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Fostering Pedagogical Content Knowledge about Electric Circuits Through Case-Based Professional Development

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Abstract

This paper reports results from one component of a comprehensive evaluation of the *Science Cases for Teacher Learning* project. The study analyzes changes in in-service elementary grade teachers' pedagogical content knowledge about electricity and magnetism before and after they participated in a course centered around science teaching cases. We use the term *pedagogical content knowledge* to refer to understanding what makes the learning of specific topics difficult to learn, and knowledge about ways to formulate, sequence, and represent subject matter to make it comprehensible to learners. In-depth interviews conducted with 18 teachers between 2000-2003 elicited rich information about their (a) perceptions of student difficulties understanding electric circuits; (b) instructional strategies for addressing those difficulties; (c) approaches to helping students understand what would happen if one of the bulbs were unscrewed in a parallel circuit; (d) interpretations of sample student responses to that problem; and (e) instructional strategies they would use to help those particular students. The study was designed to allow comparisons between *different cohorts* of teachers who participated in the project in two successive years; *over time* among pre, post, and one-year follow-up interviews; and *for different amounts and kinds of experience* in the project, including teachers who participated as discussants, facilitators of case discussions, and case writers.

Through iterative review of transcripts, we developed a rubric for analyzing teachers' interview data. In post interviews, teachers more often made accurate statements about science content related to a parallel circuit problem, were better able to describe what makes learning difficult for students, and demonstrated increased detail and complexity in their descriptions of teaching strategies. Teachers also more often gave examples of how students' conceptual difficulties were manifested in student work or performance, and made more explicit links between specific student difficulties and instructional interventions. These gains were even stronger for the second cohort of teachers, an especially powerful result in light of the transfer of course delivery in that year from project staff to teacher-facilitators. Facilitators and case writers demonstrated high levels of content and pedagogical content knowledge along all dimensions in the rubric.

BACKGROUND AND PURPOSE

The fundamental goal of the Science Cases for Teacher Learning project is to foster teachers' pedagogical content knowledge about science. All of the course materials and activities are designed not only to strengthen teachers' knowledge about science content and their repertoires of pedagogical strategies, but also to bring about "the *integration* or the *synthesis* of teachers' pedagogical knowledge and their subject matter knowledge that comprises pedagogical content knowledge" (Cochran, 1992, p. 4). The aspects of pedagogical content knowledge that are central to this work were first identified by Lee Shulman:

> Within the category of pedagogical content knowledge I include . . . the ways of representing and formulating the subject that make it comprehensible to others. . . . [It] also includes an understanding of what makes the learning of specific concepts easy or difficult: the conceptions and preconceptions that students of different ages and backgrounds bring with them to the learning. (Shulman, 1986, p. 9)

Thus, teachers not only need to have a strong grasp of the subject matter content, but also to know how to teach that specific content in a way that actually results in students learning it. Teachers must know "how to organize, sequence, and present the content to cater to the diverse interests and abilities of the students" (Barnett & Hodson, 2001, p. 432). Over time, through the experience of teaching specific content, teachers develop this ability to organize instruction and represent content in a way that takes into consideration students' prior and actively developing concepts (Geddis, 1993; Gudmundsdottir, 1987a, b; Shulman, 1986).

> What is unique about the teaching process is that it requires teachers to "transform" their subject matter knowledge for the purpose of teaching. This transformation occurs as the teacher *critically reflects* on and *interprets* the subject matter; finds multiple ways to *represent* the information as analogies, metaphors, examples, problems, demonstrations, and/or classroom activities; *adapts* the material to students' developmental levels and abilities, gender, prior knowledge, and misconceptions; and finally *tailors* the material to those specific individuals or groups of students to whom the information will be taught. (Shulman, 1986)

In contrast, when they have not had experience teaching specific content, teachers have partial or superficial pedagogical content knowledge (Carpenter, Fennema, Petersen, & Carey, 1988; Feiman-Nemser & Parker, 1990; Gudmundsdottir & Shulman, 1987). Science teachers with little experience in particular content tend to have few ideas about difficulties their students may encounter and used inaccurate analogies and examples when planning instruction related to that content (Hashweh, 1987). Other research has found that when teaching unfamiliar subject matter, science teachers restrict classroom discourse through the use of factual and simple recall questions, and by dominating the speaking floor (Carlsen, 1987; Carlsen, 1990).

Much less is known about the conditions that foster growth of pedagogical content knowledge than on its features and relationships of knowledge structures to classroom practice (Baxter & Lederman, 1999)

> Contemporary research has focused on how to describe teachers' pedagogical content knowledge and how it influences the teaching process. We have yet, however, to clearly understand how it really develops and how better to enhance pedagogical content knowledge in pre-service and in-service programs. (Cochran, 1992, p. 8)

A central assumption underlying the *Science Cases for Teacher Learning* project is that pedagogical content knowledge can be developed through in-service experiences that teach content knowledge in combination with analysis of student thinking about that content, and instructional strategies (as described in (Shinohara, Daehler, & Heller, 2004). Previous analyses of evaluation data for this project have shown significant gains in teachers' science content knowledge, and that of their students (Heller, Daehler, & Shinohara, 2003; Heller & Kaskowitz, 2004). The current qualitative study was designed to trace how the content and pedagogical content knowledge of a small number of teachers changes over the time they participate in this professional development experience. The research addresses the following research questions, in the particular domain of electric circuits:

1. In what ways does the Science Cases for Teacher Learning in-service course on electric circuits impact elementary teachers' science content knowledge?
2. In what ways does the Science Cases for Teacher Learning in-service course on electric circuits impact elementary teachers' pedagogical content knowledge?
   (a) What impact is there on teachers' knowledge about what is likely to make specific science content easy or difficult for students to learn?
   (b) What impact does the course have on teachers' pedagogical strategies?
3. Are changes in teachers' content and pedagogical content knowledge about electric circuits maintained over time?

4. How do changes in teachers' content and pedagogical content knowledge compare in different cohort groups?
5. How do content and pedagogical content knowledge differ among teachers with increasing amounts of experience and responsibility in the project? Specifically, do case facilitators and case writers evidence content and pedagogical content knowledge beyond that achieved by case discussants?

This paper includes results that were obtained over three years of the *Science Cases for Teacher Learning* project (2000-01, 2001-02, and 2002-03 school years). This study was done in the context of an evaluation of the project's impact on participating teachers, including changes in their science content knowledge, pedagogical content knowledge, and reported teaching practices, as well as on the science achievement of their students.

A Case-Based Model of Staff Development

There is substantial evidence that teacher learning experiences that are most closely associated with improved student achievement are those that have a major focus on developing understanding of content, are sustained over time, and provide opportunities for professional dialogue and critical reflection (Weiss, Gellatly, Montgomery, Ridgeway, Templeton, & Whittington, 1999; Cohen & Hill, 1998; Birman, Desimone, Porter, & Garet 2000; Hawley & Valli, 1998). The *Science Cases for Teacher Learning* project promotes close attention to science content, teaching, and student learning through in-depth conversations among teachers. Some of these conversations take place in the context of opportunities for active learning of science content using the same curriculum materials that they use to teach their students. The science cases experience is sustained and intensive, involving monthly meetings over the full school year.

The focus of the science cases approach is on the intersection of knowledge about content and teaching—that is, on teachers' pedagogical content knowledge (Shulman, 1986). We use the term pedagogical content knowledge to refer to understanding what makes the learning of specific topics difficult to learn, and knowledge of ways to formulate, sequence, and represent subject matter to make it comprehensible to learners. Each course session focused on science content as well as teaching and student learning of electricity and magnetism concepts, and included narrative teaching cases, and hands-on experiences that paralleled the science investigations in those cases and supported each district's curriculum (e.g., FOSS *Magnetism and Electricity* unit).

Cases describe real classroom events that took place during actual lessons, events that perplexed, surprised or disappointed the teacher in whose classrooms they originally occurred. Narratives of these episodes are written by classroom teachers under the guidance of project staff, and contain student work, student-teacher dialogue, descriptions of instructional materials and activities, teacher behaviors, and the teacher's thoughts. The resulting case is then used to stimulate discussions among teachers in groups guided by teacher-facilitators.

The power of the *Science Cases for Teacher Learning* approach lies in the coupling of analytic group discussions with purposeful hands-on exploration and structured reflection. Each three-hour session begins with an introductory hands-on science investigation designed to engage participants in the case's core dilemma. For example, the case "A Complete Circuit is a Complete Circle" features a 4th grade teacher who has taught a sequence of lessons on electric circuits. Despite careful planning and good instruction, she is baffled to discover that her students persist in thinking incorrectly about circuits. In the accompanying science investigation, teachers are challenged to make a bulb light using only a battery, a wire, and a small flashlight bulb. Then they compare what works and what does not work to develop their own working definition of a complete circuit.

Following the science investigation, teachers work in small groups to examine student thinking and critically analyze the instruction presented in the case. This leads to a whole-group discussion, where teachers find themselves both wrestling with the science content themselves, and exploring alternative perspectives and solutions to a problem at the heart of the case. The facilitator has a critical role in guiding this inquiry process. Facilitators focus and deepen the discussion, often asking teachers to draw diagrams and use hands-on materials or other resources to illustrate ideas.

METHODS

During the school years discussed in this report, the electricity and magnetism case-based curriculum was implemented with teachers from four San Francisco Bay Area districts. Each year, a different cohort of teachers participated in between 20-50 hours of professional development that focused on science content as well as teaching and student learning of electricity and magnetism concepts. In addition to case discussions, the courses included hands-on experiences that paralleled the students' science investigations in the cases and supported each district's curriculum (e.g., FOSS Magnetism and Electricity unit).

During 2000-01 and 2001-02, major target outcomes in the evaluation framework were investigated with a combination of data collection methods including written surveys, content tests, interviews, and focus group discussions. The evaluation showed that teachers who participated in science case-based discussions and activities made significant gains in their science content knowledge, along with positive changes in their pedagogical content knowledge and teaching practices that were accompanied by significant improvements in student achievement.

This paper provides results from the in-depth teacher interviews, which elicited information about teachers' (a) perceptions of student difficulties understanding electric circuits; (b) instructional strategies for addressing those difficulties; (c) approaches to helping students understand what would happen if one of the bulbs were unscrewed in a parallel circuit; (d) interpretations of sample student responses to that problem; and (e) instructional strategies they would use to help those particular students.

The study was designed to allow comparisons between *different cohorts* of teachers who participated in the project in two successive years; *over time* among pre, post, and one-year follow-up interviews; and *for different amounts and kinds of experience* in the project, including teachers who participated as discussants, facilitators of case discussions, and case writers.

Participants

In 2000-01, 48 kindergarten through fifth grade teachers voluntarily enrolled in case discussions. These included 27 teachers from the Oakland Unified School District. Seven of the Oakland teachers also opted to participate in a two-year facilitator training, leaving 20 regular project participants in Oakland of which 12 were currently teaching third, fourth, or fifth grade. Participating teachers completed written surveys and content tests pre and post. Pre interviews were conducted with all 12 middle elementary grade teachers (see Table 1) and nine of these 12 (hereafter referred to as "Cohort 1") completed the course and were also interviewed at the end of the year. To look at impact over time, four Cohort 1 teachers were again interviewed a year later.

