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Identifying Multiple Levels of Discussion-Based Teaching Strategies for Constructing Scientific Models

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This study sought to identify specific types of discussion-based strategies that two successful high school physics teachers using a model-based approach utilized in attempting to foster students' construction of explanatory models for scientific concepts. We found evidence that, in addition to previously documented dialogical strategies that teachers utilize to engage students in effectively communicating their scientific ideas in class, there is a second level of more cognitively focused model-construction-supporting strategies that these teachers utilized in attempting to foster students' learning. A further distinction between *macro* and *micro* strategy levels within the set of cognitive strategies is proposed. The relationships between the resulting three levels of strategies are portrayed in a diagramming system that tracks discussions over time. The study attempts to contribute to a clearer understanding of how discussion-leading strategies may be used to scaffold the development of conceptual understanding.

Keywords: *Model-based learning; Teaching strategies; Whole-class discussion; Conceptual learning*

Introduction

Good discussion leading on the part of teachers is considered by many to be an art rather than a science. Engaging students in meaningful conversations about abstract and conceptually challenging scientific concepts can be an effective means for fostering their construction of explanations and eventual understandings of them. In this article, we will review a number of important studies that have identified a collection

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of general *dialogical strategies* for *supporting and extending student participation* in discussions. We then attempt to go beyond these findings by conducting in-depth video case studies on two experienced and successful high school physics teachers. The particular manner in which such classroom discussions unfold and the specific cognitively focused teacher-talk strategies designed to support students' conceptual understanding are not well understood and in need of further examination. We attempt to identify a collection of specific *cognitive strategies*, not just for promoting participation, but for *promoting conceptual understanding through model construction*. Since people often use sub-strategies within strategies, we also ask whether there is more than one level of cognitive strategies. We find two levels of such cognitive strategies, which, along with the dialogical level, comprise three levels of strategies being used simultaneously by these experienced teachers. Many areas pose conceptual difficulties for students of the sciences, and especially for these areas, it seems likely that understanding such cognitive strategies would be important for both theory and practice.

The term *model* has many uses; however, in the context of this study, a model in the broad sense is considered to be a simplified representation of a system, which concentrates attention on specific aspects of the system (Ingham & Gilbert, 1991). Here, we will focus on qualitative rather than quantitative models. *External instructional models* are often developed and used by teachers and curriculum developers to promote learner understanding of a particular target concept. Examples include solar system mobiles, ripple tanks, and computer simulations of mitosis and meiosis. We will concentrate here on *internal models*, using the term model to mean a mental representation unless otherwise noted. Within that, we focus on *explanatory models*, which are mental representations of causal or functional mechanisms that are often hidden, such as molecules, electrical currents, and fields, and that can explain why phenomena in a system occur. They are a separate kind of representation from empirical patterns or observational descriptions of system behavior (Campbell, 1920; Harre, 1961).

Theoretical Framework

We assume that explanatory models are cognitive representations that support explanation and understanding by simulating the structure and behavior of targeted systems (Gilbert, 2011; Hafner & Stewart, 1995; Johnson-Laird, 1983; Schwartz & Black, 1996). Collins and Gentner (1987), Gilbert and Boulter (1998), Gobert and Buckley (2000), Vosniadou (2002), Steinberg (2008), Windschitl, Thompson, and Braaten (2008), Schwarz et al. (2009), Duit and Treagust (2003), McNeill and Krajcik (2008), and Gilbert (2011) agree that engaging students in the processes of developing explanatory models can play a significant role in promoting their abilities to understand and reason about scientific concepts. These authors believe, for example, that modeling a gas as a system of colliding particles provides a flexible and predictive understanding that explains why increasing temperature can produce an increase in pressure in a container. Students can use intuitive spatial reasoning processes to argue about questions such as whether the particles can settle in one part of the container and this in turn can suggest experiments which can evaluate the current model and promote modifications, thereby mimicking some key scientific reasoning practices. However, Khan (2011) found that some teachers who believe they are facilitating model-based learning still have some important modeling processes missing in their classrooms. In order to educate teachers it is important to identify teaching strategies that can support model-based instruction.

This study investigates the use of whole-class discussion as a means for supporting students' participation in the construction and modification of explanatory models. Research by van Zee and Minstrell (1997), Hammer (1995), Hogan and Pressley (1997), Roth (1996), and Chin (2007) has identified some general strategies teachers use in whole-class discussions in order to promote student engagement and communication. These include participating mainly as a facilitator in the discussion, restating or summarizing student statements, 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. The work of these researchers has yielded important findings in the facilitation of whole-class discussions, by identifying techniques that are largely of a *dialogical* nature. We describe such dialogical strategies as not aimed at specific kinds of conceptual learning, but rather as intended to support dialogical interaction in general, encourage increased student participation and ownership in the discussion, and foster a classroom culture that promotes and encourages student input, values opinions, and considers alternative conceptions and viewpoints. 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 placed much less emphasis on, however, are the specific strategies that experienced model-based teachers use in whole-class discussions to support specific kinds of conceptual learning processes. In this study, we attempt to identify a set of *cognitive model construction* strategies that are aimed at promoting model construction and evolution. They do this through questions and comments that respond to specific strengths and weaknesses in the ideas being expressed by students. They are intended to support students' reasoning about the domain and support specific steps in the construction and refinement of explanatory models. An exploratory case study of a mathematics class by Schoenfeld (1998) suggested that several levels of strategies can be involved in instruction. In this study, we will identify two cognitive levels in addition to the dialogical strategies level.

