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Paper Title: **Understanding Conceptual Change Teaching Through Case Studies of Students' Learning**

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Abstract: A considerable consensus has evolved that in coming to understand science, students' learning must be viewed as a process of conceptual change (Driver, 1989; Strike & Posner, 1992; Smith, 1991). At the same time, it is recognized that appropriate teaching strategies cannot be derived in any straight-forward way from a view of learning as conceptual change (Scott, Asoko & Driver, 1991; Thorley & Stofflett, 1993). Furthermore, learning to teach for conceptual change is recognized as difficult (e.g. Erickson & MacKinnon, 1991). Anderson and Smith (1987) note that the knowledge base for such teaching is three-fold, requiring thorough understanding of the subject matter, knowledge of students' views about key conceptions, and knowledge of appropriate conceptual change teaching strategies. This paper describes the growth in the understanding of conceptual change teaching by a fifth grade teacher and a collaborating researcher, as they grappled with the "phenomena" of science teaching and learning in two of the teacher's classes. The teacher, an experienced specialist in science, had considerable curricular freedom and was able to devote about six weeks of instructional time to the topic of current electricity with the two classes. The researcher, a former physics teacher with a comprehensive knowledge of the literature on students' conceptions and conceptual change teaching, also spent considerable time in the classes and in interviewing students.

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Understanding Conceptual Change Teaching Through Case Studies of Students' Learning

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INTRODUCTION

A considerable consensus has evolved that in coming to understand science, students' learning must be viewed as a process of conceptual change (Driver, 1989; Strike & Posner, 1992; Smith, 1991). At the same time, it is recognized that appropriate teaching strategies cannot be derived in any straight-forward way from a view of learning as conceptual change (Scott, Asoko & Driver, 1991; Thorley & Stofflett, 1993). Furthermore, learning to teach for conceptual change is recognized as difficult (e.g. Erickson & MacKinnon, 1991). Anderson and Smith (1987) note that the knowledge base for such teaching is three-fold, requiring thorough understanding of the subject matter, knowledge of students' views about key conceptions, and knowledge of appropriate conceptual change teaching strategies. This paper describes the growth in the understanding of conceptual change teaching by a fifth grade teacher and a collaborating researcher, as they grappled with the "phenomena" of science teaching and learning in two of the teacher's classes. The teacher, an experienced specialist in science, had considerable curricular freedom and was able to devote about six weeks of instructional time to the topic of current electricity with the two classes. The researcher, a former physics teacher with a comprehensive knowledge of the literature on students' conceptions and conceptual change teaching, also spent considerable time in the classes and in interviewing students.

The instructional unit emphasized students' construction of mental models about electric circuits. It embodied a view of science as the construction and evaluation, by the scientific community, of models and theories to explain evidence about natural phenomena. There was little emphasis on presenting structured accounts of current scientific theories or even on the exercise of the "scientific method", as it is usually conceived, involving the induction of patterns and hypotheses from a base of observations. Such a curricular emphasis on the building of mental models has been used with some success with older students (e.g. Stewart & Hafner, 1991). In terms of developmental appropriateness, we were marginally ambitious. The ability to separately conceptualize and coordinate theory and evidence, described by Kuhn, Amsel and O'Loughlin (1988) as an essential component of scientific thinking, would, according to their research, be only beginning to emerge in the typical fifth grade student. There was thus an element of exploration in our research. In the classroom, frequent use was made of "Predict-Explain-Observe-Explain" activities (Champagne, Gunstone & Klopfer, 1985), usually involving small-group and whole-class discussions. These discussions and activities encouraged students to articulate their theories about scientific phenomena, and test them against the views of other students and laboratory observations.

This paper focuses on the teacher's and researcher's growth in understanding of conceptual change learning and teaching as evidence of students' learning was assembled, analyzed and interpreted. Given the large amount of data collected, from interviews with several students, videotapes of classroom processes and collected written work of all students, we found it valuable to focus in detail on three students and construct case studies of their experiences and learning. Case studies have frequently been employed to inform teachers and researchers about conceptual change teaching and learning, for example, Scott (1987), Hewson and Hennessey (1991), Eaton, Anderson and Smith, (1984), and Erickson and MacKinnon (1991). Providing as they do rich descriptions of the phenomena of teaching and learning, the case studies thus became the focus for our own coordination of theory and evidence, in this case about conceptual change teaching.

We begin by describing the goals, assumptions and beliefs that we brought to the teaching of the electricity unit, followed by summaries of the school and classroom contexts, and the diagnostic and instructional strategies that we employed. Summaries of the case studies of the three students, are then presented. These provide much, but not all, of the evidential base for our conclusions. The following section outlines our learning from the experience, attending to the three case study students as well as insights gleaned from broader experiences in the classroom. Finally, we set out what we consider to be the major insights from the project, concerning our growing appreciation of the value of probing students' understanding deeply.

ASSUMPTIONS ABOUT CONCEPTUAL CHANGE TEACHING AND LEARNING

At a broad level, our view of learning as conceptual change reflected the position set out by Posner, Strike, Hewson and Gerzog (1982): That accounts of the historical processes of conceptual change in communities of scientists can contribute to an understanding of the learning of science by school students. We saw this position as having both curricular and instructional consequences. We believed that the classroom process, which modeled the gathering of evidence and debate about the extent to which different models or theories satisfactorily explained the available evidence, provided a reasonable picture of the nature of science. Furthermore, the goal of developing explanatory models was significant. For example, while it is important to know THAT a complete circuit is necessary to make a bulb light, it is also important to have an explanation for WHY the complete circuit is necessary.

Instructionally, it was also our hope that these same processes would be effective in moving students beyond the naive conceptions about electrical phenomena that they brought to the classroom. That is, dissatisfaction engendered by disagreement both between prediction and observation, and between personal supporters of different explanatory models, should motivate students to construct better personal models. Thereupon, the modes of representation and arguments for the plausibility of different models, suggested either by other students or by the instructors, could facilitate the construction and selection of better models. The students' ability to actively consider their own and their peers' theories is crucial to this process (Hewson & Thorley, 1989). The point of contact between theory and evidence seemed well served by the making of predictions and observations, and the development of explanations for each (Champagne, Gunstone & Klopfer, 1985)

We initially viewed the conceptual change teacher as part diagnostician, part therapist: Someone skilled at monitoring students' ideas and, where necessary, implementing appropriate strategies to set them to rights. The literature is replete with descriptions of beliefs about electric circuits held by students of a variety of ages (e.g. Osborne & Freyberg, 1985; Shipstone, 1985), providing substance for what Anderson and Smith (1987) describe as "knowledge of students" and thus clues for diagnosis. We expected entering students to bring both "circulating" and "clashing" models of electric current, to take different positions on whatever is used up as a battery drives a light bulb, and to discriminate only poorly, if at all, between electric current and electric energy. These issues formed the main content goals for the electricity unit. They seemed modest goals.

