From Research to Practice: Fostering Pre-Service Science Teachers' Skills in Facilitating Effective Whole Class Discussions[1]

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Abstract

Many of the scientific topics that students encounter during their K-12 learning experience require them to grapple with very abstract and conceptually challenging ideas. This is because the phenomena involved may occur on scales that are either too large or too small to be readily observed, occur at rates that are either too fast or too slow to be witnessed, or occur in hidden or concealed situations. It is the job of classroom teachers to find ways to make these conceptually challenging scientific ideas accessible to students. Our research team has documented experienced teachers' abilities to facilitate engaging, inquiry-focused classroom discussions in order to foster students' abilities to construct, evaluate, and revise workable explanatory models for the concepts they are learning. For our team, the next step is applying the results of this research in the development of courses and learning modules in which pre-service teachers can acquire and practice these discussion-leading skills. This paper provides an overview of one of the classroom discourse investigations that our research team has carried out over the past few years and explains the process that we have developed to share what we are learning with pre-service science teachers.

Introduction

Many of the scientific topics that students encounter during their K-12 learning experience require them to grapple with very abstract and conceptually challenging ideas (Koba & Mitchell, 2011; McNeill & Krajcik, 2008; Keely, Eberle, and Farrin, 2005). This is because the phenomena involved may occur on scales that are either too large or too small to be readily observed, occur at rates that are either too fast or too slow to be witnessed, or occur in hidden or concealed situations. This includes concepts such as planetary motion, atomic theory, magnetism, circuit electricity, natural selection, human body functions, erosion, etc.

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It is the job of classroom teachers to find ways to make these conceptually challenging scientific ideas accessible to students in a manner that allows them to not simply “know” that natural phenomena occur as they do, but to “understand” how they happen and appreciate their impact on our daily lives as inhabitants of the planet. As science education researchers and teacher educators, we have tremendous opportunities to support K-12 teachers’ quests for finding optimum strategies to teach these difficult scientific concepts.

For our research team, providing this kind of support has two major phases: 1) the design and execution of studies that investigate the impact of particular teaching strategies on students’ conceptual understanding of abstract scientific concepts, and 2) the application of the results of this research in developing courses and learning modules in which pre and in-service teachers can acquire and practice these classroom skills. This paper provides an overview of one of the investigations that our research team has carried out over the past few years and explains the steps that are currently being taken in one School of Education to share what we are learning with pre-service science teachers.

Study Context and Design

As suggested in the previous section, K-12 students encounter many conceptually challenging topics in their study of science. Our research group in the Scientific Reasoning Research Institute at the University of Massachusetts Amherst has studied a wide variety and grade level of such instructional topics, ranging from upper elementary units on human circulation and respiration (Nunez-Oviedo et al., 2008), to middle level units on atomic theory and particle behavior (Price et al.,2011), to high school units on universal gravitation (Stephens & Clement, 2012) and circuit electricity (Williams, 2012). Our research team has documented experienced teachers’ abilities to facilitate engaging, inquiry-focused classroom discussions in order to foster students’ abilities to construct, evaluate, and revise workable explanatory models for the concepts they are learning.

The study that I was the lead investigator on was conducted with students and teachers from high school physics classes at various locations throughout the United States. All classes participated in 6-8 week instructional units on the fundamental concepts of circuit electricity. Within the design of the study, the classes were divided into control and experimental groups. The control group 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 traditional confirmatory lab component.

An additional 282 students made up the experimental group and were engaged in model-based learning experiences of electricity concepts through an innovative curriculum (CASTLE - Steinberg, 2004) employing various analogies, color coded diagrams, and experimental observations, including discrepant events. The curriculum also encouraged the teachers to engage students in frequent and extensive whole-class discussions for the purpose of developing, considering and amending their explanatory models of the phenomena they observed during explorations.

