# Fostering Teacher Learning in Systemic Reform:
# Linking Professional Development to Teacher and Student Learning

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**ABSTRACT**

Professional development for science teachers is widely recognized as a key element for successful standards-based systemic reform, yet there is little empirical evidence to justify design decisions for professional development. This paper presents both a theoretical model of teacher learning and an analytical framework that employs the model to link professional development to both student and teacher learning. Our approach begins with an analysis of relevant content standards for science learning, and then uses evidence of student performance to gauge areas where focus is needed in professional development. The success of our professional development designs is evaluated using a combination of teacher reflection, classroom observation, and ultimately the re-assessment of student performance. This process is used to inform a continual process of design and re-design. We present two examples of this process in use. The first example describes teacher learning about the use of modeling software by students. The second example is about teacher learning related to helping students master map reading skills related to watersheds. We argue that this form of empirically-based assessment of professional development, linking teacher and student learning, is a key to the eventual success of standards-based systemic reform efforts.

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The professional development of science teachers is regarded as a cornerstone for the implementation of standards-based teaching and learning practices (Committee on Science and Mathematics Teacher Preparation, 2001). At the heart of the science education standards (American Association for the Advancement of Science, 1993; National Research Council, 1996) is an inquiry-oriented approach to teaching and learning that is linked to pedagogical practices such as constructivism (Von Glasersfeld, 1989) and project-based learning (Blumenfeld et al., 1991) that stress the existing capabilities of teachers. These approaches are widely recognized as challenging for teachers to learn to use in the classroom, because they involve changes in classroom management strategies, the organization of knowledge, and assessment, to name just a few areas of difficulty. Coupled to this is the demand that science teachers be masters of science content. In inquiry-oriented teaching it is often necessary for teachers' subject matter knowledge to be deeper and broader than in traditional recitation teaching, in order to accommodate students' questions and investigations. School systems are under increasing pressure to implement standards-based science programs, and these pressures are translated to teachers in the form of new accountability measures such as standardized tests. There has never been a more critical need for high quality professional development of science teachers.

Yet in the face of these pressures, report after report depicts the state of teacher professional development as deficient, particularly where science and technology is concerned (e.g., CEO Forum on Education and Technology, 1999; Education Week, 1997). Many times the deficiency is reported in terms of quantity (e.g., not enough hours of professional development), but the quality of professional development is a more important issue. In fact, though the number of professional development opportunities for teachers has increased during the past five years, there has been little concurrent growth in collective understanding about *what* makes for successful professional development, or what teachers *learn* from professional development (Wilson & Berne, 1999). We believe that a central weakness of current professional development efforts is that they are not founded upon an empirical knowledge base that links different forms of professional development to either teacher or student learning outcomes.

The lack of focus on professional development as an area for empirical research is especially evident in the domain of science. Although practically every new program or innovation in science education has associated professional development opportunities, there has not been much systematic study of these opportunities (Marx, Freeman, Krajcik, & Blumenfeld, 1997); they are simply treated as necessary but ancillary components of the innovation. To compound this problem, where good research on professional development has been conducted (e.g., Carpenter, Fennema, & Franke, 1996; Marx, Freeman et al., 1997), it has focused on groups of volunteer teachers who are, more often than not, motivated to change or try something new (Supovitz & Zeif, 2000). It is as yet unclear what the implications of this focus on motivated volunteers are for our understanding of professional development, but we argue that the differences are sufficient to warrant investigation (Bobrowsky, Marx, & Fishman, 2001). We are not aware of similar professional development research conducted in settings that we call "systemic," where change is implemented on a broad scale and teachers are, for the most part, not highly motivated. This latter situation is ultimately of greater practical importance to the general cause of reform.

In this paper we explore a framework for conducting research on teacher learning from professional development in systemic reform. Using a model of teacher learning we introduced at NARST 2000 (Fishman, Best, Foster, & Marx, 2000), we present data on teacher engagement with two different professional development activities that combine various design elements and also present data on the relationship between their engagement and subsequent changes in both teacher practice and student achievement. The chain of argument and evidence that we use to support our design decisions for professional development is significant for the way it seeks information from multiple points in the life cycle of teacher learning. We begin with the science content standards, in order to understand *what* students should know. We next seek evidence of student performance to understand *where* deficiencies might be present. We design professional development activities to help teachers teach to those areas of need. We evaluate teacher response to professional development. We observe classroom enactment subsequent to professional development. We re-evaluate student performance on the area of need. Finally, we engage in continuous re-design, seeking ever-higher levels of learning.

It must be noted that we are explicitly *not* promoting or validating a particular model of professional development. Instead, our aim is to present evidence for the value of a design approach (Simon, 1996) to studying professional development similar to that advocated for the study of classroom-based innovations (Brown, 1992; Collins, 1990). We argue that it is essential to gather evidence from a broad spectrum of sources related to teacher learning, classroom enactment, and student learning in order to understand the impact of various professional development designs so that informed decisions can be made about how best to achieve the vision of the new science education standards. We present these data on teacher learning from professional development in systemic reform by drawing on our own work with urban middle-grades teachers in Detroit learning to use new standards-based curriculum materials in science. We will describe this setting more fully in the methods section below.

## OUR MODEL OF TEACHER LEARNING

We maintain that professional development should fundamentally be about teacher learning: changes in the knowledge, beliefs, and attitudes that teachers possess that lead to the acquisition of new skills, new concepts, and new processes related to the work of teaching. Ironically, teacher learning may be the most difficult thing to measure in professional development. End-of-workshop evaluations are commonplace, but they represent measures of teacher attitudes, not knowledge (this is why they are frequently and derisively referred to as "opinionnaires"). As

Fenstermacher (1994) has pointed out, reports of what teachers believe or reflect on may or may not be knowledge. To measure knowledge would require something that looks much like a test, whether it is administered on paper or given in the form of a structured interview, and this would likely only represent one aspect of the teacher's knowledge, specifically content knowledge. Pedagogical knowledge of any sort would be difficult to measure or evaluate without direct classroom observation.

We set out to develop a model of teacher learning that would serve as a guide to understanding what teachers learn as a function of professional development. To do this, we followed Richardson (1996), who states that a chief objective of professional development should be to foster changes in teachers' knowledge, beliefs, and attitudes, because these components of teacher cognition show a strong correlation to teachers' classroom practices. We have developed a model for teacher learning in this research that has teacher knowledge, beliefs, and attitudes (K/B/A) in an interactive relationship with the interpretation of student change or learning as represented by various forms of assessment, and through the practical experiences of classroom enactment. This model is represented graphically in Figure 1. In the paragraphs that follow, we will expand briefly on each of its components.