In 2001-02, 36 elementary teachers enrolled in case discussions, including 22 teachers from Oakland. All participating teachers completed written surveys and content tests pre and post, and four middle elementary grade teachers ("Cohort 2") were randomly selected to be interviewed at the beginning and end of the year.

Table 1

Teaching and Science Case Discussion Experience of Interviewees

Measure	2000-01 Case Discussants (*n* = 9)	2001-02 Case Discussants (*n* = 4)	2000-01 Case Writers (*n* = 2)	2002-03 Case Facilitators (*n* = 3)
Years of teaching experience prior to this school year:				
0 to 2 years	2	0	0	0
3 to 5 years	2	1	0	0
6 to 10 years	2	3	0	1
11 to 20 years	1	0	2	1
over 21 years	2	0	0	1
Grades currently taught:				
Kindergarten	0	0	0	1
1	0	0	0	2
3	2	1	0	0
4	4	1	0	0
5	1	0	2	0
Combinations (3/4 or 4/5)	2	2	0	0
Years of teaching science at grade level currently taught:				
0 to 2 years	3	2	1	0
3 to 5 years	2	1	0	1
6 to 10 years	3	1	0	2
11 to 20 years	1	0	1	0
over 21 years	0	0	0	0
Past case discussion experience (as participant)				
None	8	4	1	0
1 year	1	0	0	0
2 or more years	0	0	1	3
Past case discussion experience (as facilitator or case writer)				
2 or more years as facilitator	0	0	0	3
2 or more years as case writer	0	0	2	0
Gender				
Female	6	3	1	1
Male	3	1	1	2

To compare participants with different amounts and kinds of experience in the project, a small group of experienced case writers and case facilitators completed content tests and were interviewed. In 2000-01, two case writers were selected from an existing cadre of 12 who had spent a year co-planning, teaching and collaboratively writing and revising cases about electricity and/or magnetism events that occurred in their classrooms. In 2002-03, three of seven case facilitators were interviewed after they had participated in 80 hours of training over a two-year period. In these trainings, teachers learned the basics of science case facilitation including: characteristics of a good discussion, nature of the facilitator role and specific techniques for drawing groups into deeper discussions of underlying science content and student thinking. Participants also practiced facilitating and received coaching and peer-to-peer feedback.

As shown in Table 1, the case discussants in Cohort 1 and Cohort 2 were elementary level teachers with a wide range of teaching experience, from less than 2 to over 21 years. However, they had more limited experience teaching science at their current grade levels. All but one had no previous case discussion experience. The case facilitators and case writers were all veteran teachers, though the case facilitators had been teaching lower elementary grades for many years.

Intervention

Each year, teachers participated in a case-based course that began with a five-day summer institute and continued with monthly after-school meetings throughout the year for 20-50 hour of professional development. During the summer institute, teachers discussed two cases on electricity and magnetism and participated in other activities to help them become familiar with their district-adopted *FOSS Magnetism and Electricity* materials. For example, they tried the hands-on activities for students, adapted assessment items to reveal student thinking, and analyzed questioning strategies to promote inquiry. In the after-school sessions, teachers discussed six additional cases, participated in hands-on science investigations that mirrored the science presented in each case, and completed homework assignments that connected what was discussed in the cases with teachers' own classrooms.

In the first year for which discussant results are presented, project staff served as the primary facilitators for most case discussions, while several lead teachers from the district co-led other components of the professional development. In addition, novice facilitators who were in training first shadowed project staff, then gradually increased their level of responsibility to include co-facilitating case discussions by the end of the year.

Roles changed in the second year of this study when novices began serving as primary facilitators and co-facilitators of the Cohort 2 participants' discussions instead of project staff. Although staff provided additional training and ongoing facilitator support, novices assumed primary responsibilities for the monthly after-school meetings.

A second significant change occurred between the two years for which discussant results are presented—.course materials and procedures underwent substantial revision based on formative input from discussants, facilitators and the advisory board. For example, the sequence of the science content was rounded out with the addition of several cases, science investigation activities became more tightly focused, and guiding questions were added to the case discussions. Participating teachers spent more time in small-group work prior to whole-group discussions, and the support materials for facilitators were expanded to included detailed procedures and background information.

Instruments

Pedagogical Content Knowledge Interview

The in-depth interview was designed to measure the project's impact on teachers' science content knowledge and pedagogical content knowledge in relation to electric circuits. (See interview protocol in Appendix A.)

The interview contained questions about teachers' (a) conceptualizations of student difficulties understanding circuits; (b) instructional approaches to addressing those difficulties; (c) instructional approaches to helping students understand a specific area of science content—in this case, what would happen if one of the bulbs were unscrewed in a parallel circuit; (d) interpretations of strengths and weaknesses in student responses to that problem; and (e) instructional strategies they would use to help those particular students develop a stronger understanding of what happens in the circuit in terms of the flow of electricity. Teachers were not directly asked to solve the parallel circuit problem used in the interview, but in the process of describing how they would help a student understand the problem, the interviews effectively revealed the teachers' own content knowledge. The combination of questions elicited detailed information about teachers' content knowledge, instructional strategies, reasoning about student knowledge, and pedagogical content knowledge.

Parallel circuit problem. As shown in Figure 1, the problem used in the interviews asks what would happen when one of the light bulbs in a parallel circuit is unscrewed. Because electricity flows in two separate paths in a parallel circuit (one complete circuit from the battery to Bulb 1 and back to the battery, and another complete circuit from the battery to Bulb 2 and back), the remaining bulb would stay lit. Key components required for understanding the flow of electricity in this circuit include:

1. Before Bulb 2 is unscrewed, electric current flows in two independent pathways—from the battery through Bulb 1 and back to the battery, and from the battery through Bulb 2 and back to the battery.
2. When one bulb is unscrewed, the other circuit is still complete.
3. The amount of electric current going to Bulb 1 is the same whether or not the other bulb is screwed in, so the brightness of Bulb 1 remains the same.
4. The battery puts out different amounts of electric current, depending upon the number of bulbs in parallel and the resistance of the bulbs.
5. Bulb 1 does not get brighter because the battery puts out less electric current when only one bulb is screwed in.

To obtain specific information about teachers' pedagogical content knowledge, the interview included questions about teachers' interpretations of different possible student responses to the problem. In the first sample response (shown in Appendix B), the student wrote that the other bulb is brighter when Bulb 2 is unscrewed and explained, "All the electricity goes to the #1 light." Interviewees were also asked about a second scenario in which the student correctly asserted that the brightness of the Bulb 1 would be unchanged when the other bulb was unscrewed.

Content Test

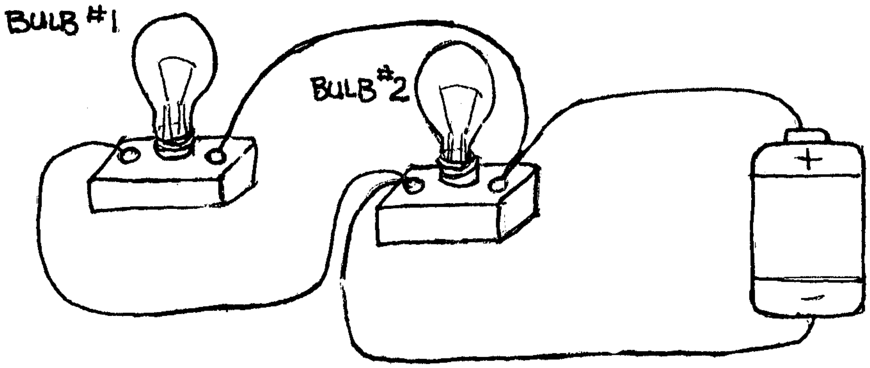
The project developed, pilot tested, and revised Electricity and Magnetism Content Tests for teachers (see Appendix C). The 30-minute assessment was created using questions that reflect the format and content of assessments in curricula such as FOSS and STC, and questions found on the TIMSS and NAEP assessments. Participating teachers in Cohorts 1 and 2 were given the content test at the beginning and end of the project year.

Written Surveys

All participating teachers received a beginning- and an end-of-year survey (see Appendix D for sample survey). The surveys contained questions about teachers' science background, preparedness, attitudes, pedagogy, and students' opportunities to learn. Post surveys incorporated items assessing teachers' perceptions of the value and impact of their

Think about the circuit shown in the picture below.

Imagine you unscrewed the #2 light bulb.



What would happen if you unscrewed the #2 light bulb?

Please explain what you would see in terms of how the flow of electricity affects the brightness of the light.

Figure 1. Parallel circuit problem used in teacher interviews.

participation and how they applied what they learned to their classroom instruction. The survey consisted of both qualitative and quantitative questions, and required roughly 20-30 minutes to complete.

Data Collection Procedures

Each teacher was interviewed individually by the first author or an interviewer whom she hired and trained. Participating teachers in both cohort groups were pulled out of project activities for pre interviews during the first project meeting, and post interviews during the last day of case discussions. Case facilitators and case writers were interviewed at the first author's research office. Each interview lasted roughly 30 minutes and was tape-recorded and transcribed.

Analysis

Interviews were analyzed using a rubric that was developed through iterative review of the transcripts. The rubric (see Appendix E) includes criteria for evaluating the interviewee's *Content Knowledge* in relation to the specific parallel circuit problem used in the interview, including both their *Answer* and *Explanation* and the interviewee's *Pedagogical Content Knowledge*, including both their *Focus on Student Thinking* and descriptions of *Teaching Strategies*. Once the rubric was developed, two researchers working together read through the transcripts while listening to the tapes. They then discussed the responses in each transcript until they reached consensus as to which description in the rubric best fit the interviewee's statements. They then highlighted language on copies of the rubric to identify the phrases that best described the reasoning of each interviewee, and noted line numbers in the transcript where evidence was found.

After all of the transcripts were analyzed and rubrics highlighted, the researchers examined the rubrics and assigned scores on a scale from 1 (*In progress*) through 4 (*Exemplary*) for each interviewee on the two aspects of content knowledge and on the two aspects of pedagogical content knowledge reasoning. Scores were assigned by determining where the preponderance of the highlighted statements were located in the rubric.

The two component scores for PCK were kept separate, but the content subscores for answer and explanation were combined to produce a single, total content score for each interviewee. In almost all cases, the answer and explanation received the same score and the total was simply that score, but when there was a discrepancy, the total score given was that for the explanation. For example, to obtain a 4, both the answer and explanation had to have been rated at the Exemplary level (4). That is, the response would be rated as Exemplary if the teacher both correctly indicated that there would be no change in the other bulb when one bulb was unscrewed, and explained the answer with reference to the amount of electricity flowing to the remaining bulb before and after one bulb is unscrewed. If the teacher gave the correct answer but the reasoning was not completely correct, the response was scored at the lower level to reflect the soundness of the explanation.