Prior to embarking on their study of electricity, all students completed a diagnostic test of their conceptual electric circuit reasoning and problem solving abilities. The test questions required the students to consider circuits and/or components therein and make predictions about their behavior. Upon completion of their respective instructional units, students in both the control and experimental groups completed an identical post-test. Statistical analysis of the results from the pre to post-test comparisons using a repeated measures analysis of variance (ANOVA) indicated that the students in the experimental model-based/ discussion-centered classes achieved large, significant gain differences over their traditionally instructed counterparts. Complete quantitative analyses and results are described in Williams (2011).

Based on this outcome, the study shifted focus to the task of examining how the teaching strategies in the experimental group may have been supporting this growth in students' conceptual understanding. For this qualitative portion of the study, the data consisted of approximately 50 hours of video recordings and the ensuing transcripts of classroom sessions in which the experimental group teachers and their students were engaged in the co-construction of explanatory models of electricity, primarily through whole-class discussions. A grounded theory research approach (Strauss & Corbin, 1998) was selected for the qualitative analysis of this classroom data because of its data-supported ability to generate theories about the impact of certain teaching strategies on the conceptual change students experienced. A constant comparison method (Glaser & Strauss, 1967) was utilized in an effort to develop plausible interpretations of teacher strategies that were believed to foster students' construction of explanatory models of electric circuit concepts.

Findings

Analysis of the student/ teacher dialogue from the whole class discussions of the experimental group teachers identified thirty-nine of what we refer to as Cognitive Model Construction teaching strategies that are believed to have supported the students' conceptual understanding of electric circuits. Although these teaching strategies were utilized within the context of high school physics classes, the descriptions of them are written in a manner such that they can be applied across a broad spectrum of science teaching and learning (Williams, 2011).

Each of these 39 Cognitive Model Construction strategies were employed at a "micro" time level (2 - 20 seconds) within the classroom discussion, and are believed to contribute to one of 4 Cognitive Model Construction Cycle OGEM phases occurring at a "macro" time level (2 – 20 minutes). This acronym refers to the phases of Observation, Generation, Evaluation, and Modification that students and teachers in this and associated studies (Nunez-Oviedo et al., 2008; Clement, 2008; Williams & Clement, 2010) were found to co-operatively engage in during whole class conversations about various conceptually challenging scientific topics. It is hypothesized that the process of fostering change in students' scientific conceptions requires support from the teacher at various stages along a learning pathway. This can come in the form of scaffolding their explanatory model construction activities at each of the Observation, Model Generation, Model Evaluation, and Model Modification phases. Examples of eight of these micro Cognitive Model Construction teaching strategies and their categorization within the macro OGEM Cycle are shown below in Table 1.

Macro Cognitive Model Construction Phase	Micro Cognitive Model Construction Strategy	Classroom Transcript Example
O **Observation**	Requests recall of experimental observations	T: Okay. How about when you added a second resistor - what did you notice?
	Provides recall of experimental observations	T: Well what's your evidence that it happens? At some point don't the bulbs cease to light? And the compass ceases to deflect?
G **Generation**	Requests generation of a model element based on evidence	T: Okay, so same amount. So, what does that tell you about the amount of charge moving through this wire, or the rate of charge movement through these wires?
	Requests an analogy to initiate model construction	T: You've already seen one analogy about water flowing through pipes. Is there any other analogy you can think of that would explain why this filament would have higher resistance than this filament?
E **Evaluation**	Requests the running of a model and comparing to experimental data	T: What does the resistor do? S3: Insulate. It acts like an insulator— T: Acts like a ***good*** insulator? S3: No, because some of the charge still gets through…
	Requests students run another student's model in a thought experiment	T: So, if charge is moving around in a circuit like this and if charge is being changed into heat, what would you expect to see in the compass as you moved further and further in the circuit?
M **Modification**	Requests examination of the relationship between two elements of the model	T: That's probably true. But is heat the same as charge? S6: Charge is like energy T: Does charge get changed into heat? Is that what we're thinking?
	Requests integration of one concept into another conceptual category.	T: Okay, so is there any real difference between a resistor and a bulb? S4: No. S6: Yeah. The only difference is that you can see the energy in the bulb, but not in the resistor. T: Okay, so can we call the bulb a resistor? Or, the filament in the bulb a resistor? S6: Yeah