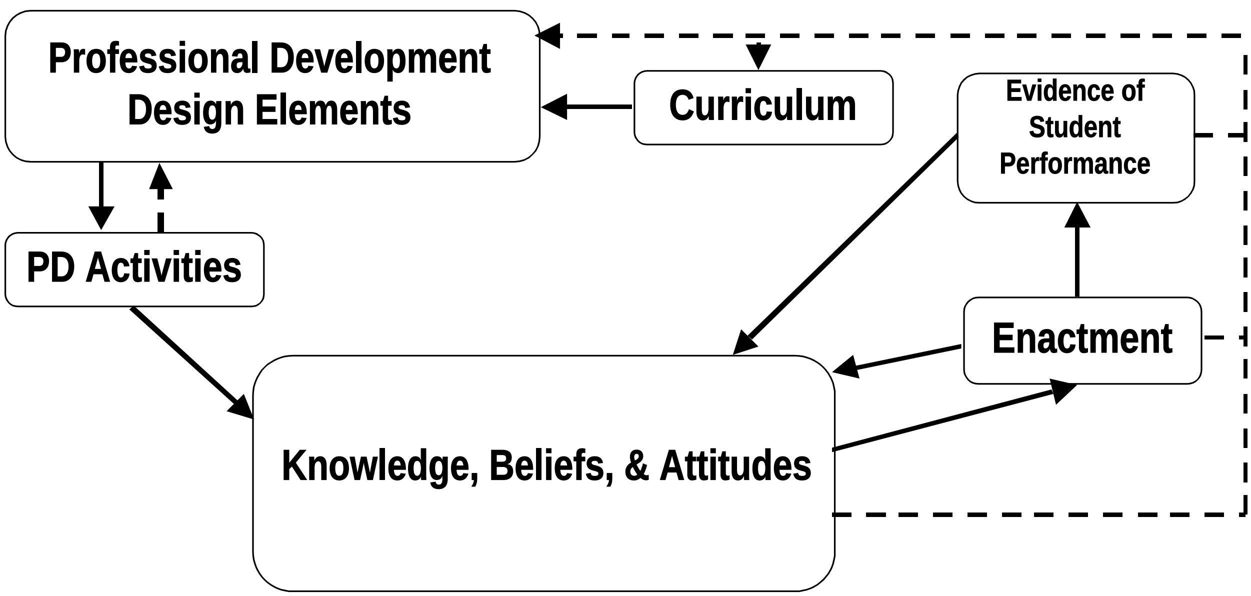



**Figure 1**. Model of design approach to professional development.

**<u>Knowledge, Beliefs, and Attitudes (K/B/A) and Enactment</u>**

We choose to represent teachers' K/B/A in seven categories: Content knowledge (CK), pedagogical knowledge (PK), and pedagogical content knowledge (PCK) (Shulman, 1986, 1987); beliefs about self-efficacy as a science teacher and as a member of a broader scientific community (Dwyer, Ringstaff, & Sandholtz, 1991); attitudes towards technology (Czerniak, Haney, Lumpe, & Beck, 1998); and beliefs about system norms and contextual issues that impinge on innovation (Cohen, 1987). K/B/A is predicted to directly influence classroom enactment of curricula with technology, but enactment will interactively and reciprocally affect K/B/A (Richardson, 1996), through a process that will be described in the following sections. Both measurement of K/B/A and observations of teachers' enactment form a feedback mechanism to inform the re-design of professional development activities to foster greater change among teachers participating in our program.

**Curriculum**

Curriculum is represented within its own box because it both shapes our professional development and is shaped by the results of professional development. We design curriculum, and that forms the core of the innovation that we help teachers to learn to enact through professional development. Our notion of what is appropriate for inclusion in curriculum is shaped by a combination of factors, such as state and district standards, but also by the capabilities of the teachers to enact the curriculum (as evidenced by "enactment" in our model) and by the performance of the students ("evidence of student performance"). Curriculum therefore plays a significant role in our overall model.

**Professional Development Design Elements**

The goal of any professional development activity focusing on content learning is to prepare teachers to enact the curriculum appropriately for its design in their classrooms. At the heart of this activity is, of course, teacher learning related to both preparation for instruction and the instructional activities themselves. What is taught or learned by teachers in the context of professional development is the "content" of teacher professional development. Teacher learning of content is facilitated by a range of strategies for professional development, which are conducted through various media that are part of the different sites for learning that comprise a professional development program. Any given professional development activity uses components from each of these elements. For example, an activity held during a Saturday workshop which focused on assessing students' written responses to a content question would involve print resources and face-to-face discussion, and would address the fostering of discourse and meaning making by students, as well as student knowledge of the content they were writing about. Following our model in Figure 1, these elements are then combined in this activity to focus on changing teachers' K/B/A. Each of these components are inter-related in its relationship to the content for professional learning as shown in Table 1 below.

These four elements (content, strategies, media, and sites) are elements that can be combined in various ways to create professional development. The various possible combinations become the design space for professional development, and this defines the range of possibilities which can possibly be explored in the design research process. These designs are intended to address all of the change mechanisms which impact teacher K/B/A and, in turn, enactment. Each teacher has a necessary threshold which must be achieved with respect to each of these change mechanisms before the innovation will be attempted. The elements of the professional development are intended to address these mechanisms, and recognize that the thresholds of each mechanism change over time. Next, we will expand upon each of these different elements.

**Table 1.** Design elements that comprise professional development programs (Note that lists are meant to be suggestive, not exhaustive).

| Content | Strategies | Media | Sites |
|---|---|---|---|
| Content Knowledge (CK) | Planning assistance | Print | Summer institute |
| Pedagogical Content Knowledge (PCK) | Tutoring | Video | Saturday workshops |
| Pedagogical Knowledge (PK) | Team/model teaching | Computers (multimedia and Internet) | After-school study groups |
| Fostering meaning making for students | Examine student work | Face to face discussion | In-class support |
| Contextualization | Examine teacher practice | Audio | Visits to other classrooms |
| Fostering collaboration | Examine teaching models | | Educative curriculum |
| Fostering discourse | Creation of professional learning goals | | Graduate extension course |
| Facilitating scientific processes | Curriculum/software review | | On-line support materials |
| Facilitating technology use | Enactment of curriculum | | |
| | Peer information exchange | | |

Content of Professional Learning

The content of professional learning (what teachers learn) can be divided into content teachers need to understand in order to prepare for classroom instruction and content they must know that actually comprises classroom instruction. In the first category are: Strategies for planning; new forms of student assessment; and subject matter knowledge that relates to teaching strategies (PCK). In the second category are: Fostering meaning making for students; creating opportunities for contextualization; fostering collaboration; fostering discourse; facilitating scientific processes, including the use of tools, technologies, representations, and modeling; the content of the curriculum; and basic pedagogical knowledge such as classroom management.

Strategies

Many of the strategies used to foster teacher learning follow from a strategic framework we use to conceptualize our own professional development called CERA (Marx, Blumenfeld, Krajcik, & Soloway, 1997; Marx, Freeman et al., 1997). CERA stands for Collaborative construction of understanding; Enactment of new practices in classrooms; Reflection on practice; and Adaptation of materials and practices. CERA can provides a general backdrop for the collaboration of school district personnel responsible for policy decisions which affect professional development and other management issues, innovation designers, such as curriculum developers (as is the case in our specific situation, described later), professional development specialists who will be designing and enacting professional learning activities, and teachers involved in professional development. Specific strategies may vary considerably, but tend to be centered on one or more aspects of CERA.