The "therapeutic" role that we adopted as instructors was more that of a facilitator of group therapy. This was partly to remain faithful to our curricular goal of modeling the construction of knowledge by the scientific community. We were also influenced by what Erickson and MacKinnon (1991) describe as their two principles of constructivist teaching: "Giving over more responsibility for learning to the students", and "validating students' ideas" (pp. 19-20). This introduced another dimension to the role of the teacher: Diagnosis and therapy of classroom process and environment as well as of individual students' ideas.

In order for students to feel free to express their ideas before peers and instructors, the classroom environment needs to be one of tolerance and safety. By age ten, much of the enthusiastic sharing of ideas seen with young children has become inhibited by the growing self-consciousness which is characteristic of the pubescent years. Teachers are the prime directors in creating and maintaining an atmosphere that encourages risk taking by adolescent students. Both by modeling acceptance and genuinely valuing the ideas of their students, teachers can lay a foundation for such a classroom climate. However, it is also necessary to learn how to minimize damaging student interactions without stifling the ideas that the students may be trying to express. In this regard, our goal was to teach children to criticize ideas, not people, and more importantly to develop the ability to hear criticism of their ideas without rancor.

<u>The School Context</u>

Achieving a classroom environment that supported the open exchange of ideas was aided by the overall school climate. The school seeks to provide a child centered humanistic education with an emphasis on individual development. Overall, the student population is upper middle class, but all classes have students from a range of cultural and socioeconomic backgrounds. Moreover, students with severe learning disabilities are mainstreamed into the regular classrooms, and found in every class. From the nursery through the high school, teachers emphasize tolerance of differences, and students are surprisingly tolerant of ideas, behaviors, and social practices. Additionally, because there are only 12-14 students in a class, it is possible for all students to be active participants. Visitors to the classrooms consistently remark on the willingness of students to ask questions and share information.

Until grade 7, students receive anecdotal as opposed to quantitative report cards. This practice has somewhat minimized competition for grades. In science at the grade 5/6 level, students do receive grades on individual projects, but assessment is based largely on portfolios and projects. Use of conventional tests is minimal.

DIAGNOSTIC AND INSTRUCTIONAL STRATEGIES

In monitoring the instruction and the students' learning, data were collected through numerous strategies, including written pre- and post-tests, video-recorded interviews before and after instruction with selected students, and other samples of students' work, such as written discussiondocuments. Whenever possible, we also videotaped whole class discussions and demonstration/discussions. These procedures are described in greater detail below.

Pre-Instructional Quiz

All students were given a pre-instructional written quiz. The quiz was composed of diagrams of four different series circuits and related questions. For example, the first diagram was a bulb connected to a battery in a circuit. Students were asked to explain why the bulb would light or not light, to show and explain the direction of the flow of electricity in the wires and compare the amount of electricity that would be found in each wire. We were deliberately vague in our use of the word "electricity" at this stage. At the time of the quiz, none of the students had studied electricity in a school setting. Additionally, few of the students showed evidence of having either a textbook or personal model of an atom that included protons, neutron, and electrons. However, most of them had played informally with batteries and bulbs. It was our hope that the pre-instructional quiz would give us a rough base line for individual student thinking and additionally provide us with general information about the types of conceptions of electricity extant in the classroom.

Instructional Activities

Almost all class sessions were taught in a small science teaching laboratory, with lab activities forming the core of the formal instruction. Initially, all lab activities involved simple series circuits similar to those given on the pre-instructional quiz. Each lab activity was based on a diagrammatic drawing of the circuit. Students predicted a result, for example whether two bulbs in series would both glow, and if so how brightly. They explained *why they had made the prediction* by trying to articulate their personal theory. Following this explanation, they set up and observed the circuit and compared the result to their predictions. In the light of their observations, they reassessed their theories. Class discussion took place frequently at different stages of the process. During class discussion, individual students frequently used the overhead projector to diagram and explain a theory.

We supplemented activities of our own design by having students develop their own hypothetical circuits and test them. After several days of structured student- or teacher-suggested activities, students also had the opportunity to use the wires, batteries, bulbs, and switches in whatever manner they choose. On such "play days", they were not required to record any information, nor did formal class discussion take place. These days were initiated both to meet students desires for "free play" and to provide us with the opportunity to watch, to listen, and to interact informally with small groups of students.

We also undertook to bridge the gulf between the micro world inside the wire and the macro world outside of it with simulations. In one such simulation, students played the role of moving charges as they walked from a large cardboard model of a battery along a rope to a cutout of a light bulb, and then followed the rope back to the battery. At the battery each student picked up a match and lit it at the bulb. The person handing out matches at the battery gave each student a small "keep moving" push as he/she left the battery. In this way, we attempted to help students separate the concepts of energy and current. This activity followed the lab class in which ammeters were introduced to "establish" that electric current has the same size at all points in a simple series circuit.

Final Whole-Class Assessments

We concluded the electricity unit with two activities. First, students took a final written quiz that involved defining and explaining a list of words that we had used during the course of our electricity study. Some of the words related specifically to electricity; i.e. atom, electron, current, energy. Others were relevant to any field of science; i.e. theory, observation, prediction; model. Again, it was stressed that this was to be a quiz of our success as instructors rather than student abilities. At no time during the course of study had students been directed to memorize or write definitions of any of the words that appeared on the quiz. A full period was given and students were encouraged to use illustrations as well as written explanations.

Second, students chose a particular circuit for a final project. We asked students to pick an example of an electric circuit about which they had developed a theory, but for which the theory had proved to be inconsistent with experimental observations. For example, one student team elected to explain their changing theories regarding a simple series circuit with three batteries. It was their original belief that if one of the batteries were reversed, so that two negative ends were together, the bulb would not light because the reversed battery would "block" the electricity. Experimentation had revealed that the bulb did light and the students had to reassess their original theory. These projects had to include a poster to be used as a visual aid when explaining the circuits to the class.

Individual Interviews

Because class discussions and written answers provide only limited insights into the conceptions of individual students, we obtained more detailed information from a small but diverse sample of students using video-taped individual interviews. One group of individuals was interviewed pre-instructionally and another group six weeks after the conclusion of the electricity study. A few students were interviewed both times. Student participation was voluntary and almost every student wanted to be interviewed. One component of the interviews was a simple bulb-lighting task. Other tasks centered on diagrams of electric circuits. The initial interviews were similar to the Interview-About-Instances strategy (Osborne & Freyberg, 1985). Interviews conducted about six weeks after the conclusion of the unit on electricity focused mainly on circuits that the students had encountered during instruction.

SUMMARIES OF THREE STUDENT CASE STUDIES

To highlight both the students' learning and our own during the six weeks we spent teaching science with strategies designed to address students' misconceptions, three case studies are summarized below. All three students took part in all of the activities discussed under Diagnostic and Instructional Strategies, but only specific examples are addressed here. The examples were chosen to stress particular problems and/or issues. In as much as is possible with a "sample" of three, an effort was made to give a representative sampling of the group of students with whom we worked.

Adam

Profile of the Student as a Learner

Adam could be considered the prototype of the ideal science student. Intrinsically interested in all things scientific, he is also a strong math student with good reading comprehension skills. He is able to memorize information easily and enthusiastically participates in class discussion. Furthermore, he comes from a family where both parents have science backgrounds and have provided him with numerous opportunities to explore the physical world via vacations to interesting natural habitats, museums, and libraries. His interest in tinkering has been supported with discarded home appliances for dissection. He also has had access to a computer, with limitations put on his use of it as a game machine, but encouragement in all other areas.