Validity of Content Scores

We validated our content assessments by looking at the relationship between the two sets of content scores—one from rubric coding of the interviews and the other from scores on a test of electricity and magnetism. Although the sample size is too small to reach definitive conclusion, the data in Table 2 are consistent with a strong, positive correlation between the two measures.

Table 2
Number of Interviewees with Low and High Scores on Content Posttest versus Content Knowledge Post Interview for Cohorts 1 and 2 Combined (n = 13)

	Content Knowledge score on post interview	
Content posttest score	Low (Rubric score < 4)	High (Rubric score = 4)
Low (< 75% correct)	6	0
High (≥ 75% correct)	1	7

Note. Rubric scores are on a scale from 1 (“In progress”) to 4 (“Exemplary).

RESULTS

Changes in Science Content Knowledge

The in-depth interview provided rich information about teachers’ understanding of the science content involved in the parallel circuit problem. We present first quantitative results generated by the rubric scoring, followed by excerpts from transcripts that show the kinds of changes that occurred in teachers’ understanding of electric circuits.

Score Results for Content Knowledge

There were improvements in both cohorts' content knowledge related to the parallel circuit problem (see Table 3 and Figure 2). As shown in Table 3, content scores were higher for the post interviews, in which six of the nine Cohort 1 teachers and all of the Cohort 2 teachers demonstrated improved understanding of the parallel circuit problem in Figure 1. Mean scores improved by one score point (out of a possible 4) for Cohort 1, and over two score points for Cohort 2.

In the pre interviews none of the teachers in either cohort were able to give complete and accurate explanations (no level 4 scores), and only two out of all the teachers in pre interviews over two years stated the correct answer to the problem (level 3). In contrast, on the post interviews, five of the nine Cohort 1 teachers and three of the four Cohort 2 teachers gave accurate answers accompanied by correct explanations containing no misconceptions (3 or above)—and all but one of these provided a complete (level 4) explanation.

Follow-up interviews (shown in Table 3 and Figure 2) a year after the post interviews with four Cohort 1 teachers indicated that their improved understanding was maintained—all four interviewees demonstrated exactly the same level of content knowledge a year after their participation, at a level higher than the overall mean for content scores on the pre interviews.

Furthermore, all of the case writers and case facilitators demonstrated accurate and complete answers and explanations in the interview.

Examples of Changes in Content Knowledge

Teachers' content knowledge increased in depth, breadth, and accuracy, in ways that were directly related to the content goals of the Electric Circuits course. Examples of the kinds of pre-post changes that occurred in the interviews are provided in Table 4. In the first example, in the pre interview the teacher exhibited a major misconception in asserting that before unscrewing either bulb, one bulb in a parallel circuit is dimmer than the other, and she was not sure what would happen when one of the bulbs was unscrewed. In the post interview this teacher correctly stated that there would be no change in the other bulb and gave a coherent and correct explanation that contained no misconceptions. This explanation included the counterintuitive but correct understanding that the remaining bulb does not get brighter because the battery puts out less electricity when only one bulb is screwed in.

Table 3

Ratings of Pre and Post Science Content Knowledge in Teacher Interviews

	Content knowledge ratings		
Interviewee ID	Pre	Post	Follow-up
00-01 Participants			
101	2	4	-
103	1	1	-
106	1	4	4
109	2	2	-
111	1	2	2
112	3	1	-
113	2	4	4
114	3	4	-
116	2	4	4
Mean	1.89	2.89	3.50
Standard Deviation	(0.78)	(1.36)	(1.00)
01-02 Participants			
202	1	4	-
214	1	3	-
218	1	4	-
219	1	2	-
Mean	1.00	3.25	
Standard Deviation	(0.0)	(0.96)	
02-03 Facilitators			
F1	-	4	-
F2	-	4	-
F3	-	4	-
Mean		4.00	
Standard Deviation		(0)	
00-01 Case Writers			
C1	-	4	-
C2	-	4	-
Mean		4.00	
Standard Deviation		(0)	

Note. Scores are on a scale from 1 (“In progress”) to 4 (“Exemplary) according to the rubric in Appendix E.

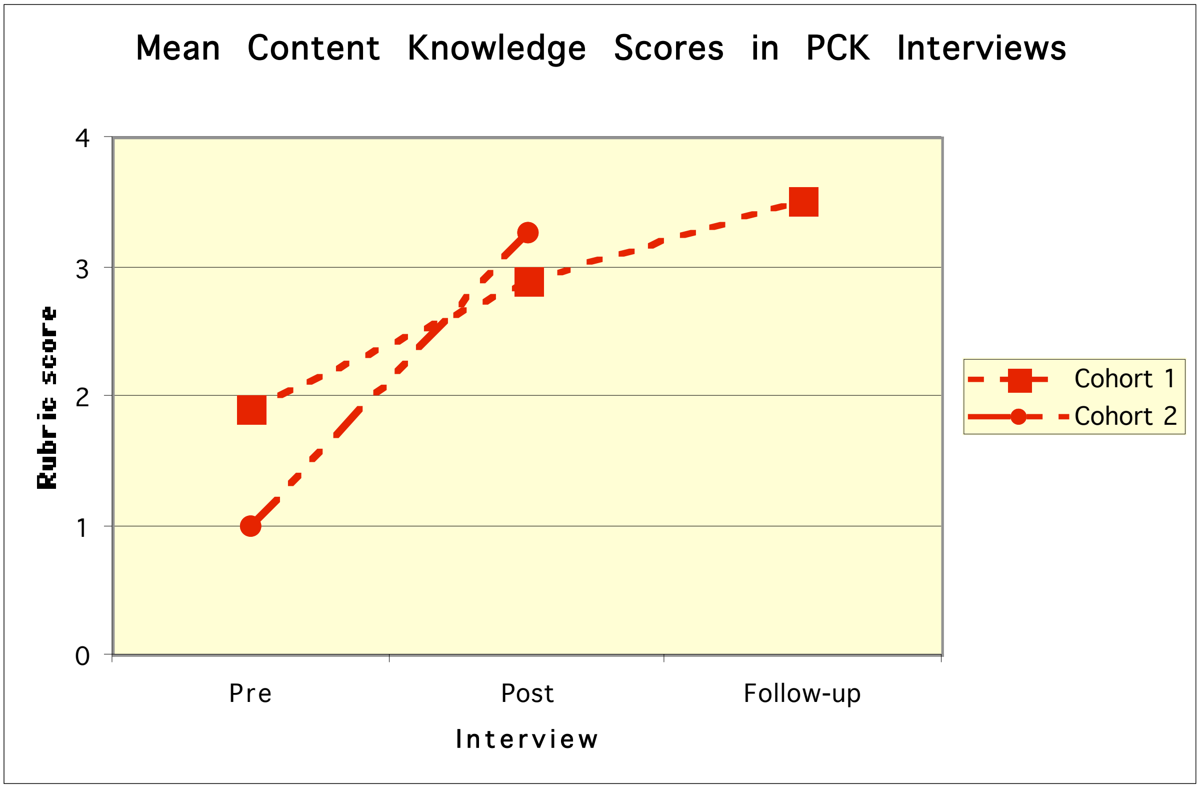


Figure 2. Graph of pre, post, and follow-up rubric scores for science *Content Knowledge* for Cohort 1 (*n* = 9) and Cohort 2 (*n* = 4) in 2000-01 and 2001-02 teacher interviews.

The second and third examples in Table 4 both show teachers who were very uncertain about the answer in the pre interview, but who could correctly identify the diagram as a parallel circuit in the post. All three examples of post interviews show an understanding of how batteries work and how electricity flows in the circuit.

Looking at the content of the teachers' responses reveals the extent to which the Science Cases project is getting across particular important concepts, one of the more challenging being resistance. Whereas none of the teachers in either cohort referred to resistance in pre interviews, just over half of Cohort 1 included correct statements about resistance in their post interview responses, 75% of Cohort 2, and all of the case facilitators and case writers.

Table 4

Pre and Post Responses from Participating Teachers #106, 202, and 214

Pre	Post
Example #1 (Cohort 1)	
T: That presumes that I know what's going on with Bulb 1 and Bulb 2. If I know what's going on, and if I'm correct in thinking that if you unscrew Bulb 2, Bulb 1 will light up, and—or at least have more electricity going to it than it did before. It could be that #1 is very dim, Bulb 2 is bright, and then Bulb 1 will light up completely.. . . See, if you take this bulb (#2) out, you'd think that this bulb (#1) would get brighter. But it might not. . .. I don't really know! If I knew the answer, I'd be able to tell you. (#106, Content Knowledge score level 1)	T: It looks like they are in parallel, and that if you unscrew this (Bulb 2), nothing would happen, it (Bulb 1) would still be lit, and they would both be the same brightness.. . .Well, that would be my explanation, that this is still connected to the battery and there would still be a closed path, even if this (Bulb 2) is unscrewed, the electricity will still see that there's this to go to (Bulb 1), so it should still work. . .. It has to do with the fact that the battery can sense how much resistance is coming up against it, and it will just put out enough—it's lazy! It will only put out enough to light the bulb. As much as necessary. That's all it will do. . .. Because the two resistors are in separate paths, it will put out enough to light each one. It's not as if they're sharing. It just puts out less. (#106, Content Knowledge score level 4)
Example #2 (Cohort 2)	
T: Again I'm not sure if this is a parallel or complete circuit. Or I mean a series. If it was series, it would. . . it would be more or less. I don't know. If it was parallel, it wouldn't matter. If it was in series. . . If you have more batteries, in series, more batteries to supply the bulbs, the more bulbs, the more resistance, so it would be more bright, less bright. I'm not sure. (#202, Content Knowledge score level 1)	T: This is a parallel circuit, so there's different paths the electricity can go. If this one's out, this one is still going to burn. And if this one's out, this one's still going to burn. Because it can go through the bulb and back, or it can go through this one and through that bulb and back the same. Either way it's got two different paths it could go. I want [students] to know that they wouldn't really see a difference in brightness, because it would be a parallel circuit. That it wouldn't be using as much electricity because we were running two bulbs, now we just have one to go through. So our battery might last longer.. . . . [T]he battery is like a commander, it sends out what electricity it detects is needed or wanted. (#202, Content Knowledge score level 4)

Pre	Post
Example #3 (Cohort 2)	
T: Umm. . . I don't know! I'd have to do this in order—I mean, for me, I'd have to see, because I really don't know. So it would be very hard to do it on paper. And I guess if you're talking about—and I'm not even really sure what happens if you take that out. That's part of my problem. But does that make an incomplete circuit? I don't know if that's a circuit or if that's just a result, and the circuit is in here. So that's where I have to honestly say I'm not sure. (#214, Content Knowledge score level 1)	T: Well, that's when we would have talked about series and parallel circuits, and if [the students] really understand those, they'll see that this is a parallel, and that bulb number 2 doesn't affect bulb number 1. Well, the strength [of the student's answer] is that they get that it still would stay on, so they seem to understand that it's a different path in the electricity. The weakness is that they think that the battery is still putting out the same amount of energy with one bulb as it did with two. And I don't believe that's the case. We had a lot of talk about that at WestEd. About how does the battery know how much to put out. . .. But it seems to know, and if you take out Bulb 2 it doesn't keep pumping out the same amount as it was. (#214, Content Knowledge score level 3)