Sites For Professional Learning

A site for professional learning simply denotes the place or context in which teacher learning may take place. Each of these sites draws upon the use of differing methods which fit the context of the site and media which are bounded by the site. Likewise, content and change mechanisms addressed within each site of professional learning vary according to the situational needs of the teachers involved. Traditional sites for professional learning include after-school in-service sessions, summer workshops, graduate-level coursework affiliated with a teacher's interests, and the ever present teacher enactment of curriculum in the classroom, which forces some level of learning from subsequent reflection and adaptation.

Media

The media through which professional development might be conducted are: Face-to-face interaction; video; audio; computers (dynamic multimedia, including the Internet); or print. These media might be combined in various ways; for instance, the Internet can be used to combine print, video, and audio. Video can be used as part of face-to-face interaction. Media are not as important as methods (c.f., Clark, 1983), but it is the case that certain media, such as the Internet, might lend themselves less well to certain kinds of change mechanisms, such as perceptions of feasibility.

## METHODS

### Setting and Context

The professional development and teacher learning described in this paper was conducted within the context of a large-scale urban reform effort taken up jointly between our research group (the Center for Highly Interactive Computing in Education) and the Detroit Public Schools. The challenge was to take work that had successfully fostered learning in the context of a number of smaller-scale design experiments and attempt to bring it to a large-scale urban and systemic context (Blumenfeld, Fishman, Krajcik, Marx, & Soloway, 2000). Below we present an abbreviated description of the components of our innovation, in order to provide a context for understanding the discussion of professional development that follows in the results and discussion sections, and how that work relates to systemic reform.

The Detroit Public Schools is a large system serving about 165,000 students from a diverse urban community and employing more than 10,000 teachers and other education professionals. Like most large American cities, students often come from poor families (about half of Detroit's children and youth live in families that are at or below the poverty line), are largely minority, and tend to be mobile. Dropout rates are high and students' test scores are low compared with performance of students across the state. The 25 schools that were involved in this work represent the broad range of schools and neighborhoods in the city, ranging from inner city schools serving communities with high poverty to schools in more suburban, affluent communities. Across the district, 91% of the students are African American, 4% are Latino, and 4% are white, and 1% are Asian.

### Curriculum and Pedagogy

Our work is rooted in inquiry pedagogy that is consistent with constructivist ideas (Blumenfeld et al., 1991). The presumption is that students need opportunities to construct knowledge by solving real problems through asking and refining questions, designing and conducting investigations, gathering, analyzing, and interpreting information and data, drawing conclusions, and reporting findings. We refer to this process as project-based science (PBS; Blumenfeld et al., 1991; Krajcik, Czerniak, & Berger, 1999). Together with Detroit, we have developed four middle school science units: a sixth grade unit on mechanical advantage, seventh grade units on air quality and water quality, and an eighth grade unit on force and motion (Singer, Marx, Krajcik, & Clay-Chambers, 2000). Our eventual goal is to develop enough units to comprise an entire middle school science sequence. Each unit is built upon national, state, and most importantly, local district standards. Our curriculum units are designed to last between eight and twelve weeks. Each includes: a) a driving question, encompassing worthwhile content that is meaningful to students and anchored in a real-world problem; b) investigations and artifact development that provide opportunities for students to learn concepts, apply information, and represent knowledge around the driving question; c) collaboration among students, teachers, and others in the community; and d) use of computational technological tools to promote inquiry. In addition, the curriculum materials include benchmark lessons that help students learn difficult concepts, illustrate important laboratory techniques, or develop investigation strategies (Krajcik et al., 1999). Furthermore, the curriculum materials themselves are intended to be "educative" for teachers (Ball & Cohen, 1996), helping to provide opportunities to learn about new teaching practices, content and classroom enactment from the materials themselves.

**Software Tools**

In conjunction with PBS pedagogy, we have developed a set of computational tools to support and scaffold inquiry based upon principles called learner centered design (LCD; Soloway, Guzdial, & Hay, 1994). LCD is founded on the idea that learners are a unique class of computer users, and thus require special forms of support from software interfaces in order to complete their tasks successfully. Furthermore, the tools can be used over and over again throughout a student's academic career in different science classes. We developed a suite of computational tools to enable sustained inquiry (Krajcik, Blumenfeld, Marx, & Soloway, 2000). These tools support data collection, data visualization and analysis, dynamic modeling, planning, information gathering from the UM digital library, the Internet and web publishing (Jackson, Stratford, Krajcik, & Soloway, 1994). Some software, like Model-It, is designed for use at single computers, which do not need to be networked. Others use the Internet, such as Artemis, which is a front-end to a digital library tailored to young learners (Wallace, Kupperman, Krajcik, & Soloway, 2000).

**Participants**

The teachers who participated in this work were faculty members at the schools that were involved in the work of the Center for Learning Technologies in Urban Schools (LeTUS). University researchers collaborated with senior district administrators in the selection of schools, which were invited to participate based on several informal criteria. First, the district required that the teachers had the capacity to engage in the professional development and innovative instructional program. Our goal with this criterion was that we would not have a large number of teachers working out-of-field or who had skill deficiencies in fundamental areas of teaching. Second, we wanted participating schools to have a sufficient computing infrastructure so students would have access to technology when it was required in the curriculum. Third, there needed to be a supportive administration in the schools so when problems and difficulties arose they could be resolved in a timely and efficient manner. Fourth, the district administration wished to insure a broad program of equity across schools so innovative programs were not concentrated in some schools to the exclusion of others. The procedure for selecting schools to participate began with a discussion at the central office, identifying the schools that met the above criteria. This was followed by an invitation to the principal and/or assistant principal, the science unit head, and the technology coordinator (if the school had such a person) to a meeting with the associate superintendent and University of Michigan researchers.

The teacher participants were regular faculty members at these schools. For most schools one to three teachers participated (many middle schools had only three science teachers). The resulting group of teachers was quite diverse, despite the use of the selection criteria. For example, 70% of the teachers were certified to teach in science; the remainder was not, although several of this group had extensive professional development experiences in science education. The teachers were highly experienced, averaging a little over 11 years in the classroom, about 7.6 years of which were in science. A small number had classroom management problems or were new teachers. The schools had a range of computer technology available for classroom use and in some schools teachers and administrators had to be creative in the way they addressed limited resources.

**Data Sources**

The data for our analysis of teacher learning in professional development come from a variety of sources. Due to the broad scope of the LeTUS reform work with Detroit, these data sources are normally meant to serve a range of documentation and development efforts, and in most cases were not designed exclusively for use in studying professional development. These data sources include student pre- and post-tests designed to measure content and process knowledge related to each curriculum unit, student-created artifacts, field notes of classroom observations, focus groups with teachers at the conclusion of each curriculum unit, videotapes and audiotapes of professional development activities, evaluations filled out by teachers at the conclusion of group professional development activities, and interviews with teachers.

**Analysis**

Our approach to analysis combines qualitative and quantitative approaches, reflecting the broad range of data used to inform our evaluation of professional development activities. Standard statistical methods are employed to student pre- and post-test data in order to compare learning gains both within and across teachers, curriculum units, and years. Qualitative data from teacher interviews, classroom observations, and observations of professional development activity are analyzed using constant comparative analysis (Miles & Huberman, 1984) for data reduction and the development of descriptive categories. Internal validity is increased through the triangulation of these various data sources (Lincoln & Guba, 1985).