Table 1 – Sample Cognitive Model Construction Teaching Strategies

Once the collection of teaching strategies were identified, described, and categorized as to their hypothesized contribution to the model construction process, the next step in the analysis was the development of diagrammatic representations of the classroom conversations that these strategies were embedded in. These diagrams, which we refer to as Whole-Class Model Co-Construction Diagrams (Williams, 2011), explore techniques for representing the student/ teacher interactions that occur during large-group model-building discussions. The diagrams: 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. 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 as "conversational guide" in the explanatory model construction process.

One of the primary features of these Whole-Class Model Co-Construction Diagrams is the distinction they make between teaching strategies at the Cognitive Model Construction levels and those we refer to as being at a general Dialogical level - strategies intended to support the clear and open communication and sharing of student ideas through class discussion. Strategies at the Dialogical level include: participating mainly as a facilitator in the discussion, restating or summarizing student statements, asking for elaboration and clarification, choosing to not directly challenge "incorrect" statements, redirecting questions back to students rather than providing answers, focusing attention on conflicts and differences of opinion, and inviting responses to other students' statements.

Research by van Zee and Minstrell (1997), Hammer (1995), Hogan & Pressley (1997), Roth (1996), and Chin (2007) has identified some central elements in teachers' leading of whole-class discussions and the impact of particular strategies at this Dialogical level on student engagement. These research findings are extremely valuable in that they provide understandings of how science instruction can move away from a traditional teacher-centered approach to one that is focused on the students as active participants in their own learning. What these studies have generally not investigated fully however, are the strategies that effective teachers use in whole-class discussions that may be specifically targeted to support students' cognitive reasoning about scientific conceptions. Here we describe research on identifying Cognitive Model Construction strategies to address this issue.

The Whole-Class Model Co-Construction 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 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 was at a given point in the discussion. 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.

