Multiple Levels of Discussion-Based Teaching Strategies for Supporting Students' Construction of Mental Models[1]

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This paper provides a description of three levels of teaching strategies used by two experienced high school physics teachers during whole class discussions to support students' construction of explanatory mental models for concepts in circuit electricity. Through extensive use of whole class discussions, these teachers appeared to foster significantly greater pre-to-post treatment gains in students' abilities to solve conceptual electric circuit problems than students who were instructed through more traditional didactic means. We found evidence that the whole-class discussion-based teaching strategies they employed were operating at three levels: 1) Dialogical strategies that support students' active participation in scientific conversation, 2) Cognitive Model Construction strategies that foster students' engagement in the development of explanatory mental models to support their understanding of scientific concepts, and 3) Model Construction Cycle Phases of Observation, Generation, Evaluation and Modification that appear to direct the specific conversational teaching strategies at Level 2. It is intended that this study will contribute to the growing body of research on the effective uses of whole-class discussion-based instructional strategies in supporting students' understandings of abstract concepts in science.

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Introduction

The goal of this study was to investigate the types of teaching strategies that two experienced high school physics educators utilized during whole-class discussions to engage their students in the construction of explanatory mental models. To anticipate the main finding, the three strategy levels found were: 1) Dialogical strategies that support students' active participation in scientific conversation, 2) Cognitive Model Construction strategies that foster students' engagement in the development of explanatory mental models to support their understanding of scientific concepts, and 3) Model Construction Cycle Phases of Observation, Generation, Evaluation and Modification that appear to direct the specific conversational teaching strategies at Level 2. This paper describes the process we used to obtain evidence for this finding and gives illustrations of the strategies being used in episodes from classroom transcripts. Ultimately, our aim is to develop a system for documenting, describing, and cataloguing specific conversational teaching strategies in a way that would make them generalizable and applicable to teaching in a wider variety of science topics and levels of study. In this paper, however, the goal is not to focus on descriptions of each of these specific strategies but rather to outline the distinct properties of and relationship between three different levels of strategies.

Background on a trajectory within our own research program that led to the theoretical framework for this study is as follows. Clement (1989, 2008) identified a cycle of model construction strategies in experts working on explanation problems in think aloud protocols. The experts were attempting to understand and give explanations and predictions for unfamiliar features of a physical system. The major phases in this cycle were "GEM" cycles of Model Generation, Model Evaluation, and Model Modification, followed again by Model Evaluation and continuing iteratively in a recurring loop. This cycle is in fact similar to one identified independently by Nersessian (1992, 2008) in the work of James Maxwell on electromagnetic field theory. Ramirez (1998) and Nunez and Clement (2008) traced the overall strategies and cycles being used by middle school teachers to lead group discussions in a model building process and found that they could be understood as GEM cycles. In this study we wanted to see if this pattern or some extension of it would be observable in exemplary high school physics teaching, and to see whether more fine grained strategies could be identified at other levels.

Study Context & Rationale: Motivation from an Initial Quantitative Study

While the teaching strategies that were investigated in this particular study were those of only two selected teachers, it is important to note that the initial data that lead to the exploration of these discussion-based instructional techniques came from a larger number of classrooms.(Williams, E.G., & Clement, J., 2006a). In particular, the control group for the larger study was comprised of 262 students who were following traditional instructional approaches (based primarily on didactic teacher lecture and extensive use of quantitative problem solving with a confirmatory circuits-based lab component). These students were members of thirteen classes which were an assortment of ninth, tenth, eleventh and twelfth grade college-prep physics classes taught by six male teachers in middle-class suburban public schools, rural public schools, and private boarding schools. Of the 262 students, 130 were female and 132 were male. The ages of students in this control group ranged from 14-18 years.

An additional 282 students made up the experimental group and were engaged in model-based learning experiences of electricity concepts through the CASTLE (Capacitor Aided System for Teaching and Learning Electricity – Steinberg, 2004) curriculum. This program employed a variety of instructional scaffolds such as analogies, discrepant events, color-coded diagrams, and the use of analogical physical devices such as syringes, air capacitors and hand-crank generators to translate kinesthetic understanding of key concepts to the learners. Throughout the instruction, the students were frequently engaged in both small group and whole-class discussions during which time they co-constructed explanatory models to help them understand the concepts under study.

These students were members of fourteen different classes taught by four other male teachers and one female teacher. The classes were primarily ninth grade college-prep physics classes at middle-class suburban public schools with an additional three being ninth grade and eleventh grade college-prep physics classes at a private suburban day school. Of the 282 students, 139 were female and 143 were male. The ages of the students in this experimental group ranged from 14-17 years.

Before beginning their study of electricity, all students completed a 20 item multiple choice diagnostic test of their conceptual electric circuit reasoning and problem solving abilities. The test questions required the students to consider circuits and their components and make predictions about their behavior. Many of these circuit reasoning problems were accompanied with diagrams of the circuits to be considered. Although the CASTLE curriculum involves the use of capacitors, the situations in the diagnostic employed only batteries, wires, bulbs, and single switches, since these were familiar to the control group students as well. The questions asked about situations which were intended to draw out known alternative conceptions. For example, a student reasoning sequentially would tend to predict that the shorting of a “downstream” bulb would not affect the behavior of an “upstream” bulb.

Upon completion of their respective 6 – 8 week instructional units, students in both the control and experimental groups completed an identical post-test. In assessing the gains experienced by students from their pre to post-instruction assessments, a comparison was done to determine whether significant differences existed between the control and experimental groups. It is important to note that the gains described below were calculated using the following two methods:

a) Raw Gain = $\dfrac{\text{(Post-test score – Pre-test score)}}{\text{maximum test score}}$

b) Hake Gain = $\dfrac{\text{(Post-test score – Pre-test score)}}{\text{(maximum test score – pre-test score)}}$

In many well-documented physics education research studies, such as those reporting results of the Force Concept Inventory, Hake gains are calculated in order to determine students’ normalized gains from pre to post-test results. Using this method, the gain that students experience is compared to their maximum possible gain rather than to the difference between the lowest and highest possible test scores. Some researchers believe this is a fairer representation of students’ growth or change than that provided by a calculation of raw gain. For each type of gain calculation in this study, the results are shown in both fraction and percentage form.