## FINDINGS

Two examples of the design process were selected for this paper to demonstrate our approach to evaluating professional development design. These examples illustrate the full cycle of the model for teacher learning described in Figure 1 above, and how we use the elements of that model to document the impact of professional development on teacher and student learning. This first example is about teacher learning about map reading skills related to watersheds. The second example is about teacher learning about modeling software to foster student thinking about causal relationships in dynamic systems. Both examples begin with the relevant content standard that motivate the inclusion of these subjects in our curriculum materials, and proceed linearly through the process of professional development design, evaluation, and re-design according to our analytic framework.

## Example 1: Teacher Learning About Map Reading Skills Related to Watersheds

> *The earth surface is shaped in part by the motion of water…, which act to level mountain ranges. (AAAS, Benchmarks for Science Literacy, 1993, p. 73)*
>
> *All students will demonstrate where water is found on earth; describe the characteristics of water and how water moves; and analyze the interaction of human activities with the hydrosphere.*
>
> *All students will describe the earth's surface; describe and explain how the earth's features change over time; and analyze effects of technology on the earth's surface and resources. (Michigan Content Standards for Science – Hydrosphere and Geosphere)*

Understanding the structure of earth systems is an important objective for middle school science. In order for students to understand how water shapes the earth's surface by erosion and deposition, they have to understand what watersheds are. In order for them to analyze environmental data and understand pollution hazards, they have to be able to analyze maps that show the connection between pollution sources and watersheds.

In response to these standards, LeTUS created a water quality curriculum that addresses a number of issues related to hydrology, earth structures, and ecosystems. Based on the driving question (Singer et al., 2000) "What is the water like in our river?", students examine a number of concepts within their local community related to water quality. Student activities begin with a river walk to contextualize the problem, and include a variety of activities designed to foster understanding of the physical geography and dynamics of a watershed, which can then lead to an understanding of the impact human activity has on the watershed, and therefore, the ecosystems that rely on that watershed. First developed in 1997, the LeTUS water quality curriculum was piloted in two schools in 1998, and again with a slightly larger group in the spring of 1999. It became a fully implemented curriculum within participant schools in LeTUS in 2000.

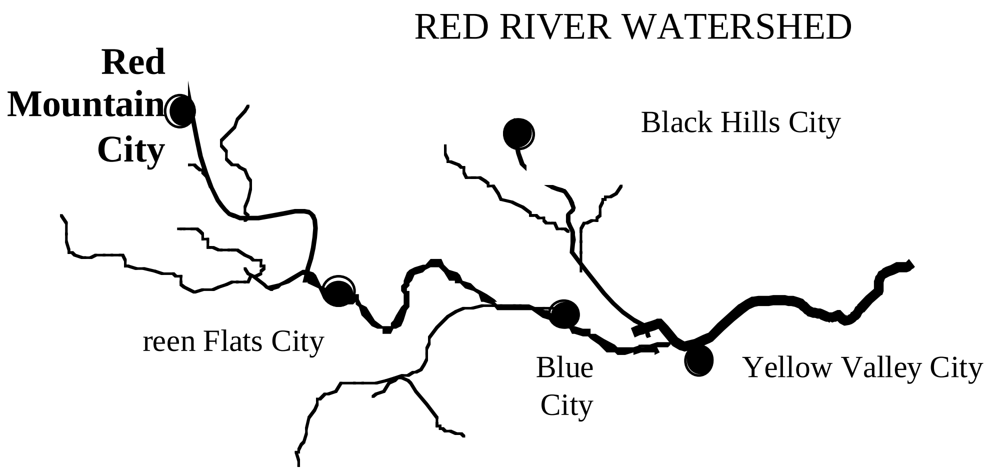
### Initial Professional Development Design – 1998-1999

In the first year the water quality curriculum was broadly enacted by LeTUS teachers (1998-99), professional development activities were designed to familiarize teachers with the goals, content, and activities of the curriculum. Described in terms of the professional development design elements from Table 1, these sessions were conducted as Saturday workshops (site), with face-to-face sessions supported by text (media) in the form of the curriculum guides. The workshops focused on building teachers' science content knowledge and pedagogical content knowledge (content), and the primary activities consisted of curriculum reviews and peer-information exchanges (strategies) to disseminate basic information about the completion of activities within the curriculum unit.

### Identifying Problematic Areas for Students' Learning

Analysis of the pre- and post-tests from the 1998-1999 enactment of the water project demonstrated that the students were having difficulty on items related to the understanding of watershed concepts when portrayed in a two-dimensional map, a standard representation and one that is frequently used in Michigan state standardized achievement tests. The test questions depicted a map of a watershed and required students to identify the flow of water in the watershed, and by inference, areas of high and low elevation within the map. Figure 2 below shows the pre- and post-test questions and Table 2 presents the distribution of students' responses on these assessments.

**Below is a map of the Red River watershed and the cities on the river. Use the information in the map to answer the questions below.**




**1. The direction that the water in the red river is flowing is from**
a. Yellow Valley City to Black Hills City
b. Red Mountain City to Yellow Valley City
c. Green Flats City to Red Mountain City
d. Blue City to Red Mountain City

**2. The direction that water in a river flows is affected by a change**
a. from lower elevation to higher elevation
b. from higher elevation to lower elevation
c. in the wind direction from East to West
d. in temperature from cold to hot

**Figure 2.** Watershed items from the Water Project pre- and post-test.

**Table 2.** Percent correct on water quality pre- and post-tests. Correct answers are in bold.

| Question | 1998-99 Pre-Test | | | | 1998-99 Post-Test | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | A | **B** | C | D | A | **B** | C | D |
| | 25 | **42** | 20 | 13 | 17 | **50** | 22 | 12 |
| 2 | A | **B** | C | D | A | **B** | C | D |
| | 32 | **23** | 22 | 23 | 36 | **29** | 19 | 16 |

Although the largest percentage of students answered question1 correctly on both the pre- and the post-test, there was not substantial improvement from the pre-test to the post-test. Students' answers to question two were not better than would be obtained by guessing on either the pre- or post-test. From these results we concluded that students were not learning these items as the curriculum was currently being enacted.

<u>Professional Development Redesign to Address Students' Difficulties – 1999-2000</u>
After analyzing these items, we sought to design professional development activities to help teachers focus on this area of students' difficulty. We decided that this should be one of the first elements discussed with teachers in preparation for the enactment of the Water Quality curriculum for 1999-2000. The curriculum unit begins with activities that first address the concept of watershed and the flow of water within the watershed, and then build to the more complex concepts of water quality and fluvial ecosystems. If map reading difficulties are not addressed early in the enactment of the curriculum unit, we realized that it would become a barrier to progressing to other activities which rely on knowledge of map representations of a watershed.