The concept of resistance also stayed with the teachers who were interviewed a year after completing the case discussions. As one teacher explained in her follow-up interview:

> To play the devil's advocate, you could take this approach [with students]. Well, there's electricity that was going through Bulb 2 and it's not anymore, so why doesn't it head on down to Bulb 1 and double the flow for Bulb 1? I'd want [a student] to be able to say, "No, that won't happen because the resistance in Bulb 1 is still the same, so therefore Bulb 1 won't let any more electricity flow through it. It has a certain level of resistance." (#113 follow-up, line 400, Content knowledge score level 4)

Both case writers explained the concept of resistance and noted that it is difficult for students to understand:

> The resistance in the filament of the bulb will cause electricity to slow down. But what's so cool, is it's not like a hose. What's hard to teach is that electricity is not flowing at a certain rate and then it gets jammed up and stops. Actually, before it even leaves the battery, the circuit has a rate established by the amount of resistance in the whole circuit. So it's like it knows ahead of time.(Case writer #1, Content Knowledge score level 4)
>
> As the electrons are traveling through the possible routes of this [parallel] circuit, they encounter one bulb on each circuit, and the filament, where the work is being

> done, where the electricity encounters resistance, is the same for both of these circuits, both portions of the circuits. So the electricity does the same amount of work either way it goes, and therefore both bulbs glow equally, because the electricity basically divides itself up equally to go through them because there's equal amounts of resistance. . . . So at any rate, when you take the second bulb out of here, the electrons [in the first bulb's circuit] still see the same amount of resistance. There's still just one light bulb in the system, with one filament, and so it glows the same. The work that's being done is the same amount of work by the electricity. And that's all very complicated for fifth graders. (Case writer #2, Content Knowledge score level 4)

In summary, at the beginning of each year the teachers struggled when asked how they would help students understand a problem involving a parallel circuit. By the end of the Science Cases course, just over half of the teachers in Cohort 1 and three quarters of Cohort 2 confidently demonstrated sound conceptual understanding of the problem. This strengthening of science content knowledge was essential if teachers were to synthesize pedagogical knowledge and subject matter knowledge to achieve sound pedagogical content knowledge.

Changes in Teachers' Pedagogical Content Knowledge

In this section we show that teachers who participated in the project evidenced increased complexity, accuracy, and sophistication in their pedagogical content knowledge. We first present results related to the teachers' comments about student thinking, and then describe impact on teachers' descriptions of instructional strategies.

Focus on Student Thinking

Ratings of teachers' comments about student thinking were higher overall for the post interviews, in which six of the nine Cohort 1 teachers and half of Cohort 2 demonstrated improvements (see Table 5 and Figure 3). In the pre interviews none of the teachers in either cohort described more than two specific examples of difficulties students encounter when learning about electric circuits (no level 4 scores), and only three out of all the teachers in pre interviews over two years gave any specific examples (level 3). In contrast, on the post interviews, seven of the nine Cohort 1 teachers and three of the four Cohort 2 teachers gave specific examples (3 or above). Facilitators and case writers were able to generate numerous, specific examples.

After participating in the case discussions, teachers were better able to describe what makes learning difficult for students. The teachers were able both to give more examples of students' difficulties, and to describe them in more detail. For example, in the pre interview, many of the teachers speculated that students might have difficulties related to a single, general science topic without elaboration, such as in Example 1 in Table 5 (left column): "I think the concept of short circuits is hard." Several teachers simply said that they did not think that students would find anything difficult (such as in Example 2) or referred to general skills such as students' difficulty explaining their work with circuits (Example 3). On the post interview, these three teachers generated several specific descriptions of what makes learning about circuits confusing or difficult for students.

Thus, there is evidence that over the course of their participation in the project, the teachers became better able to conceptualize the kinds of difficulties students might have. One of the case writers provided a good example of the eventual facility a teacher can exhibit in relation to the large number of student difficulties that can arise in this complex domain:

> The idea of flow was very hard, I think. The acceptance of what a battery is. It's just this sort of mysterious, magical thing that provides electricity, and that electricity comes out of it and goes back into it in a circle or a circuit. You don't really talk about batteries and what they are. They are just a given. . . . Resistance is very hard. The light bulb issues, the fact that in series light bulbs get—the resistance of light bulbs in a series circuit that causes the entire circuit to use less electricity, so it reduces flow. And how on earth could that be true if, in a parallel circuit, it's brighter, there's more flow in it. . . . That's just very, very hard to get across. Also that the number of bulbs and how they are arranged in the circuit affects the way the battery kicks out juice, and the fact that you've got two batteries, it's different than having one. And that's huge too. . . . I guess . . . light bulbs are tricky too. Because . . . the kids don't really think of them as part of the circuit unless you explicitly teach that or have them dissect a bulb so that they can actually look at the wire and the two places the wire touches and forms part of the circuit. That's all not something that's intuitive at all. (Case writer #1, Student Thinking score level 4)

Table 5

Pre and Post Ratings of Pedagogical Content Knowledge in Teacher Interviews – Focus on Student Thinking

	Pedagogical Content Knowledge *Focus on Student Thinking*		
Interviewee ID	Pre	Post	Follow-up
00-01 Participants			
101	3	4	-
103	1	3	-
106	2	3	4
109	1	1	-
111	1	3	3
112	3	3	-
113	2	3	4
114	2	4	-
116	2	2	4
Mean	1.89	2.89	3.75
Standard Deviation	(0.78)	(0.93)	(0.50)
01-02 Participants			
202	3	3	-
214	1	3	-
218	2	4	-
219	2	2	-
Mean	2.00	3.00	
Standard Deviation	(0.82)	(0.82)	
02-03 Facilitators			
F1	-	4	-
F2	-	4	-
F3	-	4	-
Mean		4.00	
Standard Deviation		(0.00)	
00-01 Case Writers			
C1	-	4	-
C2	-	3	-
Mean		3.50	
Standard Deviation		(0.71)	

Note. Scores are on a scale from 1 (“In progress”) to 4 (“Exemplary) according to the rubric in Appendix E.

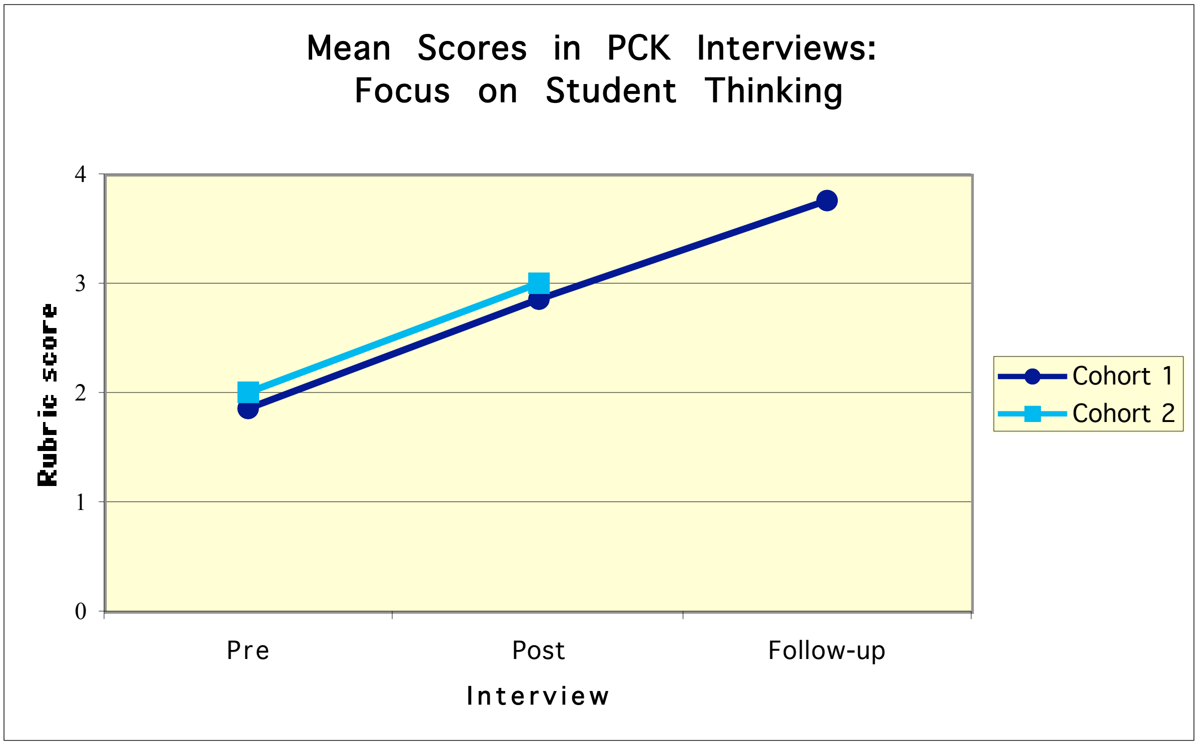


Figure 3. Graph of pre, post, and follow-up rubric scores for *Focus on Student Thinking* for Cohort 1 (*n* = 9) and Cohort 2 (*n* = 4) in 2000-01 and 2001-02 teacher interviews.

Table 6

Pre and Post Responses to Interview Question, "What would you think would be particularly difficult for students at your grade level in learning about complete, open and short circuits?"