Control Group

Mean Pre-Test Score	6.59 / 20	32.9%
Mean Post-Test Score	7.75 / 20	38.8%
Mean Test Score Gain (Raw):	1.17 / 20	5.83%
Mean Test Score Gain (Hake):	1.17 / 13.41	8.7%

Experimental Group

Mean Pre-Test Score	6.70 / 20	33.5%
Mean Post-Test Score	11.61 / 20	58.1%
Mean Test Score Gain (Raw):	4.91 / 20	24.5%
Mean Test Score Gain (Hake):	4.91 / 13.30	36.9%

Because the assignment of students to the experimental and control groups was done on the basis of locating teachers that either were or were not utilizing the model-based CASTLE curriculum, the selection cannot be considered to be truly randomized. However, the following argument and supporting data provides a rationale for drawing some initial inferences from comparing the groups.

Campbell and Stanley (1963) describe this type of study design as a static-group comparison in which an experimental group which has experienced a treatment X (model-based instruction in this case) is compared to a control group which has not, for the purpose of establishing the effect of X. In the absence of randomization, one is left to rely on pre-experimental test results as the only viable indicator of control and experimental group similarity.

In this study, comparison shows the pretest means of the control group (6.59/20) and experimental group (6.70/20) is not significantly different, supporting the null hypothesis that the two groups were drawn from similar populations. The results of these comparisons indicate that it is reasonable to assume that, while not randomly selected, the students in the control and experimental groups, whether taken as a whole or separated by gender, were not significantly different with respect to prior knowledge of electricity or confidence in their knowledge.

Statistical analysis using a repeated measures analysis of variance (ANOVA) with an alpha of 0.05 determined that the students in this study who received whole-class discussion-based modeling instruction experienced significantly greater test score gains than the students who received more traditional didactic electric circuit instruction. This was true for males, females and the entire group, while their pre-test results of control and experimental students were, on average very similar. Additionally, the effect size of the experimental treatment (model-based instruction of electricity concepts) on students' circuit problem solving outcomes is 1.293; a relatively large effect based on Cohen's scale.

Of the five teachers from the experimental (model-based) group, the two whose students' average test score gains were the greatest were in fact two of the teachers we had videotaped, and this provided an opportunity since we wished to study exemplary instruction. The mean student pre test scores, post test scores, and gains of the students from these two teachers' classes were as follows:

	Teacher A	Teacher B
Mean Pre-Test Score	6.45/20	6.73/20
Mean Post-Test Score	11.80/20	12.13
Mean Test Score Gain (Raw)	5.35/20	5.40/20
Mean Test Score Gain (Hake)	5.35/13.55	5.40/13.27

Thus the primary purpose of the preliminary quantitative study was not to generalize from the sample to a population, but to identify teachers that had showed they were worth studying because of the large learning gains in their classes.

Our next objective was to examine their teaching strategies in detail through video analysis, to see if the GEM cycle pattern would be observable in exemplary high school physics teaching, and to see whether more fine grained strategy levels could be identified. This is the major focus of the present paper.

Method

Videotaped segments and corresponding transcripts from the classes of the two teachers were used as the primary data in this study. Segments were chosen that featured whole-class discussions taking place immediately after students had conducted exploratory circuit experiments. Reflective interviews were also conducted with each teacher, as a means of gaining additional data on their selections, intentions, and outcomes of particular teacher moves or strategies. Utilizing the constant comparison method (B.G. Glaser & A.L. Strauss, 1967), a coding system was eventually developed for documenting, describing, and cataloguing teaching strategies used during class discussions in a way that separates them into three levels.

Detailed diagrammatic representations of the teacher-student discourse patterns were then developed in an attempt to: a) present the spoken contributions of teachers and students, b) describe the functions of these utterances , and c) track the evolution over time of the explanatory models being discussed. While most researchers who have studied whole class science discourse have chosen to represent their analyses through prose and/or charts or tables categorizing teacher and student contributions, a few have attempted to provide diagrammatic representations of the classroom interactions (Hogan & Pressley, 1997; van Zee & Minstrell, 1997; Nassaji & Wells, 2000; Tsai and Chang, 2005; Chin, 2007). Fewer still have attempted to diagrammatically portray student/ teacher co-construction and evolution of explanatory models within these whole-class discussions (Clement, 2002; Clement & Steinberg, 2002; Ramirez (1998), Nunez-Oviedo & Clement, 2008).

The diagrams developed in this study have expanded upon some of the methodologies utilized by this latter group of researchers, while attempting to explore new techniques for representing the student/ teacher interactions that occur during large-group model-building discussions. They attempt to provide a new diagrammatic representation of relatively short time-frame segments that identifies teaching strategies at distinct levels and provide interpretations of the teacher's role in the model construction process.

As a secondary source of data, reflective interviews were conducted with the two participating teachers in an attempt to juxtapose our hypotheses about the model construction processes we were observing with their own beliefs about what was happening in their classes. Through a process of transcription review and an orientation to the diagrammatic representations of the classroom co-construction, we were also able to acquire feedback from the educators on the intentions and perceived effectiveness of their selected conversational moves and share with them our theories about multiple strategy levels.

Overview of Findings

Through our investigation we found that the strategies employed by these two teachers did appear to fit into a GEM pattern with one modification. Because of the nature of the CASTLE curriculum, with its frequent use of student experiments and teacher demonstrations, we frequently observed that the generation phase of the GEM cycles was initiated by instances of reflection on experimental observations (O). Consequently, this study introduced an additional preliminary phase of the process, resulting in an OGEM cycle.