GEM Cycles

Part of our theoretical framework in identifying these cognitive model construction strategies was a model-based reasoning view of scientific practice, coming from cognitive science studies of experts. Clement (1989, 2008c) documented a process which he called *GEM cycles* (cycles of model Generation, Evaluation, and Modification) in case studies of scientifically trained experts solving explanation problems, as they constructed a model for an unfamiliar system. Such a cycle can lead a scientist to a successful model even if they start with a severely flawed model. Model generation processes can include starting from an analogy or simply inventing a model element using prior knowledge schemas. These processes in turn depend on processes of mental simulation via imagery and can include determining the spatial alignments and direction of effects in the model. Model evaluation processes can not only involve observation or experimentation, but can also take place via mental simulations in thought experiments (Clement, 2009). Model modification processes can deal with flaws found during model evaluation and can include making changes to the model or making new differentiations between elements of the model and accompanying refinements in the language used to describe those elements. In her investigations of the scientific practices of physicist James Clerk Maxwell, Nersessian (2008) summarizes a view that model-based reasoning involves a process of cycles of construction, simulation, evaluation, and adaptation of models that serve as interim interpretations of the target problem. As will be seen, many of these processes can also be documented in science classrooms.

Another part of our framework derives from model-based co-construction in science education (Clement, 2008b) and the identification of such GEM processes in middle school biology (Nunez-Oviedo & Clement, 2008), high school physics (Clement, 2002; Williams, 2011), and undergraduate chemistry (Khan, 2003). In these studies, the focus is on how teachers support students in refining their models during the instructional process. It was observed that teachers attempted to support students' generation of explanatory models starting from their prior knowledge about the concepts being explored. It was further observed that teachers acted to scaffold students' repeated evaluation and modification of those models through the evolution of what Clement (2000a) refers to as *intermediate models*. These intermediate models are viewed as stepping stones on a learning pathway to a *target model* or desired knowledge state that one wishes students to attain after instruction. An example of this GEM model refinement process from the study on middle school biology (Clement, 2008a) involves the evolution of students' explanatory models of the human lung. Initially the students generated a single hollow lung with a hole at the bottom and other structures, but through carefully constructed questions and responses, the teacher was able to foster students' evaluation of and modifications to the model that resulted in the addition of a second lung, closing the hole at the bottom, and proposing an interior with structures resembling bunches of grapes entwined with string (alveoli and capillaries).

In the present study, statements made by model-based teachers during discussions were first examined to see if they fit into the GEM process pattern, at a level we call 'macro strategies'. Then a larger number of 'micro strategies' were identified at a smaller grain size, such as the use of analogies, discrepant events, requesting evidence, and other less-familiar strategies.

Study Purpose and Research Questions

The primary purpose of this study was to identify cognitive discussion-based strategies that teachers use with the aim of promoting the construction of explanatory models in their classes. In particular, this case study investigated cognitive model construction strategies that two experienced high school physics teachers employed in promoting their students' development of explanatory models for the concepts of charge, energy, current, voltage, and resistance in electric circuits. A secondary purpose of the study was to determine whether these cognitive strategies appear to exist at different levels, and if so what is the relationship between those levels.

As such, we sought to answer the following research questions:

(1) What discussion-based strategies (dialogical and cognitive) aimed at fostering students' construction of explanatory models can be identified as being utilized by two experienced science teachers?
(2) Can the cognitive strategies be described as existing on multiple levels?
(3) If so, what relationships can be described as existing between these levels?

Method

Selection of Teachers

The two teachers were selected partly based on recommendations of them as experienced, exemplary, model-based science educators. They each had close to 10 years of experience in teaching the model-based curriculum called CASTLE (Capacitor-Aided System for Teaching and Learning Electricity). The CASTLE (Steinberg et al., 2004) curriculum fosters the development of causal models of charge and its flow in DC circuits and also provides experimental opportunities for models to break down, demonstrating the need for revising models. The curriculum centers on a model of charge as a compressible fluid experiencing differing degrees of pressure (voltage) and resistance, as it flows through varying components of a circuit.

In addition, the expertise of the two teachers was supported by their results on pre-/post-tests. The two teachers were included in an earlier study in which we gave pre-/post-tests to a sample of 282 CASTLE students and 262 control group students learning from more traditional curricula. The study involved 6 experienced teachers in each group and a total of 27 high school classes. The test used transfer problems designed to measure conceptual understanding, and the teachers administering it were blind to the contents of the test. Williams (2011) found that the CASTLE students as a group had higher gains, with an effect size of 1.29 (Cohen's d), suggesting that the teachers in the CASTLE group had a higher level of conceptual learning occurring in their classrooms. The expertise of the two teachers was supported by their results on these pre/post-tests, since their students had the highest average gains of all the teachers who participated. Although that study was exploratory rather than a formal evaluation, it served to support our teacher selection and gave us some reason to believe that we were studying classrooms where a significant amount of learning was occurring and studying teachers who had some expertise.