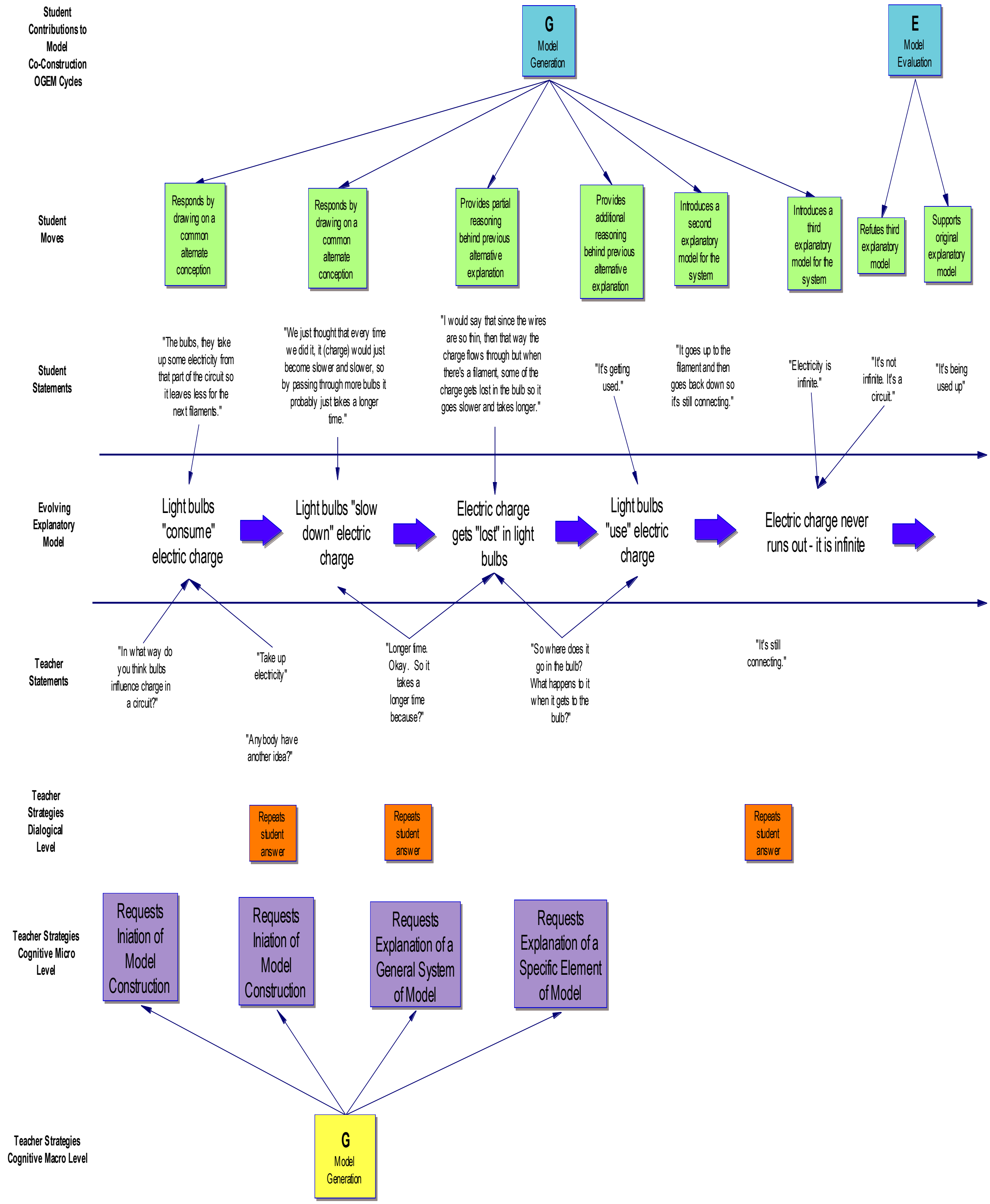

Fig. 1a - Whole Class Model Co-Construction Diagram — Part A

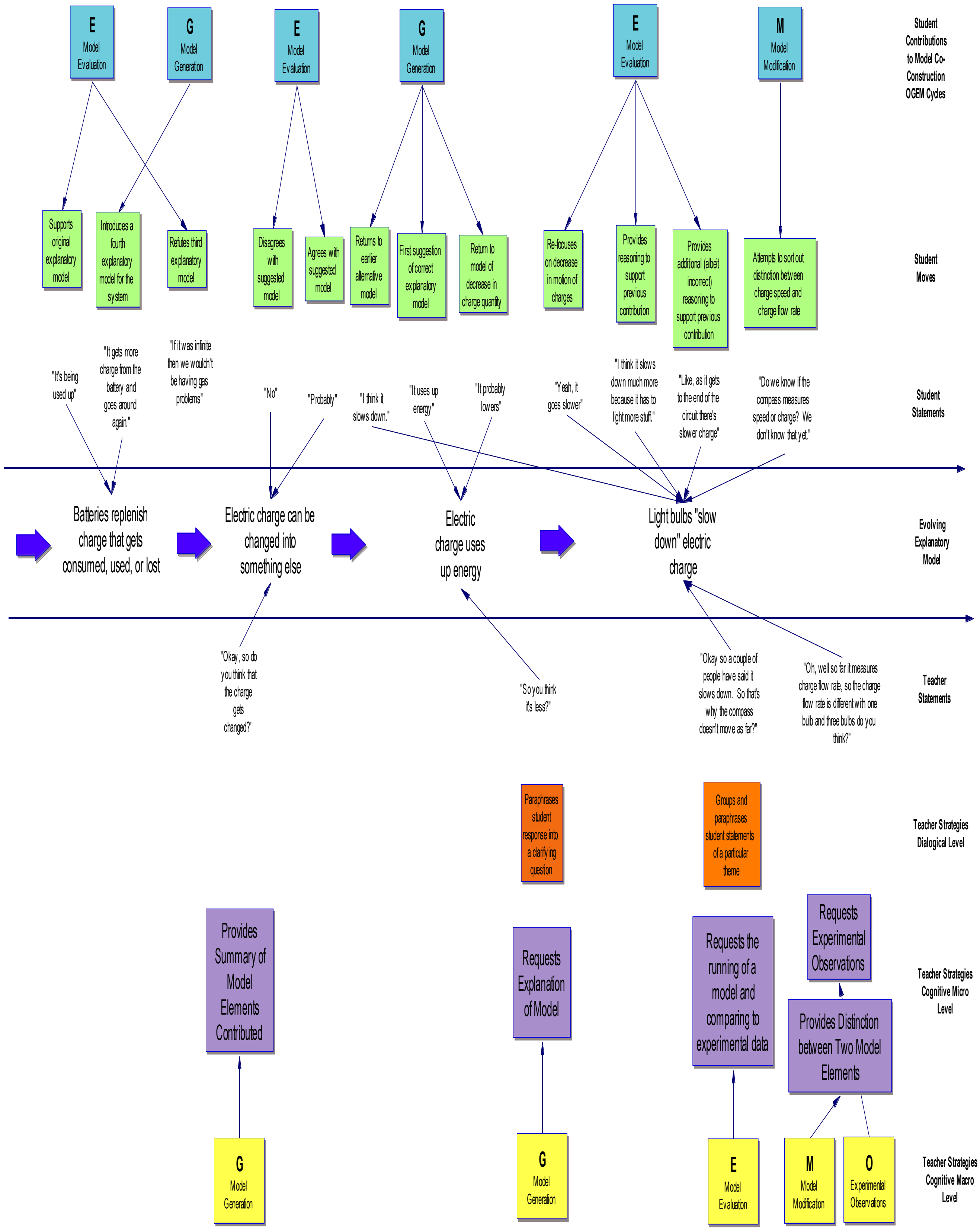

Fig. 1b - Whole Class Model Co-Construction Diagram — Part B

One layer above each student statement is a brief description of the hypothesized contribution of the utterance to the discussion, shown in green. Our focus in this research however is on the three levels of teaching strategies shown under the teacher statements. These are: *Dialogical* strategies (shown in orange), *Cognitive Micro Strategies* (shown in purple) and *Cognitive Macro Strategies* (shown in yellow). For example, in the first four purple boxes in this classroom discussion segment, three different Cognitive Micro Strategies (one is repeated) are portrayed. Each of these serves the larger Macro Strategy of encouraging Model Generation (G). In the second portion of the diagram, five different Cognitive Micro Strategies are shown, each contributing to one of the Macro Strategies of Model Generation, Evaluation, Modification, and Observation.

Because of the chronological nature of these whole-class discussion diagrams, it is possible to track transitions through the phases of the Model Construction OGEM Cycle and to determine whether these shifts were initiated by student or teacher statements. From a teacher lesson-planning perspective, it is interesting and potentially helpful for teacher education efforts, to notice the types of statements and questions that the teacher uses to move the conversation from phase to phase. 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.