Teacher statements were coded as being: Level 1 - Dialogical strategies that support students' active participation in scientific conversation or Level 2 - Cognitive Model Construction strategies that foster students' engagement in the development of explanatory mental models to support their understanding of scientific concepts. Strategies at the second level were then further coded as contributing to Level 3 - the Model Construction Cycle phases of Observation, Generation, Evaluation and Modification that appeared to direct the specific conversational teaching strategies at Level 2.

The Functions of and Relationship Between the Three Strategy Levels

As was stated above, our research has identified three levels at which teaching strategies exist during the whole class discussions of these two experienced teachers. The diagrams above pictorially represent the conversational interactions between students and the teacher as they co-constructed explanatory models of electricity concepts. The diagrams are chronological in nature with time running from left to right. The horizontal strip across the middle of the diagram contains short written phrases which describe the evolving explanatory models. In developing these phrases, it was hypothesized that they reflect the teacher's conception of what an "average" student's mental model can be assumed to be at a given point in the discussion. It was assumed that the teacher was aiming to foster model construction based on his view of the average student's model at that time, and how it differed from the target model. The development of these phrases was based on the student and teacher statements, which appear just above and below this central strip respectively as well as comments made by the teachers during post instruction interviews.

One layer further away from the student and teacher statements in each direction can be found brief descriptions of the contributions of these utterances to the discussion. Since the focus in this particular study was on the teachers' role, these contributions have been further distinguished into two categories or levels; 1) those that support the **Dialogical** or conversational elements of classroom interaction that are essential for effective two-way communication and sharing of ideas (shown in orange), and 2) those that appear to directly influence the **Cognitive Model Construction** processes that co-operatively occur between the teacher and the students (shown in purple).

Dialogical teacher strategies are generally observed to: be conversational in nature, occur within a very short timeframe, support dialogical interaction, encourage increased student participation and ownership in the discussion, foster a classroom culture that promotes and encourages student input, value opinions, and consider alternative conceptions and viewpoints. Examples include:

Repeating student statements for emphasis & clarity

Paraphrasing student statements for emphasis or clarity

Asking clarifying questions

Allowing scientifically incorrect statements to be considered

Adding contributions that compliment student explanations

Providing students opportunities to defend their statements

Seeking input from other students

Cognitive Model Construction teacher strategies can generally be observed to utilize cognitive strategies for fostering model construction and evolution through questions and comments that focus on students' pre-conceptions, patterns in the data, and the processes of reasoning about the scientific concepts at hand. Generally, these moves appeared to influence the direction of discussion for longer periods than the dialogical moves described above. Examples of cognitive model construction strategies include:

Requesting students' reflection on experimental observations

Asking students for an analogy to initiate model construction

Requesting mapping between analogy and model

Asking students to generate a model element based on evidence

Requesting experimental evidence to support a model

Requesting experimental evidence to refute a model

Suggesting running a model in a thought experiment and comparing to experimental data

Requesting creation of an experimental design

Asking for additions or changes to a model

The diagrams portray the co-construction of explanatory models by the students and the teacher through the arrows that point from specific student and teacher statements to the model descriptions running along the central strip. In the diagrams, arrows from both teacher and student statements indicate shared contributions to the changes or additions in the models. Often times, arrows from the teacher statements reach backwards, indicating a connection that has been made to a previous student contribution, as well as forward, indicating a prompt for new model additions has been offered. This teacher strategy is described by Hogan, Nastasi, & Pressley (2000) as the teacher "holding together the threads of the conversation, weaving students' new statements with prior ones to help them link ideas and maintain a logical consistency", and is a skill that both educators in this study displayed in their teaching.

The outermost levels on the extreme top and bottom of the diagrams outline the progression of the whole-class discussion sequence through a framework of phases by which the models appear to be generated and revised. This is the level of OGEM cycles that are hypothesized to be occurring throughout the model co-construction processes. Our group's research (Williams, E.G. & Clement, J. 2006a; 2006b; 2010) has identified distinct phases of Experimental Observation (O), Model Generation (G), Model Evaluation (E), and Model Modification (M) occurring in a cyclically repeating fashion during teacher-student co-construction of explanatory models in science classes.

Again, since the focus of this study is on the teachers' contributions to the model co-construction process, particular attention is paid to the relationship between their Cognitive Model Construction contributions at level 2 (purple on the diagrams) and the O,G,E,M cycle phases at Level 3 (portrayed in yellow). The reader will notice that each Cognitive Model Construction contribution at Level 2 is linked with an arrow to one of the four O,G,E,M phases at Level 3. This was done through a coding process which utilized the following criteria to determinine which of the four model-construction cycle phases that the teachers' statements were believed to contribute to. In each case this could take the form of a statement about one of the OGEM processes or a request to the students to generate such a statement.

Observations **(O):** The statement makes reference to observations made or outcomes noted either in a previous classroom experiment or demonstration, an everyday occurrence, a television or internet video, or other source. This may be done for the purpose of bringing the attention or memory of the participants to the phenomenon being discussed. Examples of key words that help identify Observation strategies: Did you see…, What did you notice…, Tell us about your observations…, What was detected…, etc.

Generation **(G):** The statement initiates or introduces a theory, model, conception, conjecture, or opinion. This may be done in an attempt to explain, convince, persuade, clarify, simplify, or describe one's thinking or understanding to others. This can be done with varying degrees of speaker confidence in the correctness of the statement and can be done in either a declarative or interrogative manner. Examples of key words that help identify Model Generation strategies: What ideas do you have about…, what do you think is happening…, and your reasons are…, Do you think that maybe what's going on is…., etc.

Evaluation **(E):** The statement refers to a theory, model, conception or explanation that has previously been or is currently under discussion. The purpose of the statement is to respond to, consider, evaluate, judge, refute, criticize, support, or endorse a particular explanatory model. Examples of phrases that help identify Model Evaluation moves: Do you agree with…, That makes sense, I also believe that…, Are you sure you can have…, Do you think that is the way…, etc.

