheless, it is important to remember that beliefs are associated with that knowledge as well.

<sup>3</sup>Again, we have used only the term knowledge in labeling the components in the figure even though in all cases they include knowledge and beliefs.

<sup>4</sup> Other science educators have referred to this component as a "functional paradigm" (Lintz & Kass, 1987); Grossman (1990) referred to it as an "overarching conception" of teaching.

<sup>5</sup> Descriptions of some of the orientations were informed by the following articles: Anderson and Smith (1987) and Smith and Neale (1991).

<sup>6</sup> A project of this type was carried out in a number of elementary school classrooms as part of a university-school collaboration led by Magnusson (Magnusson, Karr, George, & Boyle, 1994, Magnusson, Royle, & George, 1994).

<sup>7</sup> Further description and illustration of this type of progression of instructional activity is presented in Magnusson and Palinesar (1995).

<sup>8</sup> Other terms that have been used to describe these ideas are misconceptions (Helm, 1980), preconceptions (Ausubel, 1968), lay conceptions (Magnusson, Boyle, & Templin, 1994), alternative frameworks (Driver & Easley, 1978), naive theories (Resnick, 1983), and children's science (Gilbert, Osborne, & Fensham, 1982).

<sup>9</sup> These findings are confirmed by a number of studies examining teachers' content knowledge. See section of review (pp. 189-190) by Wandersee, Mintzes, and Novak (1994) on alternative conceptions in science.

<sup>10</sup> These are electronic devices attached to a computer. They can be purchased from Vernier Software.

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