Pre	Post
Example 1 (2000-01 project year):	
T: I think the concept of short circuits is hard. It's hard for me. . .. That's just sort of a guess, a good guess. Because I really haven't taught it before. (#114, Focus on Student Thinking score level 2)	T: I guess that some of the things that are not really explicitly taught in the kit, like resistance, and the idea of quantity of electricity that comes out of a battery, the difference between voltage and amperage which we don't teach. It seems to be agreed that it's not a good idea to teach it, but then how do you get at how much electricity is flowing in the circuit and what precisely we mean by flow of electricity? Issues about directionality, the two ends of the battery, and . . . particularly in a complete [series] circuit with more than one item on it, say two light bulbs, that how much electricity is moving through each light bulb, that it's the same amount. . . . And, oh, the architecture of the light bulb . . . if you don't get that, it's pretty hard to make the conceptual leaps about a complete path.(#114, Focus on Student Thinking score level 4)
Example 2 (2000-01 project year):	
T: I would say—nothing is hard for the students to learn if you can plan the lesson in an enjoyable activity, interesting for the students, and simple enough to get them into in-depth knowledge. I don't think there is anything that is hard for students to learn, so it depends on the teacher. . . . Because if I know what to do with the wires and connections and everything, then I can explain it hands-on—you know, model it, demonstrate the procedure step by step, and I think with good classroom management strategy plus good explanation, then if I make it interesting, they usually like to learn. (#111, Focus on Student Thinking score level 1)	T: When I've taught [other] science topics, they always have something concrete to work with, for hands-on activities. For this unit, it's more abstract. Because it's hard to explain the flow of electricity, and then the end result will be whether the light will come on or not. So there's something between there that they cannot see or touch that will affect the end results, so I think that's the hard part. . . .Personally, for me, at the beginning, I was confused with closed and open circuits too. Because I thought a closed one would be shut. It would not be working. The open would be one that is open. So it's in the reverse. I guess the students would have the same misconception. (#111, Focus on Student Thinking score level 3

Pre	Post
Example #3 (2001-02 project year)	
T: I can't remember anything specific [being difficult for students]. . .I know like when we were doing complete circuits, and how you know, you could have a circuit breaker, and then you can close it so that the electricity flows through, there were some kids I remember just, you know, they could show it to you, using the materials, but then when they had to write about it or explain things, I think it was a harder step. (#218, Focus on Student Thinking score level 2)	T: I think one thing that even as adults is a little difficult is how a battery knows how many bulbs it's lighting up and then it sends an appropriate amount [of electricity], you know, it doesn't send the same amount out. It gets really confusing when you have the parallel circuit and there are a lot of bulbs, and if you look at just a simple [series] circuit, and there are the same number of bulbs, the dimness or the brightness differs. That's one thing I think that would be really difficult for fourth graders to understand. . . . Because there isn't really a way to . . . explain really well how a battery knows how much to give out. I think [electricity] is a hard concept to quite really understand. It's just so abstract and you just have to take it by faith, just accept it as truth. (#218, Focus on Student Thinking score level 4)

Some of the teachers also were able to speculate in great detail on the post interview about the thinking that might account for the sample of student work they were asked to comment on (Appendix B). For example, two teachers reasoned as follows about what specific confusion might have led to the student's incorrect response that the remaining bulb would get brighter when one was unscrewed:

> Two light bulbs in a series compared with one light bulb in a series—this is analogous to that in a very broad sense. That you had two light bulbs hooked up, and now the one is gone, and now you have one light bulb hooked up, . . . in which case the bulb would be brighter when it was by itself. . . . And so I think that's what this student is confusing this with. (#116 follow-up, Focus on Student Thinking score level 4)
>
> I'm wondering if this student [in the sample of student work], if he is incorrect, he's transferring knowledge from a series circuit to a parallel circuit. But he's transferring the knowledge from a series circuit, not if you take a bulb out, but instead of having two bulbs being lit up, just one bulb. That's what it looks like to me." (#218 post, Focus on Student Thinking score level 4)

Thus, through participating in this project, teachers became better able to recognize and describe what makes learning about electric circuits difficult for students, and to consider those difficulties when thinking about pedagogical choices. In the next section, we describe in more detail changes in the teachers' reasoning about instructional strategies.

Teaching Strategies

There were no pre-post differences in ratings for the kinds of instructional strategies teachers described in the interviews (see Table 7). Mean ratings were remarkably consistent (averaging around 3.00) from pre to post interviews, for different cohorts, and for participants, facilitators, and case writers. There were few pre-post differences on this dimension for Cohort 1, and none for Cohort 2. However, there were changes in the accuracy, detail, and complexity of responses.

Models and Analogies

Both in pre and post interviews, the teachers described various demonstrations, models, and analogies they would use to help students understand how electricity flows in a circuit. However, because the teachers' science content was more limited on the pre, their representations and analogies were correspondingly more basic. For example, as shown in Table 8, when asked how she would help students understand what happens when they unscrew Bulb 2 in the parallel circuit, on the pre one teacher focused on communicating only the notion of a complete circuit. In contrast, on the post, her more sophisticated knowledge about resistance and the way a battery works prompted her use of a strong analogy using sucking on straws to represent the way in which each circuit in a parallel contains its own separate path for and amount of electric current.

Other accurate models and analogies that only appeared on post and follow-up interviews include:

> The thicker the wire, the more chance there is for the electricity to go through. It's just like a pipe. . . . Isn't there a fair amount of resistance in water? . . . You've got a big pipe, goes right fast, doesn't it? That's sort of the way it is. The water metaphor really does work on that. You want speed in your wires, make them thicker." (#106 follow-up, Teaching Strategies score level 3)
>
> Because we talked about how the D cell, as I understand it . . . is divided down the middle so that two materials that would like to react can. But the way they can react is to go around. I actually used the analogy, because they are going into middle school next year, it's like a dance. And the girls are on one side and the

> boys on the other, and of course they want to dance with each other at the dance, but there's a big wall here. So instead they need to go around. (#113 follow-up, Teaching Strategies score level 4)

Table 7

Ratings of Teaching Strategies in Teacher Interviews

	Pedagogical Content Knowledge Rating		
	Teaching Strategies		
Interviewee ID	Pre	Post	Follow-up
Cohort 1			
101	3	3	-
103	2	3	-
106	2	3	4
109	2	2	-
111	1	3	2
112	4	3	-
113	4	4	3
114	3	3	-
116	3	3	3
Mean	2.67	3.00	3.00
Standard Deviation	1.00	0.50	0.82
Cohort 2			
202	3	3	-
214	3	3	-
218	3	3	-
219	3	3	-
Mean	3.00	3.00	
Standard Deviation	0.00	0.00	
Facilitators			
F1	-	2	-
F2	-	3	-
F3	-	4	-
Mean		3.00	
Standard Deviation		1.00	
Case Writers	-		
C1	-	3	
C2	-	3	
Mean		3.00	
Standard Deviation		0.00	

Note. Scores are on a scale from 1 ("In progress") to 4 ("Exemplary) according to the rubric in Appendix E.

Table 8

Pre and Post Responses from Participating Teacher #214

Pre	Post
It could be any sort of simulation, whether kids are standing together holding hands, and if you take one person out, what happens. . . . You can do things like that to show them a complete circuit, a really simplistic form of it. . . . You could always do that squeezing game. . . . You have the kids hold hands, and somebody squeezes and you have to pass it on. Whatever direction you're squeezed on, you go that way with it. It can demonstrate how electricity will flow. Does it go around counterclockwise or clockwise? I'm not sure! I don't think it's coming out of both ends [of the battery]. But I don't know. (#214, Teaching Strategies score level 3)	I'm trying to think of how you could demonstrate [the flow of electricity in a parallel circuit]. . . . It's sort of like two straws sucking out of a glass, and the glass will keep giving it juice, but if you take that one [pointing to Bulb 2] out, then it just still sucks out enough for that one [Bulb 1]. (#214 post, Teaching Strategies score level 3)

The facilitators and case writers also referred to various models and metaphors to communicate the nature of electricity flow and the concept of resistance:

> I know one of the models we talked about in one of the cases was like follow the Ping-Pong balls, like all the kids in a circle. Because there's a metaphor of a circuit is a circle. . . . The FOSS uses that a circuit is a circle. So you get the kids in a circle, and everybody has a tennis ball or a Ping-Pong ball, and then to show the flow of electricity, they pass it along, and they take from the person next to them, they pass to the person on this side. And it keeps going, and that's kind of a model for showing how the electricity flows in a circuit, how it keeps moving all the time. And nobody is ever without a Ping-Pong ball or a tennis ball, so that's one potential model for showing the flow of electricity in a simple circuit. (Facilitator #3, Teaching Strategies score level 4)
>
> I think using some sort of physical models would be helpful. For instance with demonstrating the flow of electrons. You know, the human model, with passing marbles along, I think would be really helpful. That was helpful to me in just doing it. It made it more concrete and more visual. … There was a lot of discussion about metaphors and whether or not they're useful or more confusing. But I think in a lot of cases it can be very helpful, using metaphors like water in a hose or a tube could be helpful. (Facilitator #2, Teaching Strategies score level 3)
>
> We do modeling about what it would be like for them . . . if they are riding their bicycles and they are applying the brakes very gently, and how that increases the effort they have to put out their pedaling. That's resistance. We try to make it something they can feel as they're looking at these bulbs. (Case writer #2, Teaching Strategies score level 3)

When the teachers were themselves clear about how electricity flows in the circuit, they could detail sharply focused strategies for helping students understand. For example, teachers often emphasized having their students think about and trace different paths for the current:

> I would again ask them to conceptualize where the electricity is flowing. They know that electricity originates in the D cell, with the chemical reaction, and that it's trying to get from the negative back to the positive side. So we unscrew Bulb 2, it no longer has a route through Bulb 2, but it still does have an alternative route through Bulb 1. So I'd want them to think about that. Think about when Bulb 2 was screwed in, it had two routes, and therefore it was taking both routes. But when Bulb 2 was unscrewed, it only has one route. (#113 follow-up, Teaching Strategies score level 3)
>
> This is a parallel circuit, so there's different paths the electricity can go. If this one's out, this one is still going to burn. And if this one's out, this one's still going to burn. Because it can go through the bulb and back, or it can go through this one and through that bulb and back the same. Either way it's got two different paths it could go. (#202 post, Teaching Strategies score level 3)

Linking Teaching Strategies, Student Thinking, and Science

After participating in the case discussions, teachers also gave more examples of how students' conceptual difficulties were manifested in student work or performance, and made explicit links from specific student difficulties to instructional interventions that would address those difficulties. Below are two examples (from a teacher and a case writer) about helping students understand the architecture of the bulb:

> [One student difficulty is] the architecture of the light bulb. . . . If you don't get that, it's pretty hard to make the conceptual leaps about complete path. . . . I think taking a bulb apart is obviously another step in just trying to figure out what's going on inside a light bulb. . . . When you show where the wire is soldered inside the light bulb, . . . for many children, for me, it seemed a close observation can help. I'd never paid that much attention. But I think that if you think about and you explain that the electricity needs some way to get in the bulb and out the bulb, and that you can look at it and see it, I'm sure that some children wouldn't find that, but some would. (#114 post, Focus on Student Thinking score level 4)
>
> I'd say a particular difficulty is that [students] didn't think of the bulb as part of the circuit. The bulb was just an independent little thing. And what I did to deal with that was I went out and found really large clear light bulbs, and had some parents really carefully take off the base of the bulb, and so the kids saw the sticking out part, the wire sticking out and the wire coming down that connected to the base. And so they could actually . . . see how it could be connected to one

> wire and then to the other wire. Then they have to follow and draw how a light bulb, . . . they could see that a light bulb was part of [the circuit]. (Case writer #1, Focus on Student Thinking score level 4)

The facilitators and case writers provided numerous exemplary descriptions of teaching strategies to address students' difficulties. For example, one facilitator described a rationale for using schematic circuit diagrams that was motivated by specific difficulties students have seeing how electricity flows through a parallel circuit:

> In the diagram, [seeing that the electricity has two pathways] can be problematic. The students can have trouble seeing that [the current] goes in here [to Bulb 2] and then it almost looks like it goes backwards out to the other bulb. This is one of the real important things about introducing diagrams. . . . it's a really useful tool because it simplifies the concepts in some ways. So I think giving them experience with both [pictures of actual objects and T-junction schematic diagrams], and having them recognize that this [set of objects] also looks like this in a diagram. It sort of makes it easier to see that when you remove that bulb, this bulb would continue to light. (Facilitator #2, Focus on Student Thinking score level 4)

The teachers often mentioned how important it was to set up situations that would create cognitive dissonance for students, to confront them with evidence that they need to reconcile with their belief.