The first water quality workshop for the 1999-2000 enactment was held in March. The workshop was designed to focus on three primary elements: familiarizing teachers with the curriculum unit, including necessary materials, scheduling, classroom activities, etc.; a detailed modeling of one of the initial activities of the curriculum unit which focuses on the concept of a watershed and the movement of water over land; and practice with the tool Model-It (described more fully in example 2 below), a software tool used in the unit which is critical to the building of student understanding of complex interactions in a watershed (in that order). Teacher participants in this workshop had a range of experience with the LeTUS program and the activities of this curriculum unit, so the workshop activities were designed to take advantage of this by having experienced teachers guide new teachers in the program. The focus on map reading skills took place as a part of the detailed watershed activity. Again, using our design elements terminology from Table 1, the workshop content was content knowledge and pedagogical content knowledge; the site was a Saturday workshop; the media was face-to-face supported by text (curriculum materials), and the strategies included curriculum review, technology review, and model teaching.

The March 2000 workshop was designed to first review/introduce the curriculum materials to the teacher participants and acquaint them with various activities and materials, in a similar manner to the previous year's professional development designs. However, this activity was limited in time, so that teachers could quickly move to the hands-on watershed activity. In this activity, workshop leaders modeled the teaching strategies that might be used with students by having teachers conduct the activity as their students would. Teachers were grouped into clusters of 3 or 4, and performed a watershed modeling activity using butcher paper to represent land molded over various objects to simulate varied topography. Using a spray bottle, teachers were asked to spray their paper with a dyed water solution so that the dye would help trace the water movement. Immediately following this activity, teachers were asked to examine their papers and use markers to create a map of streams, rivers, and other water features which would exist on their watershed. All of these activities were performed as directed within the curriculum guide.

This set the context for a discussion of the mapping items from Figure 2 above. Copies of the problems from the pre- and post-test, along with percentages of students' responses for each answer were distributed to teachers, generating a discussion among the group about why so few students were able to respond correctly on the post-test. Teachers then brainstormed strategies which might be employed in the classroom to address this concern.

Teacher Participation and Engagement in the March 2000 Workshop

During the discussion about potential reasons for the disappointing student learning reflected in the mapping items, teachers generated a list of potential problems which might limit student understanding, including challenges such as the conventions for mapping waterways and how water flow is assumed from these conventions, the vocabulary used to describe watershed phenomena, and a lack of connection between the paper-spraying watershed activity and identification of map representations. Discussions addressed each of these issues subsequently, and led to a set of strategies which might be employed to improve student performance on these items. Some recommendations included modifications in the test design which might draw increased attention to mapping conventions and seeking greater congruence between classroom language and the language that would be used on tests. The bulk of the discussion, however, focused on meaning making strategies that teachers might employ to improve student performance. These included: a modification of the paper-spraying activity to include an examination of widths of markings created by the dye to illustrate mapping conventions for upstream and downstream elements of a watershed, making specific connections during and immediately following the activity which would illustrate impact of topography on water flow, and replicating these ideas from the activity on a map (as modeled by the workshop leaders), and including repeated use of watershed maps throughout the curriculum, including subsequent activities where water flow concepts are critical.

Following the workshop, teachers were asked to evaluate the activities of the workshop by listing critical learning points of the workshop, and responding to a questionnaire asking for their confidence before and after the workshop in a number of areas, which mapped directly to the stated goals of the workshop presented at the start of the workshop. Two of these goals mapped directly to this watershed activity. Using a five point scale, teachers indicated that they felt increased confidence with respect to supporting student understanding of watershed and water flow concepts (3.86 before workshop, 4.83 after; n=8) and in helping students build conceptual models of watersheds (3.88 to 4.5).

Effect of Professional Development on Teachers' Classroom Enactment

Following the workshop, teachers' use of strategies from the workshop to address various concepts within the unit were recorded by classroom support personnel. Field notes from weekly visits to the teachers' classrooms indicated that many teachers were employing strategies suggested during the brainstorm exercise. Many teachers employed a review strategy with students known as bell work (typically quick problems for students to complete immediately following the ringing of the bell marking the start of class) where maps of watershed were depicted with questions similar to those shown to teachers at the workshop. Most of the teachers present at the workshop used the strategy modeled in the workshop for moving directly from the paper-spraying exercise to a map making exercise. In general, maps were used more frequently by teachers in subsequent activities where a local watershed was studied. Two teachers including map representations of the watershed as a part of a "driving question board" (another strategy employed within the curriculum to encourage opportunities for student reflection on questions critical to this unit) to better illustrate the representation of local topographical and hydrological features.

Effect of Professional Development on Students' Learning

Student understanding of these concepts were assessed using the same pre- and post-test items described earlier (see Figure 2). During the previous (1998-99) school year, correct responses on these items increased only 8% and 6% respectively following the enactment of the unit, with a combined average between the two items growing from 0.65 to 0.79 (out of 2.0 items). Student learning improved considerably in year two (1999-2000) when compared with year one ($F_{(3, 2922)}$=34.34, p<.001), with the professional development activity designed with a focus on student data. Learning on these two items from both the first and second years' enactment of the water quality curriculum is shown in Figure 3 below, with the percent of students answering correct for each question on the pre- and post-test shown in Table 3.

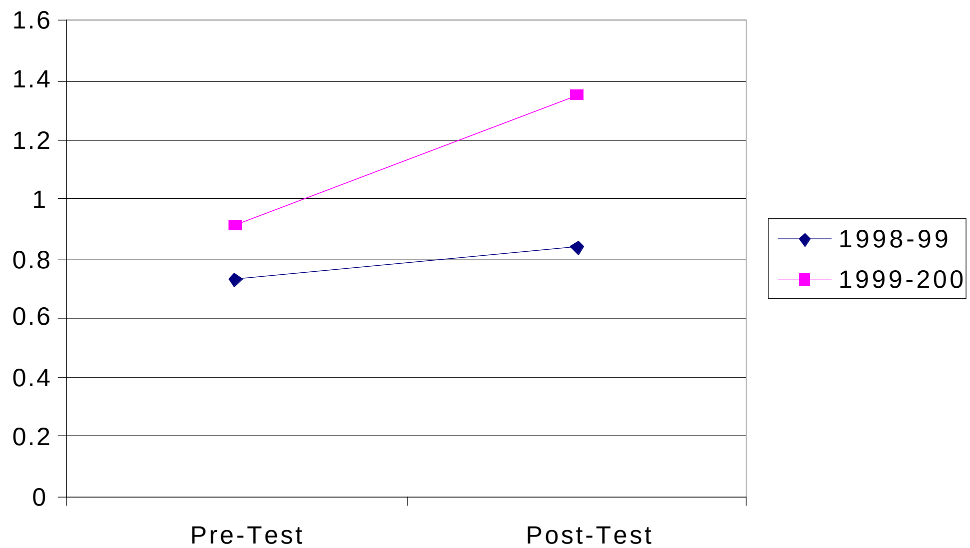



**Figure 3.** Comparison of student scores from 1998-99 enactment of water quality to 1999-2000 enactment on watershed mapping items. Student learning was greater in second year of enactment ($F_{(3, 2922)}$=34.34, p<.001).