Given his background, it is not surprising that Adam is one of the most confident students in his grade 5 science classroom. To date, school has provided him with a rewarding and interesting environment in which he has thrived. Adam's background indicated that he would represent the most knowledgeable end of the student spectrum of pre-instructional understanding of electricity. This was borne out in his pre-instructional interview.

Beliefs About Electricity

Given a bulb, a wire, and a battery, Adam quickly was able to make the bulb light with one wire. In the process he explained the necessity of having a "complete circuit". The battery was the source of energy that made the bulb light. Additionally, he explained how the thin wire in the bulb, which he correctly called a "filament", heated up and lit when the electricity was "squeezed" through it from the fatter connecting wires. Thus, he concluded the bulb is simply part of the circuit.

Adam also gave a detailed and functionally correct description of how to make a switch, of the difference between a motor and a generator and finally explained how he had once built a working motor. In response to questions about the source of his knowledge, he replied that he had read a good deal about electricity. At this point, Adam seemed to accept his level of understanding in the spirit that he accepted the technology of the computer: If one learns what keys to push, remarkable things can be produced. What made circuits or computers work was not naturally on his list of things to explore. His goal appeared simply to get them to work.

Throughout our study of electricity, Adam stayed involved. Although he had considerably more experience with electricity than the majority of his peers, he appeared neither impatient nor bored by their questions. In fact, Adam was a very active participant in discussions of theories of electricity. He had a confidence in his own abilities that enabled him to risk presenting unusual ideas. For example, one student in a presentation was trying to explain how it was possible that the energy of a battery could be supplied equally to three bulbs in a circuit. The student drew upon a classroom experience in which students had modeled electrical current and picked up matches, energy, which were lit at each bulb. The problem was: Using this model, how could a current of "students" manage to light all three bulbs? Adam suggested that each student bypass two thirds of the bulbs and light a single bulb, and then follow the circuit back to the battery for more energy. This would allow for a constant current and equal distribution of energy. In the end, Adam became tangled in his analogy, but it caused him no loss of face or concern. This self-assurance was not common to most grade 5 students. It has been our experience that students view sharing their personal theories with their class as anything from a slight to a great personal risk.

Given the amount of factual knowledge that Adam brought to our study of electricity, it was interesting to see the differences in his understanding and factual knowledge when he was interviewed six weeks after the conclusion of the instructional unit. He had by then integrated his new information about the atom, which had been presented didactically in class before the start of the electricity unit, with electrical theory. Predictably, he correctly placed the protons and neutrons in the nucleus and assigned the electrons the role of movement in wires as the current. Additionally, he realized that the world was full of unbalanced atoms called ions that could have positive and negative charges. All of this information had been acquired from classroom discussions and films. He had never been required to memorize this information for a test or activity. He saw the battery as being the source of energy (energy being defined by him as "a force that makes things happen") which was used up over time by the circuit. The current was the carrier of the energy and consisted of electrons that "jump from one atom to another". He had difficulty remembering how he had viewed electricity before our class study of it.

Teacher: Do you remember any of your ideas about electricity before we studied it?

Adam: I don't know...I can't remember. I think that I thought it was the atoms that were moving before in the wires, not just the electrons.

Teacher: You now [earlier in the discussion] say that there are electrons and energy; and energy is used up, but not the electrons.

Adam: I thought [before] that energy and electrons were the same thing. I didn't really have that great an idea of how it [electricity] worked, but I knew how to make it work.

Teacher: What did we do in class helped you come to the energy/electron model?

Adam: Once in the centrum, [a small theatre in the school] the kids were electrons and matches were the energy. The kids went back to the battery, but the matches stayed at the bulb.

At this point, Adam was shown the diagram that we had discussed earlier which showed a simple battery and bulb circuit with ammeter readings. He had explained that measurement of the current in the wires throughout the system would be constant.

Teacher: Did this kind of experiment help you form your ideas?

Adam: Well, it showed something wasn't being used up.

Teacher: How do you know then, that something IS being used up?

Adam: Watch a light bulb and battery circuit [for a long time] and when it goes out you'll know something was used up.

In many respects, Adam could be considered a student who gained from our approach a deeper understanding of how electricity works. The model he has of a circuit, several months after the classroom activities, shows that he has correctly incorporated the concepts of current and energy into a model of electricity. Moreover, he has some appreciation of the fact that he now knows "how it works". Yet, there is some room for discomfort in feeling that his accomplishment validates our approach. Adam is a bright student who will take all the higher level science classes offered in high school and likely pursue an undergraduate major in some area of the physical sciences. Therefore, he is a student who probably will come to a scientific understanding of many concepts even if left to the limitations of conventional curriculum in which underlying theories are assumed or rarely explored.

However, it was Adam's apparent lack of appreciation for the real difference between pushing the right buttons to see if something works and understanding the buttons themselves that finally proved a frustrating aspect of working with him. For a science fair project, developed in the month following our study of electricity, Adam elected to set up a series of experiments using fruits as electrochemical cells. He worked on this project with another student who has a similar science background and innate abilities. They are the grade "techies". Together they expanded the project to test not only an assortment of fruits, but also metals. Probably unknowingly, they were exploring the difference in the electronegativity of common metals. They presented all of their research on an impressive poster display of data and procedures. At no point in the presentation, either oral or poster, did they question WHY some metals or combinations of metals successfully worked to produce an electric current. Willingly they stopped at the level of: Here's what works. In fact, when it was suggested to Adam that he might be interested in trying to determine the WHYS of his electric circuits, he was markedly resistant. During both the pre- and post-instructional interviews, he was asked if there was anything that he'd like to explore further with electricity. Initially, he wanted to build another motor. In the end he wanted to create a circuit with clips that would allow a fan, bulb, motor, etc. to be placed inter-changeably in the circuit. Although his commitment to technology was consistent, he never demonstrated more than a passing interest in the "whys" of the world.

Does Adam's unwillingness or inability to appreciate the need to look beyond observations to underlying theory reflect a fault of classroom teaching, a developmental inappropriateness of the objective, or some other factor? In a way, he had a natural gift for the "scientific method" as the seeking of patterns among observations. Adam appeared to prefer this rather "inductivist" approach to our encouragement of the construction of explanatory models. Whatever the cause of his lack of engagement, there is a need here for further exploration. Without a realistic understanding of what is possible for grade 5 students, as teachers we will continue to miscalculate, misguide, and mismanage science education.

Kelly

Profile of the Student as a Learner

In a textbook based grade 5 science program, Kelly would thrive. A conscientious worker with good reading skills, she prefers the structure of an assigned chapter on electricity to open discussion about theories of electricity. Memorization of vocabulary for a test is a comfortable niche in which she moves confidently. Kelly wants expectations clearly defined and science problems to have black and white answers. In short, our approach to science with open ended questions and discussions was in many ways a daily challenge to her need for predictability and order. Kelly is happy to visit the science room to reorder the glassware shelves. She is less enthusiastic about taking part in videotaped interviews in which she is called upon to express her own ideas. Kelly's intrinsic difficulties with the type of instructional interactions that we hoped to initiate made her a valuable subject for studying the effects of our program.