Implications for Teacher Education

The analysis of the high school electricity classroom episodes and the subsequent development of the representative diagrams described above, combined with our work in other instructional units and grade levels, have led us to the point where we believe we have valuable pedagogical information to share with K-12 science teachers. As a result, the most recent phase of our research has been the development and implementation of an eight-week instructional unit for pre-service science educators in the one-year post-graduate education degree program at Saint Thomas University in Fredericton, New Brunswick, Canada. This unit took place in the months of January & February, after the students had experienced their first semester of coursework (September & October) and their first of two nine-week practice teaching internships (November & December). The instructional unit was designed to develop our students' skills in leading effective model-based whole class discussions and employed the following components:

1) Before the course began, we accessed the pre-service teachers' prior knowledge about model-based learning and leading discussions; uncovering their experiences and beliefs about the manner in which teachers: ask questions, respond to student comments or queries, prompt students to examine and critique their own and peer`s ideas, encourage students to develop plausible arguments for explanations, and foster students` revisions of their own reasoning once new evidence is presented. For research ethics purposes, this was done through an interview and survey process conducted by a research assistant so that I, as course instructor and primary researcher, could not link any of the responses to individual students. A summary of sample student responses to selected survey questions is presented in Table 2.

Survey/ Interview Question	Sample Student Responses
What strategies can science teachers use to initiate whole class discussion?	Discrepant events, concept maps, questioning, small group activities
What strategies can science teachers employ to sustain whole class discussion?	Giving everyone a chance to talk, using good questions, redirecting, probing
What percentage of ideas considered in whole class discussions do you feel should be teacher generated vs. student generated?	Responses ranged from 70% vs. 30% to 20% vs. 80% with an average of 34% vs. 66%
What percentage of the evaluation of ideas during whole class discussions do you feel should be done by the teacher vs. students?	Responses ranged from 60% vs. 40% to 20% vs. 80% with an average of 42% vs. 58%
What strategies can science teachers utilize during whole class discussions to get students to evaluate their own and other students' explanatory models?	Asking questions, thought experiments, think aloud, think-pair-share, presenting ideas/information/events that conflict with their models
What are some of the methods science teachers can use in whole class discussions to help students modify their explanatory models?	Get other students to provide feedback, provide counter examples, ask questions to challenge their thinking
Students were presented with a segment of transcript from a whole class discussion in a grade 9 science class. For each of five teacher statements that were highlighted, they were asked to select the strategy from a list of ten possibilities that they felt best described what the teacher was attempting to do with that statement.	Scores ranged from 0/5 to 3/5 correctly identified strategies with an average of 1.7/5

Table 2 – Summary of Student Responses to Selected Pre-Instruction Survey Questions

2) The instructional unit began by introducing the future educators to a series of research articles on whole class discussion techniques and model-based teaching and learning in science that provided insights on the tasks teachers undertake when leading a class discussion. This included such things as: maintaining classroom management, providing a classroom culture that supports student contributions, fostering students' construction of explanatory models, supporting student meta-cognition, and encouraging classroom conversations that allow students to make mistakes and learn through a process of idea evolution as opposed to getting the right answer first. Three articles from the Tools for Ambitious Science Teaching website http://tools4teachingscience.org/ developed by Mark Windschitl's research team in the College of Education at the University of Washington, as well as those written by members of our own group, formed the basis for much of the course readings.

3) During the first four weeks of the course, the students were engaged in a variety of classroom activities that encouraged them to explore the concepts of teacher/student model co-construction as well as the various strategy levels for fostering effective whole-class discussions. These included reviewing video recorded segments of secondary science classrooms, both from the

TIMSS (Trends in International Mathematics and Science Study) Video Study Series and from the database of video recordings of the teachers who participated in our own studies as described earlier.

Transcriptions of the teacher/ student discourse from these videos were provided to enable the pre-service teachers to critically evaluate the kinds of Dialogical level conversational strategies that the teachers on the videos were utilizing. Once students started gaining a level of familiarity with the names of particular Dialogical teaching strategies such as deferring judgment, probing, paraphrasing, voting, etc. they were challenged to play a learning game in which they worked in pairs to match cards containing sample teacher statements with corresponding names or brief descriptions of the strategies that those statements exemplified.