Modification **(M):** The statement offers a suggested change, adjustment, or modification to a theory, explanation or model that is under evaluation. This may involve only a minor alteration, variation or addition or could introduce a completely revised model with little resemblance to the original. Sometimes the modification statement comes with little verbal evidence that an evaluation process has been underway as students often engage in this process internally. If the statement appears to make little or no reference to the previous model, it may be better considered to be initiating the generation of a completely new model. Examples of phrases that help identify Model Modification moves: Does anyone see it a different way…, Would anyone suggest changing…, Maybe if we explained it like this…, Could it be more like this…, etc.

In the following sections we give examples of the strategy levels analysis for one episode of whole class discussion from each of the two teachers' classes. For each example we give: a) a brief explanation of the background context for the discussion,
b) a diagrammatic representation of the teacher/ student discussion and subsequent model-evolution that is believed to have resulted, and c) a brief commentary about the episode. Following that we describe the function of and relationship between the three

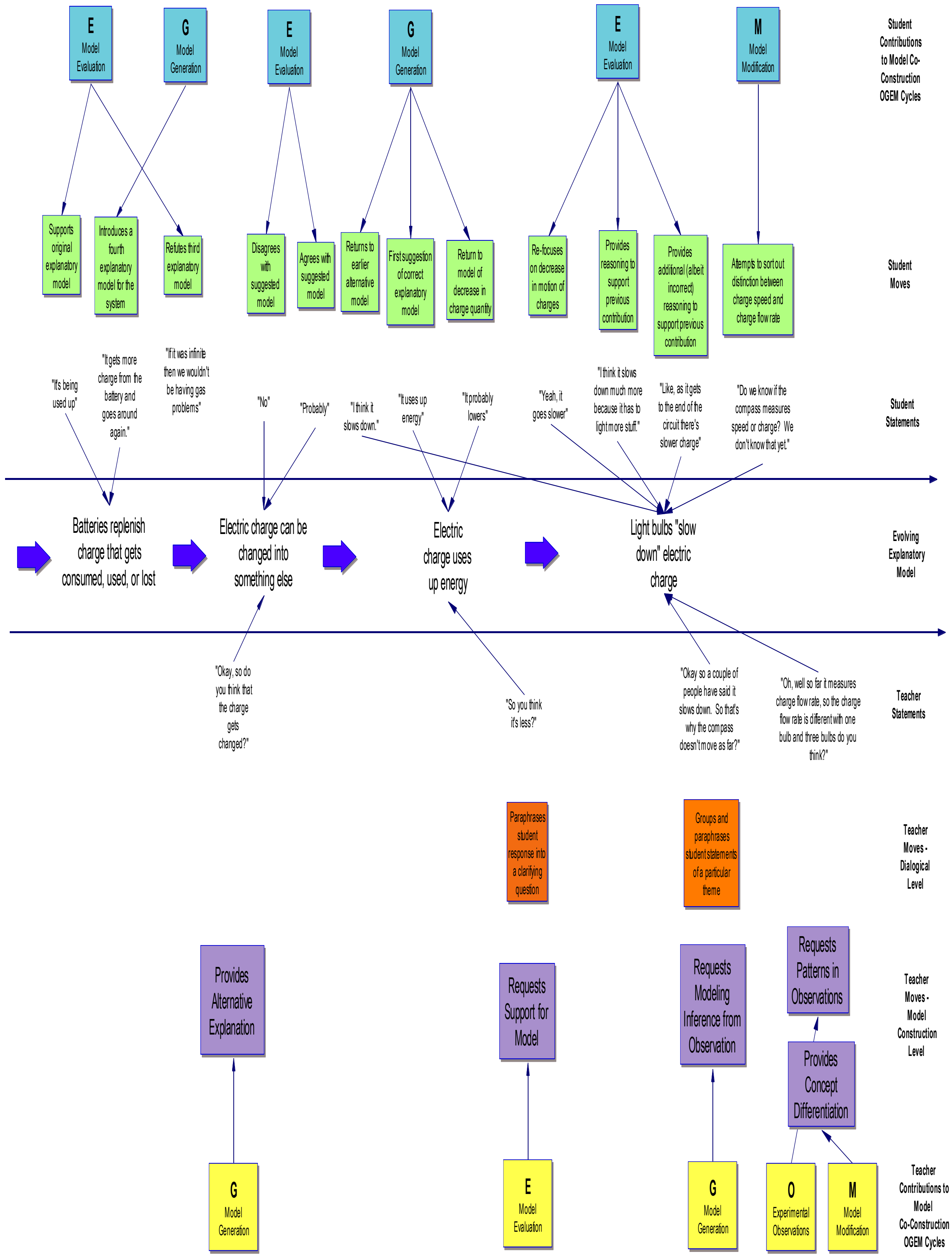
levels of strategies (portrayed by the orange, purple, and yellow boxes in the diagrams) used by each of these teachers.

Background for Episode #1 – Teacher A

The overall aim of the unit containing this first episode was to develop a concept of electrical resistance in circuits. Just before the whole class discussion that took place in Episode #1, the students in Teacher A's class conducted an investigation from the CASTLE curriculum in which they started with a simple circuit containing one light bulb in series with a battery pack. A compass was placed under the wires of the circuit as an indicator of charge movement in the wires. The students then made adjustments to the circuit by adding a second, and eventually a third bulb in series with the first and were asked to take note of the subsequent bulb brightnesses and compass needle deflections that occurred as a result of these changes.

This exploration is designed to provide the students with the necessary relative direction of change data (brighter vs. dimmer bulb brightness, increased vs. decreased needle deflection) they require to engage in the construction of explanatory models for the effects of light bulbs on the behavior of electric charge in circuits.