It is important to note that in some ways Kelly is a classroom leader. That is, she is the classroom watch dog, ever alert for students who tread in the wrong direction and/or fail to do their part. As such, she is comfortable speaking out in class and she volunteered often during classroom discussions. However, her contributions were almost always on the level of protocol details or observations about trivial specifics. Rarely did she venture to question a theory. At the same time, she showed interest in putting forth her own models if she was allowed the time to first draw them on an overhead. With this visual aid, she presented with comfort until someone questioned the basis of her ideas. At this point she became uncertain and her lack of confidence usually lead her to either abandon her idea or simply be unable to access its origins. An embarrassed "I don't really know" was the common result of such interactions. For this reason, it was interesting to interview her privately several months after our classroom electricity unit had concluded.

Beliefs About Electricity

Once assured that the video tape was to be a resource for teachers to learn more about their teaching and not a means of measuring her worth, Kelly talked freely. She showed a good grasp of the process that we had been using with students: Look at a situation, try to explain it with a theory, test the theory by checking the observations against the predictions, and finally reassess the theory. Unfortunately, she showed little evidence of a gain in her real understanding of electricity. Two examples, the first from a presentation that she gave at the end of our electricity study and the second, from a video-taped interview done six weeks later, reveal these limits of her understanding.

For her final project, Kelly elected to explain a simple parallel circuit that involved two bulbs and a battery. This particular situation had been the source of classroom discussion and activities for many days.

Kelly demonstrated her understanding of conservation of current in correctly predicting what would happen to the current in a parallel circuit. She gave an oral presentation in which she explained that the amount of current before and after the battery source would measure the same, but that it would be halved at the intersection of the parallel bulbs . This model allowed each bulb to receive the same amount of energy and the amount of current leaving and entering the battery to remain the same. (See Figure 1).

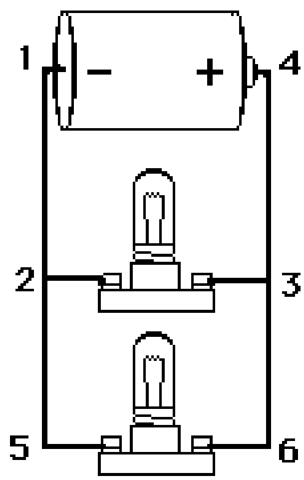

Figure 1. Kelly's Parallel Bulb Circuit.

Kelly (as recorded on her poster):

> "Our original theory was that the electricity came out of the negative side and went down through the wires and went every other one through the bulbs and met together on the other side and went together into the positive side of the battery. In other words some went 1,2,3,4 and some went 1,5,6,4. We discovered that our theory was correct because when we put the milliamp [sic] in each of the places it was 1=250, 2=125, 3=125, 4 = 250."

Yet, two months later when we discussed current during our interview, she had reverted to an earlier idea common to most students, that the amount of current before the bulb will be more than the amount of current after the bulb because some of it is being "used up" by the bulb. The teacher showed Kelly a drawing of a simple battery-bulb circuit.

Teacher: If we got a reading of 100 milliamps on this side [pointing to wire from the negative side of battery] what reading do you think we'll get on the other side [after the bulb}.

Kelly: Um...I think it will be less

Teacher: How much less?

Kelly: A couple less [milliamps] because when it [electricity] goes through the bulb it uses up so it can't be the same as when it goes back to the battery... I think that it [electricity] when it hits here [the bulb] it uses up some and what is left returns to the battery.

Teacher: Why do you have a theory that something is used up?

Kelly: Because it [electricity] can't just go through the bulb and -
[somewhat at a loss for words; she made a new effort to explain how the bulb must be using something up]
Well because if it doesn't light the bulb it means it isn't using anything and then it would be a 100 [milliamps] on each side [of the bulb]

After further discussion of Kelly's reasons for wanting there to be a drop in current, an effort was made to clarify what she meant by electricity.

Teacher: When you talk about something moving in the wire, what is it you are talking about?

Kelly: Energy...or electricity

Teacher: Energy or electricity. Is there a difference?

Kelly: Um...[laughs nervously]

Teacher: Let's look at it this way. If you're using electricity. What is the electricity.

Kelly: I think it's...it's hard to explain.

As we talked, Kelly revealed another misconception that she still carried from her pre-instructional days. She was certain that the brightness of the bulbs in a series would vary depending on their placement in relation to the batteries. This in fact was consistent with her naive idea that current varied according to the location of the bulbs, but was inconsistent with all of the hands-on classroom experiences that she had undertaken. This has been such a common idea for many students that we had repeatedly devised experimental tests of it. At the time, students had acknowledged the same result: The bulbs lit equally. As Kelly explained the progressive dimming that she predicted would take place from bulb to bulb in the diagram before her, it was impossible not to wonder just what had happened to all of the experiential knowledge she had apparently gained two months before that belied her subsequent explanation. This incident resonates with an observation by White and Gunstone (1989), who, in reviewing a similar finding by Gauld, noted: "Beliefs conquer memories (p. 580)".

Kelly was very interested in what other students had told us during taped interviews. Looking at one student's simple circuit that he had explained by reverting to his pre-instructional idea about current coming from both sides of the battery and clashing at the bulb, she revealed how comfortable it was for her to find a few "safe" answers.

Kelly: It [electricity] can't clash together...well it might clash together, but it doesn't clash together going out of this end and this end [point to both ends of the battery].

Teacher: Why not?

Kelly: Because it can't come out of the positive end.

Teacher: Because we told you that? [earlier in the discussion, Kelly had reported this fact with confidence]

Kelly: RIGHT!

She was evidently relieved and pleased that she had remembered a correct fact that would refute the clashing current theory, at least a clashing theory that involved electricity that came from both ends of the battery. As we discussed possible evidence that might fault a clashing model, she conceded that it was possible to fault this particular erroneous theory with empirical evidence, but this did not seem to particularly impress her. We had earlier noted in class the existence of scientific evidence for a unidirectional electron flow in wires, apologizing that we could not demonstrate that evidence in the classroom. By the time of the interview, this evidence was, for Kelly, an interesting, but unessential addendum to her own ideas.

In the end, Kelly was as a painful reminder that helping students grow beyond their initial misconceptions is a much more difficult task than we had initially assumed. She is a bright and cooperative student who took active part in weeks of discussions, lab activities, and simulations that were devised to bring her to a more scientific understanding of electricity. Her final interview revealed that in the end she had hung on tenaciously to many of her earlier misconceptions. Moreover, even when she showed a change in her thinking, as in coming to reject the clashing current model, she based that belief on a "fact" that she had been told. It is questionable whether she had an understanding of why a clashing current model would be problematic.