Next, Whole-Class Model Co-Construction Diagrams for selected classroom segments from our own database were shared with the course participants in hopes that seeing the classroom conversations portrayed in this manner would allow them to start distinguishing between teaching strategies at the Dialogical and Cognitive Model Construction levels. By returning to the videos and transcripts from our research database of teachers who were attempting to foster student construction of explanatory models for various scientific phenomena, we introduced the students to the work that these teachers were doing at both the cognitive micro and macro levels to support their students' thinking.

Realizing that thirty-nine specific cognitive model construction teaching strategies at the micro level would be over-whelming for pre-service science teachers to comprehend, we selected ten that we believed were important for them to be aware of. These included: requesting/providing recall of experimental observations, requesting/providing explanations, requesting/providing experimental evidence to support a model, requesting/providing the running of a mental model and comparing to experimental data. As a means of developing their abilities at recognizing these cognitive teaching strategies in use, the course participants were asked to identify examples of them from the video recordings and transcriptions of classes where teachers were employing them. Eventually, the pre-service science teachers were even presented the challenge of completing the bottom three rows of a skeleton whole-class model co-construction diagram that contained only the teacher and student statements. All of these classroom activities were video recorded for later reflection and analysis.

4) Once the pre-service teachers had sufficient opportunity to observe, think about, and exchange views on the discussion-leading strategies of exemplary veteran educators in the field, the next step was for them to try out some of the tactics for themselves. Their opportunity to do so took place during the final four weeks of the course in the form of peer-to-peer micro-teaching sessions on a secondary science (grades 9-12) topic of their choice. In planning these 40 minute mini-lessons, the pre-service teachers were required to build in a whole-class discussion segment during which they attempted to lead their colleagues' in the construction of explanatory models for a key concept of the lesson. Some of the topics they chose were: the human circulatory system, balancing chemical equations, waves, ecological footprints, and chemical reaction rates.

5) These in-class mini-lessons were videotaped and copies were provided to the pre-service teacher and three classmates. Within a week of their micro-teaching presentations, the pre-service teachers received feedback from their three colleagues, who each had an opportunity to critically review the video recording of the lesson. Using a rubric co-operatively developed in

class, the peer evaluators made notes and comments to provide constructive feedback to their colleagues. The first part of the rubric focused on general classroom practices such as teacher verbal clarity and audibility, the teacher's awareness of student engagement and understanding, provision of differentiated learning opportunities, etc. However, the second portion of the rubric provided opportunity for the peer evaluators to note specific Dialogical level and Cognitive Model Construction level strategies that their colleagues had employed in their mini-lessons. Some examples of feedback that the pre-service teachers provided one another on these aspects of their lessons are listed in Table 3.

Sample Peer Evaluation Comments Regarding Dialogical Strategies Used in Mini-Lessons	**Sample Peer Evaluation Comments Regarding Cognitive Model Construction Strategies Used in Mini-Lessons**
You did an excellent job of *making students feel that their contributions were valued, without telling them if they were right or wrong.*	At 14:20, you said, "What does the septum do, where is it in the heart?" This is a good example of *requesting explanation of a particular element of the model (Generation).*
You did a lot of *probing* throughout the lesson. Sometimes, when you asked a question, students would simply give a yes or no response, but you made sure to follow up by asking them why, what made them think that way, etc.	At 14:50, you asked, "The respiratory system and the circulatory system are pretty inter-twined, do you think that has anything to do with this separation that Maggie says is in the heart between the left and the right sides?" An excellent example of *requesting examination of the relationship between two elements of the model (Evaluation).*
You regularly *paraphrased* student contributions so that the whole class could participate in the discussion. You *amplified* certain statements and *marked* others by saying "hold that thought", or "interesting".	At 22:50, you asked, "What does the semi-permeable membrane look like?" This is a very good example of *requesting the initiation of model construction (Generation)*
You did a great job of *deferring judgment* during the model construction phase of the discussion which is something that is really difficult to do – students suggested blocks with doors, honeycombs, and other ideas and you *gave equal consideration* to all of them by putting them on the board – Excellent work!	At 27:07, you stated, "Does that solve our issue of the tails interacting with water?" I think this is an example of *requesting additions or changes to the model (Modification)*