Whole Class Model Co-Construction Diagram – Episode #1 – Part A



Whole Class Model Co-Construction Diagram – Episode #1 – Part B

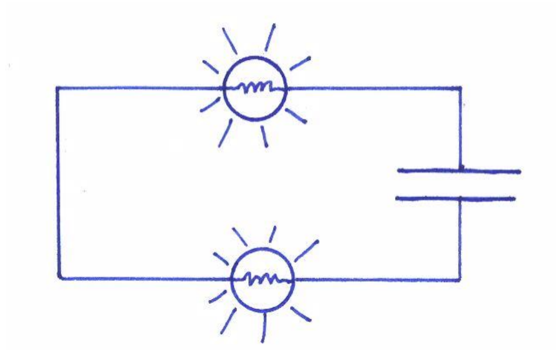
Commentary about Episode #1

What is perhaps most notable about Episode #1 is Teacher A's ability to involve his students in extended periods of discussion with minimal participation on his part. This sort of student-to-student interaction as opposed to the more common student-to-teacher discourse is explored in the book "Science Formative Assessment" (2008), in which author Page Keeley uses the analogy of ping-pong and volleyball to describe discussion interaction. Ping-pong represents a back and forth question-answer pattern: the teacher asks a question, a student answers, the teacher asks another question, a student answers, and so on. Volleyball represents a different discussion pattern: the teacher asks a question, a student answers, and other students respond in succession; each building upon the previous student's response. Discussion continues until the teacher "serves" another question.

Through this type of "volleyball" discussion, Teacher A appears to be fostering a wide range of student engagement with the scientific ideas. Through this type of interaction, students feel comfortable challenging and clarifying ideas without the necessity for teacher intervention. By reviewing the original videotape of this episode, it appears that the greatest contributing factor to this high level of successive student participation may be the teacher's use of periods of silence, often referred to as "wait time" or "think time". Whether through the use of post-teacher question wait time or post-student response wait time, the teacher appears to have developed a whole-class discussion atmosphere in which students have come to learn that they will be provided ample opportunities to speak.

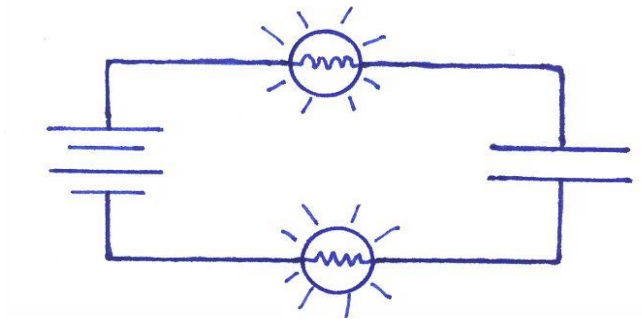
Background for Episode #2 – Teacher B

Just prior to the whole class discussion featured in Episode #2, the students in Teacher B's ninth grade science class had conducted an investigation in which they first assembled an electric circuit (referred to in the transcript as Circuit A) containing two light bulbs connected in series with a previously discharged 1 Farad non-polar capacitor as shown in Fig. XXX below.



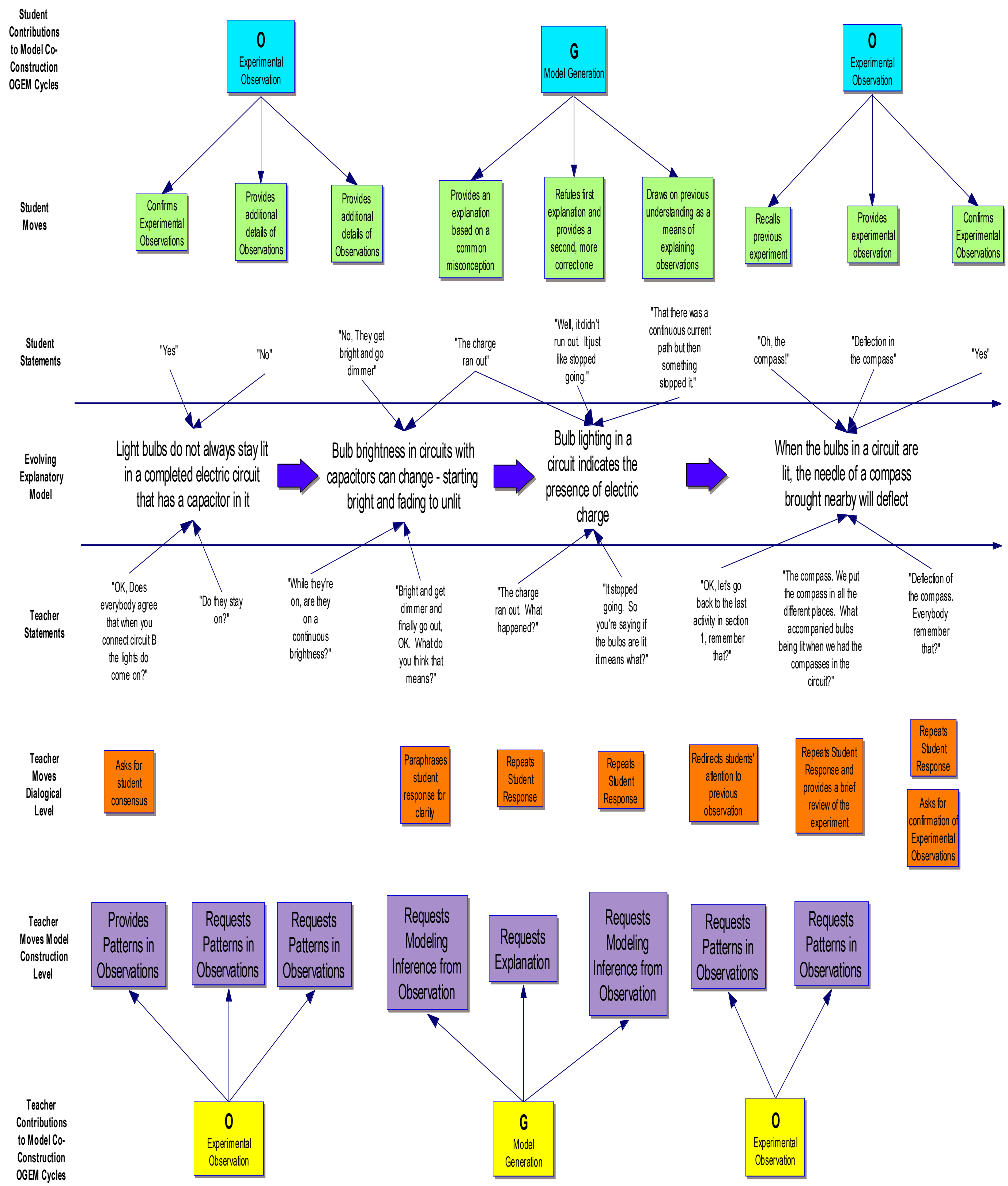
Circuit A – Two bulbs in series with a discharged capacitor