> I had a couple of kids who didn't get anything! . . . We were doing just one bulb, with two wires and a battery, how can you light the bulb. And [one student] just drew two wires to the tip, and I said, "Michael, is that what we did in class? Did you see that happening?" And he said, "Oh, yeah." "Oh yeah? Try it." So he got the battery, he got the two wires, put it to the tip, no, that's not it. "Oh yeah, now I remember!" And then he put it to the sides. You know, it wasn't that hard to get it across to him. There are some kids that if you actually have them do it again, then they'll get it. It may take more than once for them to get it. They can't just do it once and have it in their heads. (#106 follow-up, Focus on Student Thinking score level 4)

A frequently mentioned strategy was to have the students make predictions, then experience the phenomenon, and think about the discrepancy between their prediction and the evidence. Using this approach, a facilitator described addressing students' misconceptions about the remaining bulb getting brighter by relating the brightness of the bulbs to the amount of electric current:

> I think they would have to have some more experiences with this actual circuit to see that that's not what happens. That'll be a real discrepant event for the kid when you set up this situation, that matches the picture in the diagram, and then they're really going to expect that [remaining bulb] to get brighter. And then when it doesn't, then they're going to want an explanation about why that is. And then you can talk about the bulb as an indicator of the current, and, ask them, "Well, if we agree that the brightness of the bulb indicates the amount of current, then the evidence is that the amount of current is the same now, even with this bulb undone." And then that would get back to what's happening with the battery, that the battery is putting out a different amount of current, depending on what resistance is out there. . . . And they'll be shocked and amazed. And then hopefully it'll make them call into question what they were thinking. (Facilitator #2, Focus on Student Thinking score level 4)

One teacher commented on the fact that this strategy at the same time generates rich information about students' thinking:

> Ideally I think you could ask them to build and ask—you know, put them in a situation where such and such a thing doesn't work and ask them what they think about it, and how could they get it to work. Or why doesn't it work. You could get a better fix on their deeper understanding of the concepts. (#116 follow-up, Focus on Student Thinking score level 4)

Thus, when describing instructional approaches, teachers' comments revealed deeper and more accurate understanding of the science content and of students' ways of thinking about that knowledge.

Organizing Instructional Sequences

The higher levels of the rubric for teaching strategies were intended to detect descriptions of increasingly coherent sequences of learning experiences for students, in contrast to fragmented, disconnected activities. Results indicated that teachers mentioned organized sequences of activities with the same frequency on pre and post interviews, but on the post their sequences contained more subparts, and allowed more systematic comparison of the behavior of different circuits. The descriptions on the post interviews also contained more detail and complexity, as a function of their stronger content knowledge.

Pre-post changes were sometimes stark, such as when a teacher demonstrated very little prior knowledge on the pre, and had meaningful understanding of concepts on the post. For example, as shown in Table 9, one teacher recognized on the pre that it would be important to structure a sequence of experiences for the students, but she did not know enough about the content to specify what such steps might be. On the post, she was able to articulate a sequence of introducing series circuits before parallel, and teaching the students about the flow of electricity and the “different paths” it can take in series versus parallel circuits before posing the kind of circuit problem presented in the interview.

Table 9

Pre and Post Responses from Participating Teacher #214

Pre	Post
Well it seems like if you could set this up with bulb one, two, and three. . . maybe another experiment similar to it, but with another step. Seems like something with the wires, but I don’t know what. Beyond that I can’t think of anything. I’m sure there must be something. It depends on what the goal is, what is the goal for this lesson. I think that’s the big thing. You have to be—what is my goal. Is it just to see—is my goal just to have the child realize what happens if you take out the bulb? Or is it some goal that I am not aware of, not being familiar with that curriculum. I don’t know. #214, Teaching Strategies score level 3)	Well just introduce, do a lesson on series circuits and an activity where they’re using series circuits, and then an activity on parallel circuits, and you know, show them the different paths that it has. And talk about the flow of electricity a lot, and then you could introduce this sort of problem to them and ask them. (#214, Teaching Strategies score level 3)

A facilitator expressed why such structured sequences were important for establishing prerequisite understandings:

> Well, I think, you know, having them really clear on the steps leading up to this [parallel circuit problem] Complete circuits, that if a circuit is interrupted, then there won’t be a current flowing through that circuit—that has to be really clear. They have to know what’s going on in the light bulb. They have to know it’s lighting up because there’s current flowing through that filament and out a different end, and back to the battery. They would have to be pretty firm on the idea of the bulb as an indicator of current, so less light means less current. More light means more current. That really gets to the heart of this. So before they get to this, they have to have quite a bit of background with simpler situations than this. (Facilitator #2, Teaching Strategies score level 3)

An example of teachers’ developing capacity to structure detailed sequences of activities is provided in Table 10. In the pre interview, the teacher emphasized careful observation of what actually happens when you build the apparatus in the problem and unscrew a bulb, followed by a vague mention of adding more lights to see whether it still happens. On the post, the teacher focused on the importance of a carefully ordered sequence of student experiences, first with a simple circuit, then series, and finally parallel.

Table 10
Pre and Post Responses from Participating Teacher #101

Pre	Post
Perhaps going back to the idea of observing exactly when the bulb went out, watching it in terms of unscrewing it slowly and seeing what change might happen. [pause] Perhaps lights in a circuit. You know, adding more lights to the circuit, and trying to see whether it happens with three or four lights, and at what point. (#101, Teaching Strategies score level 3)	Well, I would allow them to unscrew it and see if the results are different, to see how the results vary if they do. But they would have to have the prior experience of a simpler circuit first, of a circuit with just one bulb. And then going into circuits with two bulbs and seeing how it lights, and then telling them to unscrew and screw in and see what differences they see. And to hypothesize from that, I think. (#101, Teaching Strategies score level 3)

Another teacher (see Table 11) also described providing the students with a careful sequence of different circuits, but he raised a concern about students' getting confused or not remembering from one circuit to the next.

Table 11
Pre and Post Responses from Participating Teacher #116

Pre	Post
I would think diagrams would help [students understand the problem], and then also since we'll have the materials on the table in front of them, . . . you could have students . . . remove this and see what happens, remove this and see what happens, and have students make observations about what arrangements allowed the bulbs to stay lit. (#116, lines 115-119, Teaching Strategies score level 3)	So we would build a circuit just like in the picture here and disconnect bulb number two, and observe that bulb number one doesn't get brighter. . . . Other than that, it's useful to build the series and compare it and trace the path. I think if they could build the two lights in parallel, connect and disconnect the involved light bulbs, trace paths when it's connected and disconnected, and pair that up with, okay, the brightness of these bulbs when it's getting its full electricity, and then to run through all the steps on this series too. Here we have half the brightness, two bulbs in series—just show them all the possibilities. May be if they are presented with all those variables moving at the same time, [it would be good] to make a table or some kind of record. Because if you say, one bulb, two bulbs, parallel, series, brightness, half brightness—if the child was already confused, then it's not enough to show them everything and say, "Look at this, look at this, remember this, remember this." But to go at whatever speed and record things and diagram things and trace things until the kid is able to replicate it themselves and talk about it themselves. (#116 post Teaching Strategies score level 3)

Whereas on the post interview in Table 11, teacher #116 had the students record their observations to address the problem of students' unreliable memories, on the follow-up he solved the problem by having the students build more than one circuit at a time so they could simultaneously compare the results:

> I would have them build this [parallel circuit with two bulbs] and then take out light bulb 2 and compare that with what you thought was going to happen. And they would realize that light bulb 1 did not get brighter. And then we could build a circuit with one light bulb in a series, and compare the brightness of two light bulbs in a series with one light bulb in a series, and if we could build all three of those setups, and look at them simultaneously, I could have the student identify, well, "When and where do you see the light bulb getting brighter or dimmer?" (#116 follow-up Teaching Strategies score level 3)

Another teacher also described in her post interview this strategy of building a number of circuits and systematically comparing what happens before and after a bulb is unscrewed in each one, as well as recording information in journals (see Table 12). In contrast, on the pre she only mentioned providing hands-on materials and having the students "do it," presumably meaning build the one circuit in the problem situation and unscrew a bulb.

Table 12
Pre and Post Responses from Participating Teacher #106

Pre	Post
Well, first of all, the kids would all have to do it. They'd all have to have it in front of them. (#106, Teaching Strategies score level 2)	Well, we would certainly start with series. We would start with series and put . . . one battery, two bulbs, in a series, you know, the bulbs connected to each other, and see the difference between one battery and two bulbs [in series] . . . and then both bulbs being connected to the battery [in parallel] versus just to each other. And to compare the difference, unscrew one and see what happens. You unscrew it over here and unscrew it over here, this one stays on and this one goes out. . . . I would have them build different circuits . . . and see exactly what really happens. (#106, PCK2 score level 3) And then we would also do schematics. I'm really definitely planning to teach them schematics, how do to the schematics and how to represent it, so that we can do it in the journals, and talk about it afterwards. They have schematics in the journals so that we can talk about it without having to have the stuff in front of them. (#106, post Teaching Strategies score level 3)

On the follow-up a year later, this same teacher described having used exactly this strategy of simultaneous comparison with his current class, using groups of students who built and compared different circuits:

> We had series circuits—I had groups of 4, and we had groups on this side test a series with 2 or 3 bulbs, and group on that side did the parallel with 3 bulbs. And

> then we compared them. What happens when you unscrew one bulb here, they all go out. What happens when we unscrew one bulb there, the other two stay on. How come? (#106 follow-up Teaching Strategies score level 4)

The strategy of systematic comparison was applied by a facilitator to the problem of helping students think about the amount of electric current flowing in different circuits.

> I would want to go back and compare, have them build the parallel circuit, and build a simple circuit, and compare the brightness of the two . . . . Next I would have him build maybe two parallel circuits, side by side, so that he has two of them, first. And then a third simple circuit. Then I would have him take out bulb number 2 and have him compare it to the parallel circuits, to see if bulb number 1 was brighter than either of the lights in the parallel circuit. So that he could see that it didn't get any brighter. Something had to be adjusted to the flow, and then compare it to a simple circuit. He would see the brightness of a simple circuit, so that he could know that the flow in the simple circuit was the same as the flow in that parallel circuit with the bulb gone. (Facilitator #1, Teaching Strategies score level 2)

Finally, in the example shown in Table 13, a teacher described the same basic comparison between series and parallel circuits pre and post, but in the latter she elaborated in detail the procedures she would use to help the students trace and understand the flow of electricity.