Table 3 – Sample Peer Feedback on Dialogical and Cognitive Model Construction Strategies Identified in Mini-Lesson Presentations

6) At the end of the eight-week course in late February, and just before they began their second nine-week practice teaching internships, the students participated in a second interview/survey process to provide them an opportunity to reflect on what they had experienced in the instructional unit and also to evaluate whether any changes had occurred in their knowledge and opinions about leading class discussions. Since the deadline for submission of this paper for inclusion on the NARST conference CD occurred while these post-instruction interviews were being conducted, results of this process cannot be shared at this time. A brief summary outlining the post-instruction interviews will however, be provided during the conference presentation.

7) During their second nine-week teaching practicum, the student teachers will be encouraged to seek out opportunities to engage their students in discussion-based co-construction of explanatory models for concepts within the science curricula being taught.

8) Upon completion of their internships at the end of April, when they return to classes for their final semester of coursework (May & June), the post-graduate science education students will participate in the interview/ survey process a final time to evaluate the impact that having an authentic classroom opportunity to practice their model-based discussion leading strategies had on their understanding and comfort with the techniques.

Conclusion

Many of the scientific topics that students encounter during their K-12 learning experience require them to grapple with very abstract and conceptually challenging ideas. Our research team has documented experienced teachers' abilities to facilitate engaging, inquiry-focused classroom discussions in order to foster students' abilities to construct, evaluate, and revise workable explanatory models for the concepts they are learning. This paper provides an overview of one of the classroom discourse investigations that our research team has carried out over the past few years and explains the steps that are currently being taken in one School of Education to share what we are learning with pre-service science teachers.

Analysis of the student/ teacher dialogue from whole class discussions veteran high school physics teachers in a previous study (Williams, 2011) identified thirty-nine of what we refer to as Cognitive Model Construction teaching strategies that are believed to have supported the students' conceptual understanding. These strategies differ from those we refer to as being at a general Dialogical level - strategies intended to support the clear and open communication and sharing of student ideas through class discussion. We have developed a new diagramming system that illustrates the distinction between these two strategy levels and that connects the Cognitive Model Construction strategies to the longer time-frame Model Construction Cycle Phases of Observation, Generation, Evaluation and Modification.

Based on these findings, the most recent phase of our research has been the development and implementation of an eight-week instructional unit for pre-service science educators in the one-year post-graduate education degree program at Saint Thomas University in Fredericton, New Brunswick, Canada. The instructional unit was designed to develop our students' skills in leading effective model-based whole class discussions and employed a variety of learning activities such as journal article reviews, classroom videotape observations, teacher/ student transcript analyses, teacher strategy identification exercises, classroom discourse diagramming assignments, and peer-evaluated micro-teaching sessions, all of which were videotaped for later review and analysis. The unit attempts to address all three levels of strategies shown in Figure 1 but does this gradually, one level at a time, over a period of several weeks.

At the time of writing of this paper, the data for our exploratory study on the impact of these pre-service teacher preparation practices is only partially complete and the analysis of it is in the beginning stages. In the months ahead we look forward to reviewing the video recordings of our recent instructional efforts with these emerging teachers and scrutinizing their responses to the three sets of feedback interviews/surveys. This is seen as an essential stepping stone toward developing more systematic ways of evaluating these new aspects of the course.

It is believed that this study's contributions to an understanding of both model-based instruction and whole-class discussion leading strategies can support the work of teachers and teacher educators by dividing the extremely complex act of science teaching into several basic sets of teachable skills. It is hoped that in sharing our own experiences of putting our research findings into action in our teacher preparation program, we can further a shared understanding of what constitutes effective science teaching and learning.

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