The purpose of this investigation was for the students to establish that a neutralized or discharged capacitor placed in a circuit without a battery would not result in the lighting of the bulbs. The second part of the investigation involved the insertion of a battery pack into the circuit as shown below.

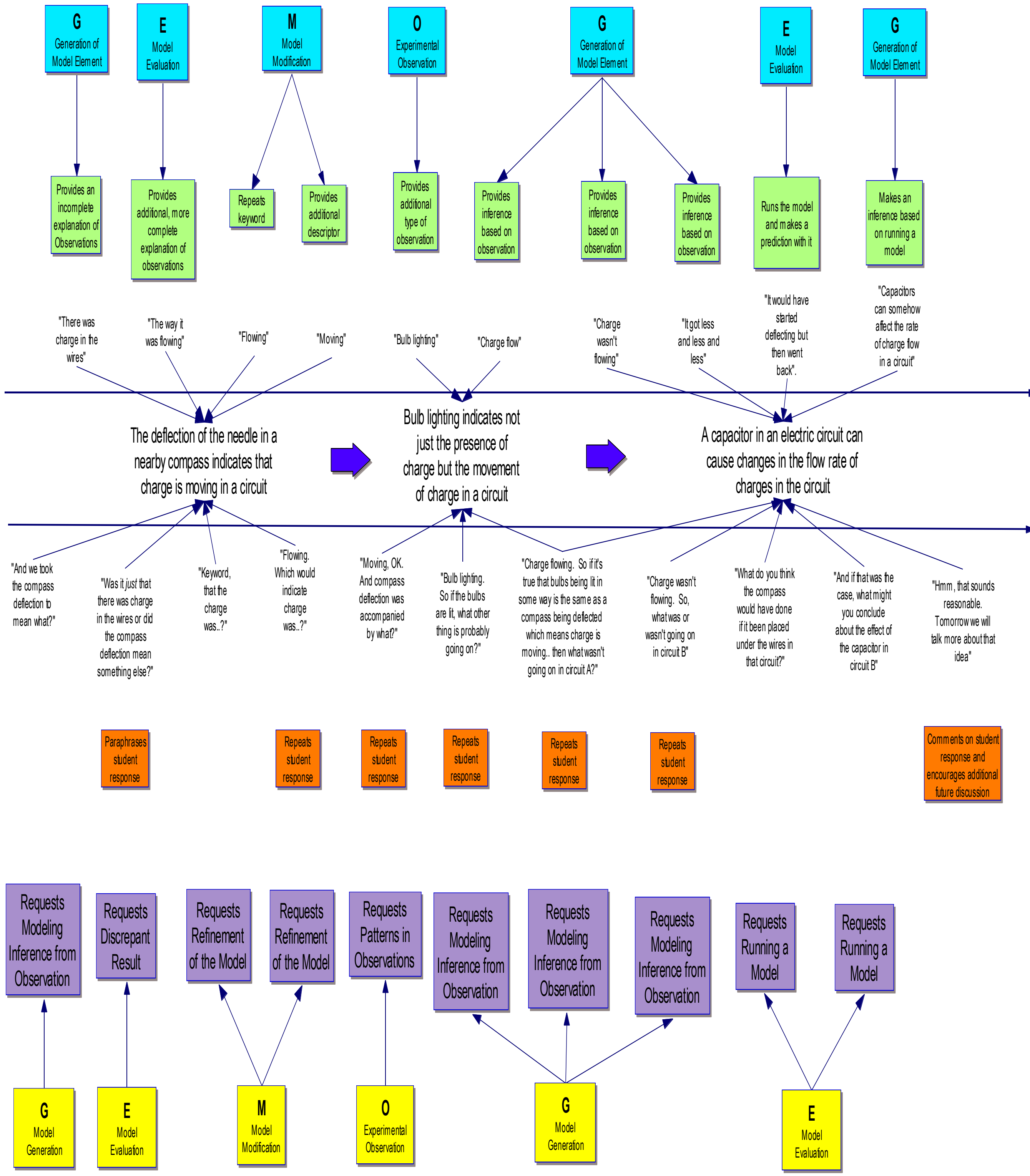


Circuit B – The same as Circuit A but with a battery pack inserted in series

The purpose of inserting the battery pack into a circuit that previously experienced no charge flow was twofold: 1) to cause the discrepant event of the bulbs lighting momentarily and then fading out, and 2) to intentionally support the common misconception that bulb lighting in circuits requires the inclusion of a battery. In a later investigation, the battery pack would be removed and the wires re-connected resulting in another discrepant event; the brief re-lighting of the bulbs in a circuit without a battery pack, thus challenging the previous misconception.



Whole Class Model Co-Construction Diagram – Episode #2 – Part A



Whole Class Model Co-Construction Diagram – Episode #2 – Part B

Commentary about Episode #2

What is most salient about Episode #2 is Teacher B's ability to guide his students in generating explanatory models by developing inferences from their own experimental observations. This activity is part of an approach to teaching that more closely fits a constructivist approach to learning as compared to a more traditional one in which students are first taught the theory and then conduct experiments to confirm it.