Summary of Results

All of the rubric score results are summarized in Figure 4 for two cohorts of teachers. The graph shows mean pre, post, and follow-up scores for teachers' science *Content Knowledge* in relation to the specific parallel circuit problem used in the interview, and their *Pedagogical Content Knowledge*, including both their *Focus on Student Thinking* and descriptions of *Teaching Strategies*. Although the details are easier to see on the graphs in Figures 2 and 3, the overall pattern among all of the scores can be seen best in Figure 4. First, there were large improvements in rubric scores from pre to post interviews for both cohorts on all but the Teaching Strategies dimension, for which qualitative analysis showed that changes were more nuanced. Second, changes were most pronounced for Content Knowledge for Cohort 2, after the course materials and procedures underwent a significant revision and course leadership was transferred to teacher facilitators. Finally, scores on follow-up interviews a year after the post, for a subset of Cohort 1 teachers, were at or above post score levels.

Table 13

Pre and Post Responses from Participating Teacher #202

Pre	Post
I think I would design a few experiments . . . where they have series and parallel circuits, and compare them, how they would affect each other, and what happens in a series if the circuit, like if it was a series circuit, what happens if that series is interrupted. Would it shut down the whole system, or would [the current] be able to branch around and go through? You know, vary the power source, so it would put more voltage going through a series circuit, so they get the relationship between voltage and current, and then comparing that to parallel and see how that's different. (#202, Teaching Strategies score level 3)	Well, I think I would set up—or let them set it up, just like it is there [in the problem], and then also set up a series circuit, so two bulbs and one battery in a series. And then tell them, "Okay, this is where the electricity comes from." Just point to one end, and say, okay this is where it starts. I want you to show me where it goes. Where it ends up." And do that for both circuits. . . . I guess I would start with them both screwed in, so they can [realize] "Oh! It's got a choice here. It can go both ways. It can go through the bulb, or it can go through here. And if I unscrew one, well it can't go through that one, but it can still go through there." . . . Then they'd want to do it with the series, and they'd go "Well, it's only got one way through here! The only way it can get over to this bulb is going through this and it can't make it around, there's no escape." . . . [Then] maybe add another bulb onto the series version and another bulb onto this [parallel] one, and show these [in the parallel circuit] stay the same, those [in the series circuit] get dimmer. So that they can see that the amount of electricity . . . is being consumed differently in the two circuits. (#202, Teaching Strategies score level 3)

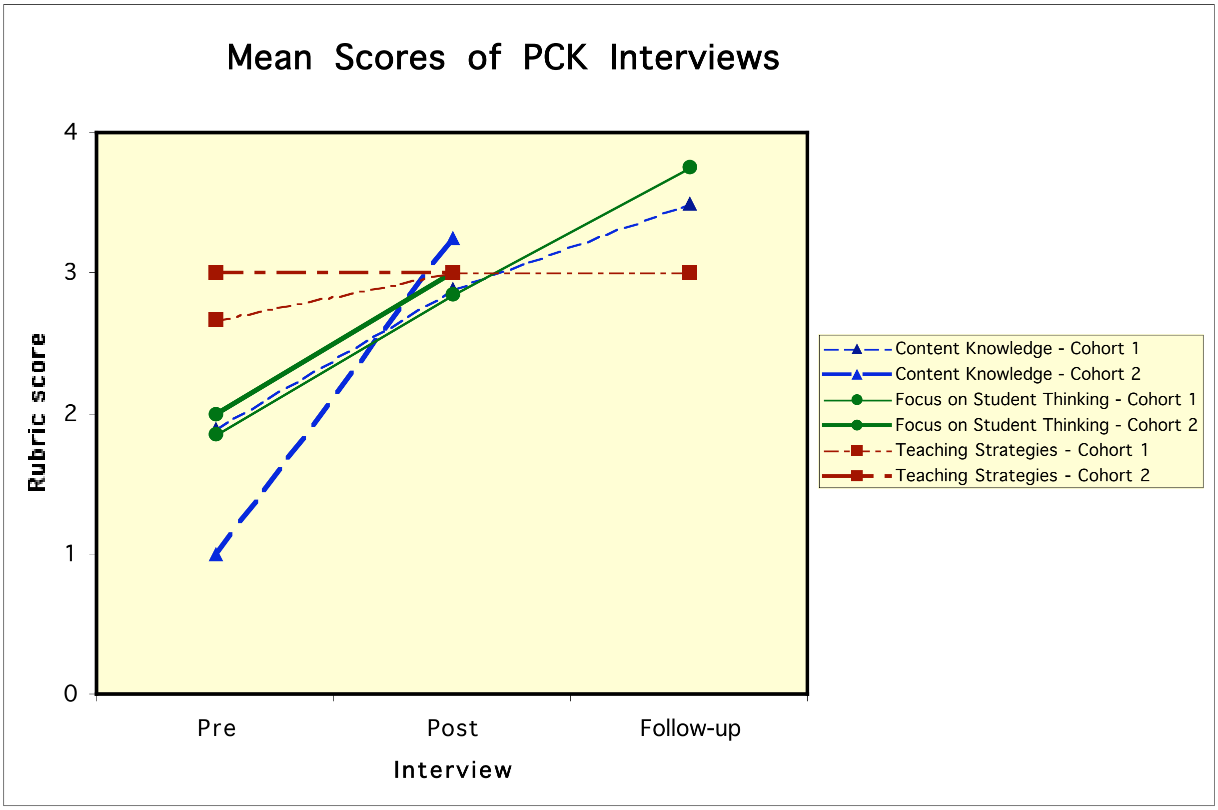


Figure 4. Graph of mean pre, post, and follow-up rubric scores for *Content Knowledge*, *Focus on Student Thinking*, and *Teaching Strategies* for Cohort 1 (*n* = 9) and Cohort 2 (*n* = 4) in 2000-01 and 2001-02 teacher interviews.

Closer analysis of interview transcripts in each score category revealed a rich variety of ways in which teachers' content and pedagogical content knowledge changed over time. Results in relation to the research questions were as follows.

1. *In what ways does the Science Cases for Teacher Learning in-service course on electric circuits impact elementary teachers' science content knowledge?* There were large pre-post gains in Content Knowledge scores of interview responses for different cohort groups in two successive years. Mean scores improved by one score point (out of a possible 4) for Cohort 1, and over two score points for Cohort 2. By the end of the Science Cases course, just over half of the teachers in Cohort 1 and three quarters of Cohort 2 confidently demonstrated sound conceptual understanding of the problem. Teachers' content knowledge increased in depth, breadth, and accuracy, in ways that were directly related to the content goals of the Electric

Circuits course. The teachers exhibited fewer misconceptions on the post interviews, and evidenced correct understanding of new, more complex concepts such as resistance.

2. *In what ways does the Science Cases for Teacher Learning in-service course on electric circuits impact elementary teachers' pedagogical content knowledge? (a) What impact is there on teachers' knowledge about what is likely to make specific science content easy or difficult for students to learn?* After participating in the case discussions, teachers were better able to describe what makes learning about electric circuits difficult for students. The teachers were able to give more examples of the kinds of difficulties students might have, to describe them in more detail, and to speculate in greater detail about the thinking and student conceptions that might account for samples of student work.

   (b) What impact does the course have on teachers' pedagogical strategies? After the course, teachers made more explicit connections between specific student difficulties and instructional interventions that would address those difficulties. At the same time, the teaching strategies they described reflected deeper and more accurate insight into the nature of the science content. For example, teachers mentioned organized sequences of instructional activities with the same frequency on pre and post interviews, but their sequences on the post were more elaborate, addressed students' common misunderstandings about the flow of electricity, and were ordered in a way that allowed more systematic comparison of the behavior of circuits with different properties. The descriptions on the post interviews also contained more detail and complexity.
3. *Are changes in teachers' content and pedagogical content knowledge about electric circuits maintained over time?* Follow-up interviews with four Cohort 1 teachers indicated that pre-post gains in content knowledge were maintained—all four interviewees demonstrated exactly the same level of content knowledge a year after their post interviews. With respect to teachers' reasoning about student thinking, all of the teachers were at or above their post-level scores—and three of the four teachers scored at the highest level on this aspect of pedagogical content knowledge after a year, whereas none of them had on the post interviews.
4. *How do changes in teachers' content and pedagogical content knowledge compare in different cohort groups?* The kinds of changes that were found for Cohort 1 in 2000-01 were

replicated the next year with Cohort 2, with even greater changes in science content knowledge in the second year, after course materials were revised.

5. *How do content and pedagogical content knowledge differ among teachers with increasing amounts of experience and responsibility in the project? Specifically, do case facilitators and case writers evidence content and pedagogical content knowledge beyond that achieved by case discussants?* All of the case writers and case facilitators scored at the highest levels with respect to content knowledge—they demonstrated accurate and complete answers and explanations about what would happen if a bulb were unscrewed in a parallel circuit. These results were stronger than about half of the teacher discussants' scores, even on their post interviews. The facilitators and case writers were also stronger than the discussants on the *Focus on Student Thinking* aspect of pedagogical content knowledge, but were indistinguishable with respect to scores on *Teaching Strategies*.

Conclusion

This study provides evidence of impressive and sustained pre-post gains in elementary grade teachers' pedagogical content knowledge about electric circuits after they complete the *Science Cases for Teacher Learning* course on this topic. The pattern of outcomes suggests particular ways in which the Science Cases teacher professional development experience might have contributed to these results.

There is a direct relationship between gains in teachers' pedagogical content knowledge and critical design features of the professional development experience. The *Science Cases for Teacher Learning* courses are based on the premise that, to develop pedagogical content knowledge, teachers must have opportunities to learn subject matter content in combination with the analysis of student thinking and instructional strategies. The professional development model therefore includes three main features: *Exploration of Scientific Meanings*, *Focus on Student Thinking*, and *Critical Analysis of Practice*. These features are woven together through every major activity in course sessions, such as during science investigations and case discussions. Thus, teachers' attention to any one of the features is always in the context of the other two. It is consistent with these emphases that teachers demonstrated improvements in their science content knowledge, ability to interpret student thinking about the science, and the quality of their instructional strategies they described.

The professional development model acknowledges, and mirrors, the complexity and interconnected nature of pedagogical content knowledge. The Science Cases courses target specific pedagogical content outcomes, not just separate outcomes for subject matter content, student thinking, and pedagogy. Course sessions provide opportunities for teachers to link instructional decision-making to particular student difficulties, in a way that takes into account challenges inherent in the structure and process of the science. As a result, the teachers emerge more able to construct representations and sequences of learning experiences for the students that both logically encompass the nature of science, and anticipate or address possible student difficulties.