<u>Jason</u>

<u>Profile of the Student as a Learner</u>

Theatre, dance, music, social awareness, and caring; these are the strengths that most teachers would identify with Jason. An active member of community theatre and a very popular student with peers and adults, Jason has found his niche in the humanities. Possessing both an eleven year-old's desire to succeed and an erratic commitment to sustained effort, Jason's class work varies from poor to excellent. In an average science class, the Jasons of the world are rarely acclaimed. The uncertain quality of their work can be frustrating and their social needs a disruption. Yet when given a specific physical phenomenon to ponder, Jason confidently and enthusiastically developed a theory to explain it, tested his theory and analyzed his observations. He did not settle for merely having it work as was Adam's propensity. Nor did he need coaxing to explore the reasoning behind his theory as was Kelly's.

<u>Beliefs About Electricity</u>

On the pre-instructional quiz, Jason showed with diagrams and sparsely written explanation that he had a circular model of current electricity. He also had the common misconception that the amount of electricity before the battery was greater than the amount of electricity after it, but just what he meant by electricity was not clear. When asked to explain his ideas he reported: "It is just a guess" and "I don't know if this is right I just think that [it] is right to me." A resistant writer, Jason's pretest tells us little about his ideas of electricity although they do show an intellectual honesty that became a hallmark of his work. He was never afraid to confess ignorance nor to share orally his ideas.

To the end, Jason remained an unwilling writer. He completed the final written assessment entirely with diagrams, only adding some explanatory text when it was requested. This was not surprising because Jason had emerged as a student for whom the physical manipulation of materials and discussion played a large role in his interpretation of electricity. This is illustrated in the following example, where Jason is explaining why he set up a series circuit that connected a battery, two bulbs, a string of paper clips and a pin. (The interviewer in this case was the researcher).

Int: Why did you want to do this - what were you hoping to find out?

Jason: Before I was thinking that maybe there wouldn't be enough energy that would make it across the - paper clips. So, I was thinking if it would or not ..then I decided - well, if there's enough energy then it would go across because - there's so much energy going through the paper clips, that it would make it. Then I thought about - maybe the pin is too small to make it go through.

Int: You mean so thin?

Jason: Yeah so thin - the electricity wouldn't be able to cross because it's so thin - the electricity is like so big in quantity (Int: OK) and I tried it out and it did light up.

Int: You did try it? (Jason: yes) What did that tell you? What was your conclusion after it lit up?

Jason: I said that - really - if you hook up metal with metal - you could hook up wires - with metal then it would pretty much light up

Int: So as long as it was metal, it lit up?

Jason: Yes

Int: What would you have concluded if it didn't light up?

Jason: Well I would have said [hesitates] - lets see -

Int: Suppose you set it up and the bulb didn't work - what would your conclusion be?

Jason: That there was not enough space for the energy to come through the paper clips and the pin - not enough energy to get across you know get into the bulb - or another thing is it wasn't hooked up right.

In the above exchange, Jason shows the skill with which he can visualize a problem, test it, and reassess his theory. However, the experience of actually having worked with the materials and discussed them with us was key to having him make these connections. Left to paper and diagrams, he generally fell back on "I don't know". Given his dependence on physical events to help him move from "I have no ideas" to "here's why", it was predictable that class simulations might also have had an influential effect on his thinking. Indeed, as the following conversation reveals, this was the case. This discussion refers to a class simulation where students had moved in a circuit as electrons, depositing pennies (simulated energy) at a bulb, and returning to the battery (the source of the pennies). During this event, a student had suggested analogy that just as hamburgers are energy for humans, the pennies were energy for the bulb.

Int: What's "it" when you talked about electricity flowing down - what's "it" made of?

Jason: We used it - as McDonalds hamburgers - this is the person [pointing to the bulb] and this is McDonalds [the battery]. This is coming down (Int: What is coming down, hamburgers?) yes, hamburgers coming down and feeding the person - the person is getting energy. So, talking about the light, the energy is coming down through the wire (Int: right) and giving energy to the light bulb so it makes - the light bulb has to - let the energy out - to keep on going.

Int: Hold on - what keeps on going now?

Jason: The energy - it sort of throws off some, and then it keeps on going [moves hand up towards negative of battery]

[A brief return to hamburger analogy followed]

Int: OK - you're talking about hamburgers. Could you talk about what really happens? I presume that you don't really mean there's hamburgers in the wire.

Jason: There's lots of packages of energy - [draws short squiggles inside the battery] all over the place - and the energy is coming out one side

[Jason then decides it comes out of the negative side rather than the positive, resulting in a short interchange with Int.]

…

The battery is giving out energy - when the energy comes out it has to go someplace and it goes to light the bulb and it comes around and it goes right back in again [points to positive of battery]

At this point, Jason had all sorts of new information to relate about electricity that was far from his pre-instructional uncertainty. Moreover, he initially appeared to have also acquired a more accurate model of electric current. During the same conversation, he presented a revised model of current that could be traced directly to his experiences with the ammeter.

Int: [referring to a simple battery-bulb circuit] Suppose we put a meter there [on the left wire] and it read 100 milliamps - what do you think would happen if you put another meter over there [on the right] - what would that read?

Jason: 100 [confident] (Int: 100?) Yep.

Int: How do you know?

Jason: Once when we did it, it was fif - I don't know what it was but let's say 15 for example - and there was EQUAL going around.

Int: You mean you can remember it being equal when you did the experiment?

Jason: Yes

Jason then attempts to explain just how the equal amounts come to be:

Jason: The energy is coming out [points to the negative of battery]... going in [points to the ammeter] keep on going, then it goes in here [the bulb]
Before when I said [showing hesitation] coz I was just thinking right then- it would go up into here [points to the filament]

Int: It being the energy?

Jason: Yes- the energy's going up into the light bulb and I said that the waste comes out - but now I'm thinking about - when it goes up into here [drawing squiggly line up the filament stem] it's giving a flicker of um - electricity - but the electricity's still going with the flow of the other electricity - so it keeps on going up [the other wire to battery]

Int: OK so the amount of electricity over here is the same (Jason: Yeah)
Is there anything that's less? (Jason: ummmm [hesitates]) over here?
Actually you talked about both energy and electricity - are they the same thing? You've used both those words now. (Jason: Yes) So it's the same thing (Jason: Yes) that you're talking about there?

Jason: Yes - the energy is the electricity that comes out of the battery (Int: OK)

Jason had begun our study of electricity with an idea that batteries and bulbs must operate in a circuit for unknown or inexpressible reasons. He had moved to a more complex model that integrated energy for bulbs; energy that now somehow stayed the same even while the batteries "ran out". He had a variety of analogies for electricity: pennies as energy; people as current, hamburgers... The question, of course remains, what does his shift in thinking really express? Is he any closer to understanding electricity now than before our period of instruction? During some of the "free play" sessions, while some students were seeing how many batteries it took to blow a light bulb, and the "techies" were building electromagnets and relays, Jason showed a real flair for posing and testing questions about underlying causes. He had found that a bulb placed lower than the level of a battery in a circuit will light no more quickly or brightly than one placed above it; and that a bulb placed far from a battery in a series circuit will light as quickly as a bulb placed close to a battery. In the interview he demonstrated his belief that the current in a series circuit will be the same everywhere (although he confused current and energy). It is probable that each additional activity added a new wrinkle, edge, or interpretation to Jason's overall view of electricity. We were able to glimpse only a small portion of whatever changes occurred and even making sense of this small portion was a far greater task than we had imagined. Jason responded well to our approach in that he blossomed with ideas, although what he had learned about electricity was sometimes difficult to assess, especially if the assessment required writing.