What is also important in this episode are the teaching strategies that Teacher B utilizes when students' attempts at constructing explanatory models are not as developed or sophisticated as are required to adequately move the process in the direction of the target model. In particular, the teacher uses two instructional tactics to support the students' evaluation of the model in question. First he **requests discrepant results by** asking the students for experimental evidence to refute the model and secondly he **requests refinement of the model by** asking for a repair to the language describing the model. These are important strategies because they help the students see the errors and omissions in their own models without directly telling them that they are wrong, serving to encourage them to continue with the model construction process and to see that model building is a process of continual Evaluating and Modifying.

Feedback from Teacher Interviews

As mentioned briefly above, the development of these diagrams, the descriptions of the teacher strategies at both the Dialogical and Cognitive Model Construction levels and the linking of these latter strategies to the phases of the OGEM cycle phases was done with feedback from the teachers themselves. Interviews with each of the teachers were conducted in person within 6 months of the instruction, as soon as the classroom dialog could be transcribed and model co-construction diagrams prepared. These interviews were conducted as a means of gaining additional data from the teachers on the selections, intentions, and outcomes of particular teaching strategies.

The process included the following steps:

1) Each teacher was provided with copies of the model co-construction diagrams from three or four 5-6 minute whole-class discussion episodes and asked to read through them. Unlike the finalized diagrams included in this paper, the initial versions presented to the teachers consisted only of the teacher/ student discussion transcript running chronologically from left to right across the page. This allowed the teachers to re-familiarize themselves with the discussions that had taken place and come up with an initial general description of what each discussion was about and what concept of the electricity unit it was centered on. The teachers were also asked to comment on what their major instructional purpose or goals were with the whole-class discussion taking place in the segments. In doing so, one of the teachers commented:

T: *Well, in this episode I was trying to get them headed toward the idea that adding resistors does something to the current and that a bulb is just another resistor – that was what the "big idea" was.*

2) The teachers were then encouraged to identify sub-sections of the 5-6 minute episodes in which sub-goals or constituents of the larger purpose appeared to be addressed. One teacher described the sub-sections as follows:

T: *I think this whole thing (points to the entire diagram) is called constructivist teaching or learning. What I think I'm trying to do here is construct the learning.*

I: *Can you say any more about that?*

T: *Well, like this (points to sub-sections of the diagram) is a brick and here's another brick and here's another brick and what I am doing is trying to piece these together so the students can understand the concepts. Generally, they are pieces of the puzzle. For example, here we are focusing on observations from the experiment. And in this next part we are talking about how we know these observations tell us that, even with a bulb and two resistors, charge is still flowing. In this third part I am trying to get the students to tell me what effect they think resistors have on charge flow in wires.*

3) Throughout the process of starting macroscopically and gradually narrowing in on the particular, the teachers were next asked to speculate about what the students' explanatory mental models might have been at certain points throughout the co-construction process. During one interview, this was explained as follows:

I: *What do you think is going on in the students' head? One of the things that we'd like to talk about today is what your impression is of where the students were at.*

In responding to that challenge, one of the teachers identified a section of transcript in which students were debating the effects of resistors on current in wires, and hypothesized about what their explanatory models might be:

T: *So here (points to diagram) a student says it (current) slows and then here's a student (points to later section of the diagram) who said it stops. Well. did this student think that the bulb going out means that charge is not flowing? And then (points to even later section of the diagram) someone else said "no it doesn't." So here's at least one student who thought that because the bulb doesn't light, charge doesn't flow. And here's a student who gets it, I think.*

4) The next phase of the interview had the teachers attempting to identify and describe individual strategies or conversational moves that they used in their teaching, in terms of what the particular instructional goals or desired outcomes were. This task was described to one teacher this way:

I: *What I'd like to do now is go back through the transcript within the diagram and have you look at each thing that you said. The goal here is to take each one of your statements and try to get a description of what that statement is contributing to the class.*

In responding to his statement from the classroom transcript,

T: *The light was dimmer and the compass didn't move as much*

One of the teachers described his strategy:

T: *I was just putting those two things together - so kind of summarizing the observation so everybody was on the same page.*

He also described his question to students,

T: *Okay, there's still charge moving – how do you know?*

In this way:

T: *So, in line 14 (*at this point in the analysis, the statements were numbered to simplify later identification*) I'm asking for evidence for statement number 13, and in statement number 15 the student response was the evidence that I was looking for.*

Because each 5-6 minute episode contained a total of between 30 and 50 teacher and student contributions, the line by line micro-analysis process of having the teachers provide their own descriptions of the functions of these statements was the most time consuming aspect of the interview process but essential to gaining a source of triangulation for our own perceptions of what was occurring in these model-based class discussions.

5) The final part of the interview process was to share with the teachers the detailed diagrammatic representations that we had prepared of their classroom discussions. Much like the diagrams presented in this paper, these versions of the diagrams contained not only the classroom discussion transcript but also brief descriptions of the teacher moves, divided into Dialogical and Cognitive Model Construction categories. Also, each of the Model Construction teacher strategies was linked through arrows to the particular Model Construction Cycle Phase (O,G,E,M) it was believed to contribute to. Finally, these diagrams contained the horizontal strip between the student and teacher statements that contained descriptions of the perceived evolution of the collective class model.