**Table 3.** Percent correct on water quality pre- and post-tests from 1999-2000 enactment of water quality (on questions shown in Figure 2). Correct answers are in bold.

| Question | 1999-2000 Pre-Test | | | | 1999-2000 Post-Test | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | A | **B** | C | D | A | **B** | C | D |
| | 18 | **54** | 24 | 5 | 12 | **67** | 17 | 4 |
| 2 | A | **B** | C | D | A | **B** | C | D |
| | 25 | **38** | 24 | 13 | 14 | **69** | 11 | 6 |

## Example 2: Teacher Learning About Fostering Scientific Modeling with Software

> *Students should know that models are often used to think about processes that happen too slowly, too quickly, or on too small a scale to observe directly, or that are too vast to be changed deliberately…*
>
> *Students should know that different models can be used to represent the same thing. What kind of a model to use and how complex it should be depends on its purpose. (AAAS Benchmarks for Science Literacy, 1993, p. 269)*

The LeTUS program makes use of computational technologies to help students learn challenging science content and concepts. One of the tools developed for use in these classrooms is a dynamic modeling tool called Model-It (Jackson et al., 1994). Model-It allows students to create complex models to represent scientific phenomena through both a visual depiction of causal relationships between objects and a simulation of variables related to these objects over time with differing inputs. Students can set-up and test relationships between objects by simulating quantities for the independent variables and seeing the values of the dependent variables depicted numerically and graphically. In the water quality unit, Model-It is used to depict relationships that exist in the context of a watershed, including precipitation, runoff, erosion, pollutants, and other factors that contribute to overall water quality. Students' models are built using an iterative process, with Model-It being used several times during the unit to allow students to create more complex models as their understanding of the phenomena improves.

### Identifying Problematic Areas for Students' Learning

In the first year of Model-It use in the curriculum (1998-99; Model-It is used both in our water quality curriculum and in our air quality curriculum), many teachers elected not to use Model-It in their teaching at all. According to teachers and classroom support specialists, the reasons included teacher apprehension about using the new technology and insufficient access to sufficient resources to use it properly. In classroom where students did not use Model-It, modeling of phenomena was conducted with either static paper models similar to concept maps or was dropped from the curriculum altogether and replaced with discussions of specific objects and variables. In those classrooms where Model-It *was* used, teachers did not get appreciable value from using the tool because of the way that they used it. For example, in several classrooms all students' models were the same—the result of following a step-by-step process of model construction led by the teacher in a didactic fashion. This reflected a more limited use of Model-It with a predetermined goal for understanding, as opposed to an inquiry-based process for testing and constructing knowledge. From our perspective, it was clear that we were not doing an adequate job of professional development to prepare teachers to use Model-It to foster meaning making among students.

### Professional Development Design and Re-Design to Address Students' Difficulties

In response to problems with student learning using Model-It during the 1998-99 school year, we designed two workshop sessions for the 1999-2000 school year that were focused on the use of Model-It. Our goals was to encourage use of Model-It with teachers and to suggest and discuss inquiry-based pedagogy teachers could use in the classroom connected to the use of Model-It. Though both workshops centered on the use of this tool within the upcoming Water Quality curriculum, these two professional development sessions were very different in nature and illustrate our design process for creating professional learning opportunities for teachers. Based on our observations of the use of Model-It in the 1998-99 school year, these sessions were set up with a primary goal of encouraging teachers to incorporate use of the software to help build student understanding of the interactions of water quality and watershed concepts. Our initial thought was that the design should focus primarily on teacher comfort level with the software, since this seemed to be the primary barrier limiting its use in classrooms. It turned out that our initial assumptions about the best response were off the mark, as our own analytic process for evaluating professional development revealed.

Design of the First Workshop

The first workshop (March 2000) focused on introducing teachers within the LeTUS program to the water curriculum, an inquiry based curriculum centered on the question, "What is the water like in our river?" and focusing on concepts of watershed, the water cycle, fluvial ecosystems, water quality, and sources of pollution or degraded water quality. This was the same workshop described in Example 1 above where teachers were introduced/reintroduced to the water quality curriculum and focused on student work related to watershed map reading. This workshop concluded with an introduction to the use of Model-It, designed as a tutorial for teachers. This tutorial was led by a member of our research team who argued that teachers needed greater exposure to Model-It in order to gain comfort with it and thereby come to use it in their classrooms.

During previous years of using Model-It during pilot enactments of the curriculum, we had received positive feedback from teachers suggesting that a curriculum review (highlighting major curriculum activities and grounding these activities in discussions of constructivist pedagogy and student learning approaches) and tutorial/demonstration approach to introducing Model-It worked well. For this reason, we remained with this approach in our design of the first workshop. The software tutorial is a very common way to present software to teachers, with a presenter at the front of the room showing how to use software using a projection device and teachers following along in pairs at computers. Ironically, this recitation approach to professional development is at odds with the inquiry-oriented and constructivist approach embodied by the curriculum materials, but this irony escaped us at the time.

We believed that this workshop design would provide a review of the curriculum for teachers who had previously enacted this unit, and an introduction for teachers new to the program. Furthermore, we believed that the tutorial/demonstration of the software would provide an initial experience in the use of the software and would allow teachers to feel more comfortable with its use, thereby increasing the chance that teachers would use the tool in class. Our workshop design included engaging teachers who had used the tool in this curriculum unit in prior years in discussion following the software demonstration. By including more experienced teachers with novices in the use of this tool, the design would allow for discussion of experiences in using this tool, and raise suggestions regarding classroom practice. In the language of the professional development design elements in Table 1 above, the site for this activity was a Saturday workshop, the media was face-to-face with computers, the content was content knowledge related to technology and pedagogical content knowledge related to technology, and our strategy for teaching Model-It was a combination of software review and model teaching (though modeling a form of teaching that was not endorsed by our curriculum), and peer information exchange.

Teacher Participation and Engagement in the First Workshop

The portions of our March 2000 workshop that focused on Model-It were not as successful as we had anticipated. Comments from workshop evaluation forms solicited from teachers at the end of the workshop indicated that many teachers felt a need to continue with more workshops focusing on the use of technology. An analysis of video recordings of the workshop revealed the problems in the workshop with much greater clarity. When the workshop moved to a focus on acquainting teachers with the software tool, teachers were grouped in pairs or threes to include experienced and non-experienced teachers and each group was given a laptop computer to use during the subsequent activity. Teachers were instructed to follow along with the workshop leader while the steps in using the software were illustrated to the group by the use of a data projector, and were told that this method has been most successful in acquainting students with the software in prior years. Several teachers complained that the use of a projector would not be possible in their classrooms as they did not have access to similar equipment. Discussion quickly changed from use of the tool to planning to gain access to these resources, frustrating many teachers. Comments in the participants' reflections suggested that the workshop leaders lost their authority with the group by demonstrating a lack of understanding of the context of the teachers' classroom situations with respect to technology access. Once discussion had refocused on the tool and how it is used, there was insufficient time to demonstrate all aspects of how to use the tool. In an attempt to present all of the remaining information in the remaining time, the workshop leader asked teachers to refrain from using the tool on their own and simply follow along with his actions. For the remainder of the session, most teachers simply sat and watched as the workshop leader completed the activities with the software.

Design of the Second Workshop

Because of the apparent lack of success of the first workshop in responding to teacher discomfort in working with the software, a second workshop was designed to try again. In this instance, we did not apply our full model for analyzing the success of the professional development by observing classroom enactment and evaluating student learning, because we did not feel these steps were necessary in light of what seemed to us an obviously flawed professional development experience.