LEARNING ABOUT CONCEPTUAL CHANGE LEARNING AND TEACHING

In this section we will outline what we have learned about conceptual change learning and teaching, both from the detailed considerations of Adam, Kelly and Jason, and from our more general experiences with the electricity project. As the emphasis is on our own learning, we will concentrate on those factors we saw as significant: The role of classroom discourse, simulations, the general classroom environment, and our knowledge of students' ideas. In the concluding section, we will comment on our methods of inquiry. However, because discussion of conceptual change teaching would be hollow without some attention to the question of whether we have seen any evidence of conceptual changes, we will first summarize the results of the three case studies.

The Students' Understanding of Electricity

As noted earlier, our "content" goals could be summarized briefly as (a) the adoption of a circulating current model, (b) the conservation of electric current and (c) the making of a distinction between electric current and electric (potential) energy. We gave no to-be-remembered definitions of these conceptions, instead expecting them to be manifest in the predictions and explanations the students would make about simple circuits.

All three case-study subjects subscribed to a circulating current model, with Kelly being particularly firm in her advocacy, if not her justification, for it. On the other points, however, the students' views showed considerable lack of clarity and divergence from the "scientific" perspective by the time of the final interviews, which were conducted six to eight weeks after the end of the teaching unit.

Adam came to understand the current-energy distinction, attributing this gain in understanding to classroom events, and also developed a sophisticated view at the microscopic level. However, as we observed previously, it is doubtful that we can look to Adam's achievements to justify the considerable pains we took in the teaching of these conceptions. Kelly, on the other hand, failed to conserve current at the time of the final interview, although she appeared to do so in her final project. Similarly, she could not clearly distinguish between current and energy. Most significantly, she had reverted to a belief that a sequence of bulbs in series would show progressive dimming. Jason adhered to a circulating current from the beginning, even to the point of suggesting the possibility of current flowing up a wire and back down the same wire during a class discussion. He showed a firm commitment to, and recollection of, the conservation of current as indicated by ammeter readings. He could also move with some confidence between an analogy and a "real" model of a simple circuit. He could not, however, make a clear distinction between current and energy; and showed at some points a hesitation that suggested a conflict between the need for energy to get "consumed" as in the hamburger analogy, and the equal ammeter readings, of which he was confident.

Another curricular goal was the development of the ability to separately consider an explanatory theory or model of electrical phenomena, and the evidence related to the theory. Both Adam and Jason moved competently between model and evidence, although Adam showed limited enthusiasm for the former. Jason demonstrated a sophisticated ability to propose models and ask what evidence might bear upon them. We have insufficient evidence to make any firm claims on this issue for Kelly, although at various times she showed limited concern with evidence, even to the point of "forgetting" about the ammeter readings and bulb brightness to which she had been exposed during the unit. Probably the most telling evidence of an inability to coordinate theory and evidence came from another student at the time of the presentations of the final projects. On this occasion, the student had failed to recognize contradictions between ideas presented in close succession. She had presented to the class the same final project as Kelly (a circuit with a battery and two bulbs in parallel) but had arrived at the very opposite conclusion: She was certain that the current in the circuit would get progressively less. When Kelly presented her solution and explanation 15 minutes later, reporting that the current would be the same if measured before and after the battery; the student with the opposite opinion failed to see a conflict:

Teacher: Is Kelly's circuit the same as yours?
Student: Yes, it's the same.
Teacher: Did you come to the same conclusion that she did?
Student: Yes, just the same.

Unfortunately, the period soon ended, making it impossible to take up discussion on this point. The failure of this student to recognize (or at least acknowledge) that she and Kelly had come to opposite conclusions about the same phenomenon is striking evidence that the thoughtful weighing of theory and evidence was not achieved by all in the class.

Finally, comment should be made on the curricular model we were promoting: Emphasizing an image of science as the construction and evaluation of theories and models to explain evidence. Adam, Kelly and Jason showed different levels of commitment to this perspective. Adam, very much a competent student and "technician" with a sound scientific knowledge base, showed limited interest. As noted earlier, his commitment to seeing what works, and his distinctly "inductivist" bent, suggest that he would be happier in a process-oriented science curriculum based more on the "scientific method". Kelly, given her general profile as a learner, would almost certainly prefer science curriculum as the presentation of the principles and laws of science in a more structured manner. Of the three, Jason showed the greatest enthusiasm for the approach, and competence in it. At the same time, he is by conventional measures a rather less able student than Adam and Kelly, and his difficulties with writing and mathematics will probably conspire to limit his success in the more conventional science courses that he will encounter later in his school career. We are reminded that any single model of curriculum will disadvantage some proportion of the student body. However, an innovative approach such as the one we are promoting has the potential to encourage success in those who would otherwise be regarded as "less able" students.

Classroom Discourse

Classroom talk and writing were central to our approach. As will be argued below, language served two crucial functions. First, records of classroom interactions and students' written work, along with the interviews conducted with selected students, formed the evidential basis for our monitoring of both student learning and classroom process. They served our role as diagnosticians of students' ideas. Second, the students' talk and writing provided the opportunity for them to articulate their beliefs as they developed explanatory models, as well as providing a vehicle for the debate and learning that underlay the curricular and instructional goals of our approach.

Student Writing and its Limitations

At the 5/6 grade level most students find writing difficult. For some it is physically difficult, resulting in an almost illegible handwriting. Spelling skills are still weak and this fact alone makes some students reluctant writers. However, the greater problem is one of articulation: Ideas that are often difficult enough to verbalize simply stall when students try to write them down. Asked to explain energy, Kelly wrote: "I am not sure how to write it down but I know what it is." From our experience with Kelly it is questionable that she really does understand the scientific conceptions of energy, but it is unquestionable that she has ideas about energy. Expressing these ideas on paper proved difficult for her. Again and again, students made comments similar to Kelly's. Despite the difficulty of expressing their ideas in writing, students generally made a reasonable effort to do so if the material was presented to them as part of a quiz, even a non-graded quiz. The structure of having everyone work quietly over a written page seemed to provide a greater degree of focus on this task. At least, the answers were more complete than the ones received on lab papers. Once students were given materials to manipulate and the opportunity to share their ideas with a partner, it was hard to draw them back to the written format. Thus, what we learned from lab activities came much more from our personal interactions with students than from what they wrote about the activities. Given the limitations of circulating successfully among even 14 students, many times it was difficult to know just what an individual student learned from a particular activity.