Developing teachers' pedagogical content knowledge requires equally vigorous attention to developing their content knowledge. In this study, only teachers who themselves had a deep and accurate understanding of the science were able to provide strong interpretations of student work and identify numerous sources of difficulty for students. Similarly, highly detailed and complex reasoning about instruction was only observed when teachers also had a solid understanding of the science. The Science Cases course provides multiple opportunities for teachers to learn the content, throughout every activity in each course session. However, science content is communicated most directly and explicitly through Content Notes that are distributed with each case, and by engaging teachers in Science Investigations. The Science Investigation combines analytic group discussions with purposeful hands-on exploration of the science related to the case. Focused by a set of guiding questions and activities, teachers replicate the instructional activities experienced by students in the case. The goal is to develop an adult understanding of the underlying science, and uncover different ways of thinking about those ideas. Together the teachers interpret the hands-on evidence, discover different ways of interpreting the data, and explore the logic behind common yet incorrect student (and adult) ideas about the science. The significant gains observed in teachers' content knowledge scores reflect the effectiveness of this multi-faceted approach. The fact that these gains were even stronger for Cohort 2 than Cohort 1 is especially powerful in light of the transfer of course delivery for the second cohort from project staff to teacher-facilitators.

Less is more. A fundamental design feature of Science Cases courses is that they take extended time to develop concepts in depth, in a way that builds on and returns to core concepts over a series of meetings. The *Electric Circuits* course studied for the current paper, for example, targets content and pedagogical content knowledge related to the teaching of electric circuits in grades 3-6. The course targets roughly 60 specific outcomes for teacher learning which fall into four groups: major ideas of K-8 science; common ways of teaching those ideas; parts of the idea frequently understood, missed, or misunderstood by students; and tradeoffs of the common teaching approaches above. It is necessary to constrain the breadth of content coverage if the courses are to strengthen teachers' content and pedagogical content knowledge in relation to these intended outcomes.

Maintenance of gains is made possible by multiple interconnections among components. The three-fold focus, plus an interconnected approach, and the choice to take on less content in great depth, offers a rich learning experience with many "hooks" for teachers to situate their new knowledge. Such an intense and intentional design may account for the maintenance of gains in teacher knowledge from one year to the next.

Finally, we end with some comments on the methodology used in this study to measure teachers' pedagogical content knowledge. The study relied on one source of evidence—teachers' verbal responses during an in-depth interview. The interview was highly effective at eliciting the kinds of rich information it was designed to generate, namely teachers' knowledge about topics in the domain of electric circuits, their ability to articulate what makes learning those topics difficult for students, and their reasoning about instructional strategies for addressing those difficulties. A rubric was created to describe and quantify teachers' responses. Based on scores produced using the rubric, changes were detected in teachers' content knowledge and thinking about students' thinking, but scores of the kinds of instructional strategies teachers described did not change from pre to post interviews. Examination of the teachers' descriptions of instructional strategies revealed important changes in the quality, detail, and scientific accuracy that were not captured by the rubric. The rubric should be revised to make it more sensitive to changes in descriptions of teaching strategies. Furthermore, attention should be given in the future to discovering whether less labor-intensive methods may capture some of the information that was obtained here through in-depth interviews. Such methods are needed to evaluate on a larger scale the impact of professional development efforts on pedagogical content knowledge.

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Appendix A

SCIENCE CASE METHODS PROJECT
Teacher Interview (Post Electricity)
April 2001

Materials needed
- *circuit problem, blank and with student response*
- *2 pencils*
- *tape recorder with counter function and batteries*
- *labeled and blank tapes*

Before starting to tape
- *Do a sound test*
- *Set counter on tape recorder to 000*
- *Record starting time* __________

General interviewer instructions

Start the tape, introduce yourself, give the name of the interviewee and the date. Tell a little about yourself by way of an introduction to the teacher. During the interview, make liberal use of general follow-up prompts, like: "Tell me more about that," *and* "Can you give me an example from your own classroom?" *Record tape recorder counter times at the beginning of each question.*

Begin interview here

The purpose of this interview is to give you an opportunity to tell us about your experience teaching electricity. We realize that electricity concepts are particularly difficult to teach and we would like to ask you a few questions about how you approach it.

I'd like to audio tape this interview because otherwise I won't remember what you say. Is that okay with you?

Please let me know if you want the tape recorder stopped at any time for any reason.

____________ 1. Ok, I'd like to start by asking you a bit about your science teaching.
Counter

1a. About how many case discussions have you participated in? __

1b. Have you ever taught electricity? _______

1c. Have you taught electricity this year, or are you planning to? ______

[if yes] When during the year did [or will] you teach the unit involving circuits? (approximate month) ______________

1d. [if have taught electricity]

What have you found particularly difficult for students at your grade level when learning about complete, open, and short circuits?

Can you describe a specific example of a student with one of these difficulties?

What did you do?

What might you do if this happened again?

1e. [If have not taught electricity]

What do you think would be particularly difficult for students at your grade level when learning about complete, open, and short circuits?

What would you do if students had these problems?

2. Here is a problem involving a circuit. [Hand interviewee the circuit problem. Leave pencil & paper available.]

____
Counter

2a. How would you go about helping your students understand what happens when they unscrew the #2 light bulb?

2b. How would you help your students understand this in terms of flow of electricity?

2c. What would you want your (or fourth/fifth grade) students to include in their explanations?

[If interviewee says the #1 bulb would stay lit] What would you say about the brightness of the #1 bulb after the #2 bulb was unscrewed? Would it stay the same, get brighter, or get dimmer? ________________

2d. What about if the problem asked what would happen if you unscrew bulb #1 instead of bulb #2? How would you help your students understand what would happen?

6. Here is one student's response to this question. [Hand interviewee the circuit problem with student response. Leave pencil and paper available.]

____
Counter

This was a written problem and the student did not have access to the apparatus when answering the questions.

3a. How would you interpret this student's response? What are both the strengths and weaknesses in the student's understanding?

3b. Based on this student's response, describe in detail one or more instructional strategies you would use with this student to develop a stronger understanding of what happens in terms of the flow of electricity.

3c. What is another approach you might use?

4. Suppose another student said that the #1 bulb would stay on but not get brighter, because it still gets the same amount of electricity.

____
Counter

How would you interpret that student's response? What would the strengths and weaknesses be in that explanation?

5. Is there anything else that you would like to add that we haven't discussed?

Thank you very much!
STOP RECORDER. Record ending counter and time.

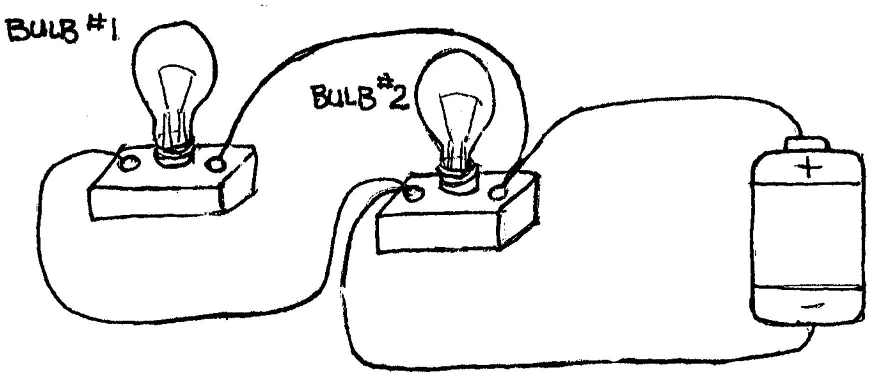
____
Counter

____
Ending time

Appendix B. Sample of student work on parallel circuit problem.

Think about the circuit shown in the picture below.

Imagine you unscrewed the #2 light bulb.



What would happen if you unscrewed the #2 light bulb?

brighter

Please explain what you would see in terms of how the flow of electricity affects the brightness of the light.

When I took out a light the other one was brighter. All the electricity goes to the #1 light. That is why it is bright.

Appendix C – Rubric for Analysis of Interviews

	Content Knowledge		Pedagogical Content Knowledge	
Level	Answer	Reasoning	Focus on student thinking (PCK1)	Teaching strategies (PCK2)
4 Exemplary	• Correct answer (no change in the other bulb).	• Coherent and correct explanation; response contains no misconceptions. • Proficient plus one of: --Resistance affects flow from battery. --Analysis in terms of Ohm's Law --Bulb does not get brighter because battery puts out less electricity when only one bulb is screwed in (or vice versa). --Amount of electricity going to bulb #1 is the same whether or not other bulb is screwed in.	• Three or more specific descriptions of what makes learning difficult in terms of science and student cognition (e.g., conceptual or perceptual difficulties • Two or more explicit links between specific student difficulties and instruction May mention: • At least one example of how conceptual difficulties are manifested in student work or behavior	• Coherent instruction with multiple strategies involving systematic student inquiry (e.g., exploration, prediction, experimentation, discussion, explanation, hypothesis testing). • At least two representations of electricity flow underlying hands-on experience (e.g., circuit diagrams, written or verbal explanations, or student role-playing). May mention: • Specific learning objectives underlying two or more instructional decisions. • Teacher joins in the learning.
3 Proficient	• Correct answer but uncertain (e.g., thinks there is probably no change in the other bulb).	• Reasonable but incomplete explanation. • Correct explanation includes any of: --Problem involves parallel circuit. --Still have complete circuit when one bulb is unscrewed. --Bulbs are of equal brightness before one is unscrewed. --Unscrewed bulb goes out, or gets no electricity. --Electricity flows in one direction --Before bulb is unscrewed, electricity flows in two independent pathways. --Bulb is part of circuit.	• One or two specific descriptions of what makes learning difficult in terms of science and student cognition (e.g., conceptual or perceptual difficulties) • At least one explicit link between specific student difficulty and instruction May mention: • Reference to student prior knowledge	• At least one strategy involving systematic student inquiry or structured sequence of hands-on activities. • At least one representation of electricity flow underlying hands-on experience (e.g., circuit diagrams, written or verbal explanations or predictions, or student role-playing). May mention: • Specific learning objectives underlying one or more instructional decisions.
2 Basic	• Partially correct (e.g., other bulb would stay on but would get brighter, or not sure whether it would stay the same or get brighter, or doesn't mention brightness).	• Flawed explanation, illogical argument or disconnected fragments. • Misconception such as: --Remaining bulb gets brighter because it doesn't have to share electricity now.	• Mention of student difficulties related to science topics, vocabulary, or general skills, or not sure what students understand • May be links between instruction and student difficulties related to science topics or general skills	• Fragmented, disconnected student activities • Unstructured hands-on exploration or individual hands-on activity so students can experience phenomenon. May mention: • Vague or general learning objectives or mention of objectives not tied to instruction.
1 In progress	• Incorrect (e.g., other bulb would go out too or be very dim) • Not sure what would happen, or multiple answers.	• Vague or very general explanation. • Major misconceptions (e.g., little or no electricity reaches remaining bulb). --Before unscrewing either bulb, one bulb is dimmer than the other --Electricity flows out of both ends of the battery	• Classroom management, logistical, or language concerns not related to science content • Claim that students have had (or would have) no difficulties	• Teacher presentation, demonstration, diagramming, and explanation. • Reference to medium or form of instruction, not content.
0	• No answer.	• No explanation.	• No student difficulties described.	• No instructional strategies described.