The second workshop would focus on similar issues of content and pedagogical content knowledge, along with facilitation of teachers' use of technology. However, the strategies employed would be varied considerably. Rather than trying to model teach a didactic walk-through of the software tool, teachers were given simulated examples of student work (models) to analyze within the software program, so that they would not only become familiar with the tool by working with its interface, but they would gain pedagogical content knowledge through an exploration of how students might use the tool and what the results of those different uses might be. Teachers were grouped according to experience with the curriculum, experience with the software, and by personality to encourage a mix within each group.

Each groups was then assigned a "student model" which was pre-loaded onto their computer to review and assess as an artifact to determine what the student really understood about watershed concepts and what misconceptions the student might have regarding these ideas. Each group examined their model, which included manipulating the software so that every possible step in model building could be assessed. Groups then developed a set of conclusions about student learning based on the model. The student models were not actual models from the previous curriculum enactments, but were created by the workshop leaders as composites of actual student models. Since the previous year's models were rather simplistic, as described earlier, these composites would not only allow teachers to see a wide range of possible student responses, but would also help to set expectations about the possible models that could be created. The intended message to teachers was that they should expect different students to create different models, and that there was no single correct design for a model.

Following the review of the models, teachers rotated from group to group to see what other groups had observed and concluded with their own models (all of which were different). This allowed teachers to see the issues that arise in the classroom as students create these models. Following this rotation, teachers went back to their original groups to share what other groups concluded and each group created a rubric for evaluating the models. Once this rubric was created, teachers again rotated from group to group to assess each of the other models, and compared their assessments with those of other teacher groups. A debriefing discussion addressed the assessment of these artifacts and included brainstorming strategies for assisting students in overcoming "typical" barriers to creating effective models using Model-It.

Teacher Participation and Engagement in the Second Workshop

Teachers participated in the workshop as designed, with considerable success in overcoming concerns regarding the use of the tool. Groupings were explained to teachers so that they could understand why teachers were being paired as they were, and the teacher groups responded by having individuals who were completely unfamiliar with use of Model-It actually work with the computer, so that they could gain more from the experience by being "hands-on".

Discussions about the potential pitfalls for students and the assessment of student work brought out a number of concerns from teachers that had not been expressed in the previous workshop. Assessment strategies for groups of students were considered, and many teachers moved beyond the point of looking at the models as the products of individual students. They then expressed several ideas for how student groups might be constructed so that the teacher would be able to manage each group's progress in model development more effectively. They also raised concerns about how to assess individual student understanding as reflected in a group-constructed model. Many commented on the workshop activities as being valuable for them in developing comfort for using Model-It, but teachers also voiced concern about how to share access to classroom computers among groups of students, and non-technology based preparations that students would need to be successful model builders. These discussions reflected an understanding of pedagogical content knowledge (PCK) that was not observed in prior use of this tool by classroom support specialists.

Workshop evaluations also indicated that the design had a positive impact on teachers' perceptions about their knowledge of a variety of strategies and concepts regarding the use of modeling as a pedagogical strategy, and the use of Model-It in the classroom to assist students with understanding the concepts of watersheds. Table 4 below lists the goals of the workshop as stated to teachers at the beginning of the event, and teachers' perceptions of their knowledge in these categories before and after the workshop. Scores are based on a scale of 1-5, where a "1" was denoted as "Unfamiliar with the topic" and a "5" as "Fully understand the topic".

**Table 4.** Post-workshop evaluation by teachers with respect to the expressed goals of the workshop.

| Workshop Goal | Prior to workshop | Following workshop |
|---|---|---|
| I know how to help students build conceptual models of physical processes (of the watershed). | 3.14 | 4.18 |
| I know how to use Model-It software to build a conceptual model. | 3.29 | 4.5 |
| I know how to have students use Model-It in ways to improve their understanding of relationships. | 2.86 | 4.25 |
| I know how to examine students' computer models to better understand their learning about content topics. | 2.79 | 4.25 |
| I know how to develop a rubric to assess student understanding as demonstrated by their computer models and to use the rubric to assess and respond to these models in the classroom. | 3.07 | 3.75 |
| I know how to recognize and respond to student misconceptions with regard to the modeling process. | 2.93 | 3.94 |
| I understand some of the management challenges of having students collaborate on computer models and know some effective strategies to address these challenges. | 2.93 | 4.06 |

Effects of Professional Development on Teachers' Classroom Enactment

A markedly greater use of Model-It in the classroom was noted in field notes and observations from classroom support personnel, as well as in discussions and interviews with teachers, subsequent to our second workshop. All teachers involved in the curriculum used the software tool with their students for at least one extended period (generally 3-5 days) in their classroom, and a majority of the teachers used the tool in multiple iterations to build more sophisticated models with complex relations and interactions between objects.

In prior enactments of the curriculum unit, as well as enactments of other LeTUS curricula which use Model-It to conceptualize complex phenomena, teachers rarely required students to use elements of the modeling experience in their final presentations of their investigations. However, following this workshop, a majority of the teachers enacting the curriculum required students to use their models as the centerpiece of the final presentations of their learning for this unit.

Effects of Professional Development on Students' Learning

Observations from classroom support personnel, as well as informal comments from teachers, reflect an increased use of conceptual models by students. In previous years, the models created by students were very simple in design, usually having two or three objects from the watershed, and depicting two simple relationships. However, following the workshop, many models were observed to have as many as fifteen different objects depicted by students, and more complex relationships were present. Written text which appears in the model for students to explain the relationships they created between objects and variables was more thoroughly developed than in previous years, when it was typically absent or when all student responses were typically the same, following the didactic instructions from teachers.

The water quality pre- and post-test did not include specific items on modeling, so it is not possible for us to represent growth in student learning in terms of explicit quantities. We recognize this as a weakness in our ability to use student learning data to inform professional development related to modeling directly, and have already taken steps to include questions related to modeling concepts in future iterations of the water quality pre- and post-tests. Furthermore, a rubric-based evaluation of student models is ongoing, which will yield further data to use with teachers in professional development.

## DISCUSSION AND CONCLUSION

In both the case of teachers learning how to foster student learning about scientific modeling with Model-It and teachers learning how to foster map readings skills relating to watersheds, we believe that our design approach to professional development enabled us to make reasoned and substantial improvements in both teacher learning and subsequent student performance. After identifying student difficulties in particular areas, we were able to analyze our existing professional development and hypothesize changes that would better help the teachers teach to these difficulties. Subsequent analysis of the impact of these changes indicated that the workshop re-designs had a positive impact on teachers' knowledge and beliefs about their teaching, and also on their classroom enactment. These changed teacher knowledge and beliefs translated into improved student performance on post-test evaluations of the curriculum enactments.

Most evaluation of professional development begins and ends with "opinionnaires" given at the end of a session where teachers are invited to express their satisfaction with the experience or rate their learning experiences (Frechtling, Sharp, Carey, & Vaden-Kiernan, 1995). We also use these questionnaires, because they do have value in gauging teachers' immediate reactions to professional development design. But in our analytic framework, such instruments are only one component, and a small one at that, of the overall range of information bought to bear on assessing the value of professional development. For us, the most important measure of whether professional development is "working" is whether teacher enactment yields evidence of improved student performance.