This process of sharing the detailed diagrams was done in an attempt to enlist their feedback as a means of triangulation for our descriptions of their teaching strategies. Since the teachers had just provided their own descriptions of their conversational moves, it was particularly interesting to immediately follow this with a direct comparison of our interpretations. For the great majority of the teaching strategies identified in the segments analyzed, the teachers agreeed with the investigators' interpretation. The following excerpts from the teacher interviews exemplify this degree of consistency in perceptions:

In one of the classroom transcripts, Teacher A responded to a student response by stating,

T: *Okay, there's still charge moving. How do you know?*

On the diagram, our description of the first part of the statement (Dialogical strategy) was, "Repeats student statement for clarity" and the second part of the statement (Model Construction strategy) was "Requests experimental evidence to support a model". In response to these descriptions, the teacher commented this way:

T: *Okay, so I repeated the student's statement and then, "How do you know?" Requests experimental evidence to support a model. Yeah that makes sense. I think that's what I was doing.*

In a section of classroom transcript from a discussion in Teacher B's class, it appears that, in receiving two different student responses to his initial question, he carefully selected and followed-up on the one that was indicative of the common misconception that a battery is required to cause charge flow.

T: *But when does it (charge) seem to get moving in a particular direction*?

S1: *When there's a battery.*

S2: *When there's a difference…*

T: *When you put the battery in there, and so called "charge" the capacitor.*

The flowing excerpt illustrates the teacher's reflection on our description of his strategy:

*I: So I said here that you "*responded by selecting and repeating only one of the students' answers*". I hypothesized that this was for the purpose of temporarily focusing on and addressing a common misconception before returning to the scientifically correct model of movement caused by charge differentials. Do you have any other description you could put on what you were doing there?*

T: No, I think that probably hits what it is I'm trying to do, because I'm gonna jump on this to make sure that we're not gonna keep pushing that forward and say we're gonna get there.

Reviewing the diagrams with the teachers also provided the opportunity to introduce them to our distinctions between **Dialogical** and **Cognitive Model Construction** teaching strategies. They had these comments:

Teacher A

I: *Is it surprising to you that we see these two kinds of different strategies going on?*

T: *Well I really wasn't sure how you were going to start to almost quantify or categorize what the teacher does and this is the beginning of that. This definitely makes sense and that I think ought to be going on as much as possible. I think these are things I try to do.*

I: *So would you say you agree with these descriptions of two different types of strategies that you're using or two different levels of strategies?*

T: *Absolutely!*

Teacher B

I*: Is there anything you would add to any of these descriptions?*

T: *No, it's remarkable that you've come up with such a good way to describe this. I don't know if I could have... my words probably wouldn't have been exactly the same, but ultimately I think the ideas of what I was trying to get at are pretty well displayed.*

In a few cases, the teachers did have suggestions for minor changes in the descriptions of their teaching strategies to more accurately reflect their original intentions. This feedback allowed a degree of triangulation that was helpful in making adjustments to the diagrams and resulted in what are believed to be more accurate and valid representations of the teacher's view of the classroom situations and of the teaching strategies that were employed. Overall, the process of conducting the initial teacher interviews provided valuable reflective input from the educators and was an important step in guiding and endorsing the descriptions of their instructional strategies.

Conclusion

Through this study's investigation of teaching strategies utilized by two experienced high school physics educators during whole-class model construction discussions, we have developed teacher strategy diagrams that we believe provide a unique portrayal of teacher/ student co-construction. In these diagrams, we distinguished between strategies at the Dialogical and Cognitive Model Construction levels. Additionally, we provided descriptions and examples of the contribution of strategies at this second level to model construction cycle phase strategies (OGEM) at a guiding third level. Finally, we described the post-instruction reflective teacher interview process that we employed to incorporate feedback from the participating teachers. We believe this procedure provided a degree of triangulation that allowed for strengthened descriptions of the instructional levels at which these teachers interacted with their students.

Contribution

Previous pioneering studies (van Zee & Minstrell, 1997; Hammer, 1995; Roth, 1996; Hogan & Pressley, 1997; and Chin, 2007) have found evidence for whole-class discussion-centered teaching strategies aimed at supporting students' scientific conceptual understanding. The study by Chin (2007) is of particular comparative interest to this study due to its similarities in goals and its differences in methodology and results.

Like the research presented here, Chin's study set out to investigate whole-class teacher-guided discussions in science classes where the intention was to foster students' construction of conceptual knowledge. As well, Chin's investigation set out to develop a typology and coherent framework of teaching strategies organized by approaches or categories, much like the organizational structure that has been developed in the present study. Chin utilized videotaped classroom observations of teachers and their students and relied on the constant comparative method (Glaser & Strauss, 1967) to derive descriptive codes for teaching strategies and organize them into categories.

In Chin's research, evidence of scientific knowledge construction was provided by the utterances of individual students who spoke in response to the teachers' questions. However, in this study, evidence of student knowledge construction is provided both in the form of student responses during whole-class discussions and quantitatively in the significant pre to post-test gains of students over the course of instruction. Chin focuses solely on teacher questioning whereas the present study also considers other types of conversational elements as factors in effective discussion-based teaching.

In her analysis, Chin moved from teacher questions and student responses in the transcripts to a categorization of teaching strategies through a process of direct coding. In the present study, the development of categories resulted from the creation of diagrammatic representations of the teacher/student discourse as an intermediate step. Additionally, in this study we utilize input from the teachers involved as a means of providing triangulated support for the development of strategy descriptions and hypotheses as to their effects on student learning.

In terms of the products of the research conducted, Chin's work resulted in a list of questioning-based teaching strategies organized into 4 separate instructional approaches. The present study identified three different levels of strategies that can operate simultaneously in parallel. Teaching strategies were first separated into two levels; 1) those that support Dialogical classroom interactions, and 2) those that support Cognitive Model Construction. The teaching strategies at this second level were further categorized as to their role in the model construction processes of Observation, Model Generation, Model Evaluation, and Model Modification.

Our hopes are that this study will contribute to a theory of model-based instruction that connects levels of instruction supporting students' reasoning and construction of explanatory models for abstract scientific concepts. Ultimately, the results will be shared with both pre-service and in-service science teachers in attempts to strengthen their understanding of how their choice of statements, responses, and questions during whole-class discussions can have dramatic effect on students' levels of engagement, reasoning and learning.

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