When we did get more detailed written answers, how much did they tell us about students' ideas? Kelly's written work provides a starting point for answering this question. She defined proton and electron in two different ways. Initially, she wrote "Protons are something that build up in the battery, on the positive side, after the electrons get used up. Electrons are something that come out of the negative side of the battery and it helps to light the bulb." For unknown reasons, she decided that this is not what was wanted so she attempted to throw out this answer before she wrote the second which was: "A proton is something that is inside an atom and never escapes. A electron is never in the atom it wanders off." Both of her answers give us clues to her thinking about electricity, but her first answer is particularly revealing of her understanding of a battery. In class, we never discussed how the battery worked. Thus, Kelly's model is wholly her own and reflects the model building that she was doing internally while other activities were being pursued. However, had she not been interrupted in her attempt to throw out her first answer, we would never have had any indication of this fact. The above example also illustrates well the limitations of trying to gauge the level of students' understanding from writing. In most cases, students only explain a very small portion of the ideas that they have about a given phenomenon, word, or concept. If this fact is kept in mind, writing can be a convenient way to gather information from an entire class and at the same time provides some permanent record of students' ideas.

Finally, it should be mentioned that if an opportunity arose to discuss students' written explanations with them individually, it was not uncommon for them to change their ideas in mid-discussion. Talking allowed them the opportunity to reassess what they had written and this process often produced a change in their perception of the problem, concept, or definition.

Class Discussion

Whole class discussion can be valuable for bringing out students' ideas. Even at a grade 5 level, students are willing to engage in a period-long discussion of theories about scientific phenomena. However, it is demanding on the teacher to monitor the content of a class discussion successfully at the same time as teaching students how to become successful group discussion members. There are also limits on how much one can learn about any given student's ideas. With only fourteen students, we were able to develop a fairly complete picture of the overall thinking of approximately three fourths of them. Individual's thinking on specific concepts, however, was not usually clear from the large group discussions alone. Moreover, it was usually not beneficial to spend too much in-class time with one student. Focusing at any length on one student, ultimately makes the larger class body impatient. They too have ideas that they want to share and the natural egocentrism of their age limits their ability to sustain interest in a lengthy interchange focused on another student. However, we suspect that some valuable insights were lost because it was not possible to follow through a specific student's idea. On the positive side, students did show a growth in the art of discussion. They began to learn to accept criticism of their own ideas, to be able to criticize others without sounding offensive, and to view both as learning opportunities. A few students, who had not previously viewed themselves as strong science students, grew in confidence as they found that they were capable of presenting their ideas coherently and successfully. Jason was a notable example in this regard.

Semantics is an ongoing problem with discussions. For example, we found that many students used the words energy, electricity, power, and current interchangeably even after they had shown evidence of understanding that there were differences. Without checking in each circumstance to clarify what was meant by a specific term, it was never certain just what was being discussed. Moreover, misuse of the word did not always mean misunderstanding. Occasionally, in their enthusiasm to present a new insight the wrong word was chosen. Interrupting a discussion to question the meaning of a term was sometimes enough to unsettle a student and block the flow of ideas. Thus, each exchange involved a judgment call by the instructors as to the validity of the words that the student had chosen to express his/her ideas and the depth of understanding that these words expressed.

Summary: The Role of Language

Our experiences with grade 5 students lead us to conclude that both written work and classroom talk are convenient ways to assess aspects of students' thoughts about an idea at a given time, but they fall very short of presenting a total picture. Interviews, discussed in a later section, serve that purpose better. Speaking and writing have different merits, and provide varying opportunities for expression. Jason, a very reluctant writer, far preferred oral or diagrammatic representation of his ideas. Likewise, although the actual print of written work may be durable, it should be remembered that the conceptions that generated it are rather less so.

Several of the episodes recounted above nicely illustrate Barnes' (1976) distinction between "exploratory" and "final draft" speech and language. The students' greater application to a writing task when it was framed as a "quiz", and Kelly's reluctance to attempt a definition of energy, or to share the first draft of her definitions of proton and electron with the teacher, all suggest the perception of writing as something that is done for scrutiny by the teacher: for assessment, not for learning. This highlights the need to attend as closely to students' perceptions of the purposes of classroom speech and writing as to the content of their scientific conceptions. We believe that in the discourse of the science classroom, exploratory language, in both written and oral forms, plays a vital role in the development of understanding, and this role needs to be appreciated both by teachers and students.

<u>Simulations</u>

Post project interviews with students were testimony to the fact that simulations leave a lasting impression on students. At one end of the learning spectrum was Adam, a highly capable and confident science student; at the other was a learning disabled student with a very poor sense of herself as a student. Yet, both of these students remembered and remarked upon the benefit of walking along a rope as electrons. Simulations, designed to give a concrete reality to abstract ideas, are sometimes memorable simply because they are unusual.

Unfortunately, simulations can introduce wrinkles of their own. It is plausible that in some ways the students-as-electrons experience interfered with the understanding that we hoped to promote. All of our students remembered the battery and bulb simulation. A few of them actually remembered that we were attempting to model the role of energy and electrons in a circuit. More significantly, however, a number of them left the simulation with a new model of the electron in which it moved of its own free will, as had the students along the rope "wire". With our attention on the creation and management of the simulation, we had neglected to reinforce the idea that electrons do not move of their own free will, but in response to external physical conditions. One very capable student, at the end of the unit, developed a model with two streams of electrons traveling in opposite directions along the same wire, much as would students in a hallway during a change of class. It was our suspicion that he had generated this anthropomorphic electron model from our battery and bulb simulation: He did acknowledge the students-in-hallway analogy as a reasonable one. Simulations can be memorable experiences. Sometimes, however, students take away more than was intended.

<u>Classroom Environment</u>

It was noted earlier that factors in the atmosphere of the school contributed positively to the achievement of our aims. Overall, these factors helped to create the non-competitive environment that we felt important if students were to feel free to risk making errors. Still, creating an arena that was deemed safe by all was not possible. Students naturally vary in their social skills and drawing students who were shy or lacking in self-esteem into class discussion remained problematic. When students were given an opportunity to evaluate the year, the majority of those students who had not been active participants in class discussion reported "a fear of looking dumb or silly before peers" as the reason for their silence. Moreover, in an open discussion with grade 5/6 students, all of the girls, although less than 10 percent of the boys, reported a reluctance to share their ideas unless they were fairly certain that their answers were correct. This was discouraging because so much effort had gone into assuring students that we were not looking for "correct" answers, but for understanding, and that understanding often comes only from having the freedom to make mistakes.

We were in the fortunate position of having many students who were, by the nature of their earlier school experiences inclined to participate actively in any class discussion. However, mere willingness does not ensure that students have the skills to engage in a successful large group discussion. We found it helpful to discuss with the students some underlying rules that would promote good discussion. During this exchange, they volunteered both examples of helpful discourse: wait your turn to speak; listen to others' ideas; and negative discourse: becoming angry at someone who doesn't agree with your ideas; shouting out ideas. Initially, most students had trouble separating their ideas from their persons. Thus, an attack of a personal theory became a personal attack. So it was necessary to continually monitor the discussion in a way that not only helped keep the discussion focused away from personal feelings, but also assuaged hurt egos when necessary. This role is initially demanding of instructors' attention and does impair their ability to focus on students' ideas. Furthermore, the teacher's perspective is not always universally shared. As teachers, we strove to be "impartial" monitors, encouraging all answers and valuing each participant equally. Despite our best efforts, however, on occasion students left the room murmuring: "They always call on 'X'". or "I never get a chance to share my ideas." At a middle school level, leaving a classroom with such a feeling is likely to override any conceptual insight that a student may have gained from the discussion.