The ultimate aim of this research is to elevate professional development beyond its current craft-oriented practice to more of a science in and of itself. Because professional development is a context-bound activity, our goal is not to develop or validate a monolithic approach and then attempt to get others to adopt that approach. Rather, progress in this area will most likely continue in the form of refined understanding of how to foster particular kinds of learning with respect to particular challenges of teaching complex, standards-based curricula. The result of this enterprise is less a new "model" for professional development as it is a way to conceptualize problematic areas for teaching with potential design responses to those problems.

Our future work includes continued tuning of our data collection and analysis techniques, and a continual evolution of professional development designs based on our research. We believe that the systematic exploration of the design of professional development linking standards to student achievement is a necessary element of future progress in systemic school reform.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## REFERENCES


American Association for the Advancement of Science. (1993). *Benchmarks for science literacy, Project 2061*. New York: Oxford University Press.

Ball, D. L., & Cohen, D. K. (1996). Reform by the book: What is—or might be—the role of curriculum materials in teacher learning and instructional reform? *Educational Researcher, 25*(9), 6-8.

Blumenfeld, P., Fishman, B. J., Krajcik, J., Marx, R. W., & Soloway, E. (2000). Creating usable innovations in systemic reform: Scaling-up technology-embedded project-based science in urban schools. *Educational Psychologist, 35*(3), 149-164.

Blumenfeld, P. C., Soloway, E., Marx, R. W., Krajcik, J. S., Guzdial, M., & Palincsar, A. (1991). Motivating project-based learning: Sustaining the doing, supporting the learning. *Educational Psychologist, 26*(3&4), 369-398.

Bobrowsky, W., Marx, R., & Fishman, B. (2001). The empirical base for professional development in science education: Moving beyond volunteers. St. Louis, Missouri: National Association of Research in Science Teaching.

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

Carpenter, T. P., Fennema, E., & Franke, M. L. (1996). Cognitively guided instruction: A knowledge base for reform in primary mathematics instruction. *Elementary School Journal, 97*, 3-20.

CEO Forum on Education and Technology. (1999). *Professional development: A link to better learning* (Year Two Report). Washington, DC: CEO Forum on Education and Technology.

Clark, R. E. (1983). Reconsidering research on learning from media. *Review of Educational Research, 53*(4), 445-459.
Cohen, D. K. (1987). Educational technology, policy, and practice. *Educational Evaluation and Policy Analysis, 9*(2), 153-170.
Collins, A. (1990). *Toward a design science of education* (CTE Technical Report 1). New York: Center for Children and Technology, Education Development Center, Inc.
Committee on Science and Mathematics Teacher Preparation. (2001). *Educating teachers of science, mathematics, and technology: New practices for the new millennium*. Washington, DC: National Academy Press.
Czerniak, C. M., Haney, J. J., Lumpe, A. T., & Beck, J. (1998). Teachers' beliefs about using educational technology in the science classroom. San Diego, CA: National Association for Research on Science Teaching.
Dwyer, D. C., Ringstaff, C., & Sandholtz, J. H. (1991, May). Changes in teachers' beliefs and practices in technology-rich classrooms. *Educational Leadership*, 45-52.
Education Week. (1997). *Technology counts: Schools and reform in the information age*, [WWW]. Education Week. Available: http://www.edweek.org/sreports/tc/.
Fenstermacher, G. D. (1994). The knower and the known: The nature of knowledge in research on teaching. In L. Darling-Hammond (Ed.), *Review of Research in Education* (Vol. 20, pp. 3-56). Washington, DC: American Educational Research Association.
Fishman, B., Best, S., Foster, J., & Marx, R. (2000). Fostering teacher learning in systemic reform: A design proposal for developing professional development. New Orleans, LA: National Association of Research in Science Teaching.
Frechtling, J. A., Sharp, L., Carey, N., & Vaden-Kiernan, N. (1995). *Teacher enhancement programs: A perspective on the last four decades* (Web Document http://www.ehr.nsf.gov/ehr/rec/pubs/eval/tep/tep.htm). Washington, DC: National Science Foundation.
Jackson, S. L., Stratford, S. J., Krajcik, J., & Soloway, E. (1994). Making dynamic modeling accessible to precollege science students. *Interactive Learning Environments, 4*(3), 233-257.
Krajcik, J., Blumenfeld, P., Marx, R., & Soloway, E. (2000). Instructional, curricular, and technological supports for inquiry in science classrooms. In J. Minstrell & E. H. v. Zee (Eds.), *Inquiring into inquiry learning and teaching in science* (pp. 283-315). Washington, D.C.: American Association for the Advancement of Science.
Krajcik, J., Czerniak, C., & Berger, C. (1999). *Teaching children science: A project-based approach*. Boston: McGraw Hill.
Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic Inquiry*. London: Sage Publications.
Marx, R., Blumenfeld, P., Krajcik, J., & Soloway, E. (1997). Enacting project-based science. *Elementary School Journal, 97*(4), 341-358.
Marx, R., Freeman, J., Krajcik, J., & Blumenfeld, P. (1997). Professional development of science teachers. In B. Fraser & K. Tobin (Eds.), *International handbook of science education*. Dordrecht, The Netherlands: Kluwer.
Miles, M., & Huberman, A. (1984). *Qualitative data analysis: A sourcebook of new methods*. Newbury Park, CA: Sage.
National Research Council. (1996). *The national science education standards*. Washington, DC: National Academy Press.

Richardson, V. (1996). The role of attitudes and beliefs in learning to teach. In J. Sikula & T. Buttery & E. Guyton (Eds.), *Handbook of research on teacher education* (pp. 102-119). New York: Simon & Schuster Macmillan.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher*, *15*(2), 4-14.

Shulman, L. S. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review*, *57*(1), 1-22.

Simon, H. A. (1996). *The sciences of the artificial* (Third ed.). Cambridge, MA: MIT Press.

Singer, J., Marx, R. W., Krajcik, J., & Clay-Chambers, J. (2000). Constructing extended inquiry projects: Curriculum materials for science education reform. *Educational Psychologist, 35*(3), 165-178.

Soloway, E., Guzdial, M., & Hay, K. (1994). Learner-centered design: The challenge for HCI in the 21st century. *Interactions, 1*(2), 36-48.

Supovitz, J. A., & Zeif, S. G. (2000). Why they stay away. *Journal of Staff Development*, *21*(4), 24-28.

Von Glasersfeld, E. (1989). Cognition, construction of knowledge, and teaching. *Synthese, 80*, 121-140.

Wallace, R. M., Kupperman, J., Krajcik, J., & Soloway, E. (2000). Science on the web: Students online in a sixth-grade classroom. *Journal of the Learning Sciences, 9*(1), 75-104.

Wilson, S. M., & Berne, J. (1999). Teacher learning and the acquisition of professional knowledge: An examination of research on contemporary professional development. In A. Iran-Nejad & P. D. Pearson (Eds.), *Review of Research in Education* (pp. 173-209). Washington, D.C.: American Educational Research Association.