In any class, there are students for whom the exchange of information orally is just difficult. They cannot follow a discussion without visual aids. We consistently used an overhead to diagram the ongoing class discussion, but even with this aid, the pace of the exchange of ideas left a few students behind. Additionally, even in a school setting that is optimally supportive of student participation, some students prefer to remain on the outside. Reaching them is difficult. Several strategies were tried, with varying success. One was to have students brainstorm in cooperative groups and let the group leader present the results. Another was to provide students with an opportunity to write down their ideas and read them to the class for general comments. A third was to reach these students during informal times when circulating among small groups of students.

One final environmental factor turned out to be very important although difficult to characterize. It could be called the "mood of the day" or "classroom flow". On occasion, discussions simply faltered and died for no obvious reason. A theory or argument that had left the class hanging when the bell rang a previous day could elicit almost no response the next. In our experience, it was wasteful to forge ahead and hope for an awakening. In 40 minute period, that was unlikely to happen. A wiser choice was to turn to a radically different activity, probably hands-on, and let students interact informally with each other as instructors circulated. Sometimes this meant laying aside well planned activities, but we found that a forced discussion can have a greater negative effect than is initially obvious.

Another example occurred early in the unit, many students showed a reluctance to continue the predict-explain-observe- explain activities on circuits of our choosing that had occupied the previous two days. For the next two days, we allowed them to experiment with circuits of their own design, provided that they first developed a "proposal" in which they outlined the circuit they wanted to test; made predictions for the outcome; and the reasons for those predictions. A "conference day" that followed these two days of independent inquiry produced some of the best discussion of the unit. Keeping students involved with their learning demands a real balancing act between the goals that one sets as an instructor and students' personal needs. For conceptual change teaching, as for any other, to ignore the mood of the classroom is to invite negativity and passivity.

Knowledge About Students' Ideas

As one's own background knowledge of common student misconceptions grows, there is the temptation to make erroneous assumptions about students' ideas as they explain them to the class. An example, drawn from a study of light (which followed electricity) highlights this problem.

Despite several days of experiments in which students had explored and discussed light and sight, Kelly continued to illustrate sight with lines exiting the eye as well as entering it from the light source. This misconception is so well documented (e.g. Eaton, Anderson & Smith, 1984) that it was in itself not surprising. However, Kelly's tenacious hold on the idea was unusual because as a learner she does not willingly persist in her viewpoint when confronted by a class full of students who disagree. Again and again, students pointed out to her that if you shut your eyes, you cannot see. Moreover, they insisted, even with open eyes, you cannot see if the source of light is blocked. It was tempting to assume that Kelly had a deep seated model of light in which some force or power of the eye had to actively leave the eye for sight to be possible. When she finally was able to communicate her true understanding, it was quite different. Kelly knew that the process of seeing involved light entering the eye. However, she also knew that what she was seeing was the outside world and not a movie image within her head. Thus, the entering arrow represented the "light" and the exiting arrow represented the "perception" of the outside world. She had made a valid distinction between the physics of seeing and the perception of what is seen. Sight is an experience of something outside of us. In trying to explain this phenomenon, Kelly was actually making a sophisticated differentiation.

CONCLUSIONS

Much can be learned about conceptual change instruction through the doing of it: Understanding the diversity of students' conceptions, skill in becoming a better listener, strategies for protecting individual egos, and so on. Our learning about the develop-ment and maintenance of these components of an appropriate intellectual environment are discussed at length in the previous section. However, from the perspective of a teacher's or a researcher's evolving understanding of the process of conceptual change, considerable insight was derived from the detailed analyses of the evidence of learning and understanding gained from the three students, Adam, Kelly and Jason. The extensive data obtained from these case-studies enabled a much better evaluation of students' understanding of, and commitment to, various conceptions than could be obtained through interview or test data, or classroom interactions alone.

At the end of the six week instructional period, most students demonstrated an apparent belief in a circulating, current-conserving model of electric current. Only a small proportion had achieved the skill in coordinating theories and evidence that we had hoped, given our investment of time and frequent use of the predict-explain-observe-explain format for inquiry. As noted earlier, the work of Kuhn et al. (1988) had suggested that this was marginally ambitious in the first place. We still hold such a goal as central to our view of science as the construction and evaluation of theories to explain available evidence. Moreover, we were encouraged enough by the ability of most students to achieve reasonable success with it, especially when assisted, that we will continue to explore that perspective. The strong contrasts in what might be termed the "curricular" orientations of each of Adam, Kelly and Jason were also notable. Our emphasis on the building and evaluation of models clearly suited and excited Jason. In the exercise, however, we have been sensitized to the needs of the "Adam's" of the world for a "scientific method" approach, and to the "Kelly's" for the presentation of a well organized body of accepted scientific knowledge.

In analyzing case-study evidence for students' understanding before and during instruction, and finally about two months later, it has become clear to us how enormously difficult it is to help a student achieve a deep and robust understanding. Lessons which had seemed powerful and successful at the time appeared rather less so when the later interviews revealed that students had reverted to earlier naive conceptions, could remember the "right answer" but not justify it, or, in some cases, had seriously misconstrued key aspects of a lesson. We observed earlier that at the start of the project, we saw the conceptual change teacher as part diagnostician, part therapist. We came armed with an understanding of the subject matter, a working knowledge of the literature on students' conceptions of electricity, and an array of strategies for diagnosing the views of our students and facilitating their construction of more scientific conceptions. The exercise was conceived mainly as the development and evaluation of a model of conceptual change instruction. The evidence cited above shows that on the score of changing conceptions we have achieved only a modest level of success. We must therefore look to the goals and strategies that we brought to bear, to revise, refine and improve upon them.

Probably the most significant outcome, for us, is a deeper appreciation of what it means to learn science with understanding. A great depth of understanding about students' knowledge can be gained by thorough interviews, and the analysis of written and video-taped records of students' participation in discussion and laboratory activities. In such an inquiry, neither the "diagnostician" nor "therapist" metaphor is appropriate. It would be fairer to regard the activity as research. It is not simply a matter of finding out what is there: It is also a coming-to-understand of what there is to look for. We have had the luxury of small classes, and frequently two adults plus a video-camera in the classroom. However, much of what we have learned could be gained by a "lone" teacher. The value in taking the time to thoroughly investigate the learning of two or three students could be immense, not so much for knowledge about those students as for knowledge about teaching, learning and understanding.

We have come to view students' learning and model-building as a process of inquiry into their own scientific understanding. To be effective, they must be committed to thinking about their own knowledge and learning, that is, to be metacognitive. They must also develop the skills, such as writing, conversing and explaining, to engage productively in that inquiry. We believe that this focus on inquiry is true of learning to teach for conceptual change. It is a paradigm example of teaching as research, of inquiry into the nature of teaching for understanding.

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