Data Collection

Over the course of the 6–8 weeks of study, approximately 30 hours of video recordings were made of classroom activity from Teacher A's and Teacher B's classes and were transcribed for analysis. Teacher A taught two classes; a ninth-grade introductory physical science class and an eleventh-grade physics class. Teacher B taught three classes of ninth-grade introductory physical science. The focus of the data collection process was on capturing whole-class discussion segments in which the teachers and their students appeared to be engaged in the co-construction of explanatory models of electricity. These conversations typically took place immediately after the students had worked together in pairs conducting explorations on various circuits. By 'engaged' we mean that the teacher succeeded in having many students participate in some types of reasoning, not that the discussion necessarily reached closure immediately in the sense of leading to correct answers. We sought to analyze sections that were sufficiently long that they contained a sustained discussion, and had more than just one or two students involved. In order to acquire a rich database but still make the analysis manageable, we focused the study on eight episodes that were on topic and lasting more than 90 seconds in which at least three different students participated along with the teacher. This criterion met our purpose of having sufficient material to identify a large set of strategies being used.

As a secondary source of data, reflective interviews were conducted with Teachers A and B in an attempt to triangulate our interpretations of strategies they used with their own beliefs about what was happening in their classes. Through a process (explained in the Results section) of reviewing classroom videos, transcriptions, and our diagrammatic representations with the teachers, we were able to acquire a cross-check on our coding for the eight discussion segments analyzed in this study.

Analysis

Micro strategies. A construct development cycle (Miles & Huberman, 1994) was utilized in an effort to develop consistent descriptions of the teachers' discussion strategies, while also building on previous research, at the level of what we came to call 'micro strategies' (e.g. such as 'Teacher provides an analogy' or 'Teacher requests that students generate a model element to explain a specific observation'). This involved a cycle of segmenting the transcript into meaningful teacher statements as the primary unit of analysis, making observations from each segment, formulating a hypothesized construct for or classification of the strategy behind the teacher statement, returning to the data to look for more confirming or disconfirming observations, comparing the classification of the statement to other instances, criticizing and modifying or extending the hypothesized category to be consistent with or differentiated from other instances, returning to the data again, and so on. The first author attempted to code each of the teacher statements from the transcripts into strategy categories. The authors then jointly critiqued and suggested directions for revisions to the initial descriptions and categorizations, and a second cycle of recoding occurred. This cycle was repeated. This was followed by a stage of condensing similar strategies in our list into somewhat more general descriptors that yielded a smaller and more manageable set of micro strategies.

Macro strategies. At a second level of description we call 'macro strategies', we were curious to see whether the discussion-leading actions of the teachers fit the larger and more general GEM processes of model Generation, Evaluation, and Modification described in the 'Theoretical Framework' section. (As will be reported in the section 'macro strategies', in the end our analysis described the strategies we had identified at the micro level as sub-processes for accomplishing the more general macro strategies.) However, the macro (GEM) processes had been described for expert scientists, not teachers, and their descriptions would have to be adapted in the case where they were found to apply. In order to do that, we attempted to apply the GEM categories to each individual teacher statement and utilized a similar construct refinement process as described earlier to develop and refine the criteria for the GEM categories in a teaching context.

Results

Macro Strategies

By attempting to classify the individual teacher statements using the GEM categories, we found that we could retain the nomenclature of model Generation (G), model Evaluation (E), and model Modification (M). However, these did not capture teaching strategies focused on establishing or recalling patterns from students' observations during explorations. When we added a fourth Observations (O) category to reflect references to data and evidence that appeared to serve as the basis for model construction, these four macro categories appeared to capture almost all sections of transcript. The following OGEM category criteria were developed at the macro level:

Observations (O): The statement either asks for or provides 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 phrases 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 either asks for or provides a theory, model, conception, or explanation. 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 phrases that help identify model Generation strategies:

what ideas do you have about . . . , what do you think is happening . . . , what explanation can you think of for . . . , I 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 statement either asks for or provides an evaluation, judgment, refutation, criticism, support, or endorsement of a particular explanatory model. Examples of phrases that help identify model Evaluation strategies: 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 either asks for or provides 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 is instead considered to be in the Generation category. Examples of phrases that help identify model Modification strategies: does anyone see it a different way . . . , would anyone suggest changing . . . , maybe if we explained it like this . . . , could it be more along the lines of . . . , etc.

We also conducted reflective interviews with Teachers A and B for the purposes of triangulating our hypotheses about their strategies; the teachers confirmed most of our coding, with only a few modifications being made to the coding as a result. As a side note, it is interesting that both educators stated that throughout their teaching careers, they had never experienced as focused or impactful a professional development opportunity as reviewing and reflecting on their classroom practice in the manner described earlier.

Micro Strategies

We also identified a larger number of micro strategies used by the teachers at a smaller grain size, such as 'Teacher provides an analogy' or 'Teacher requests (that students generate) a model element to explain a specific observation'. We found that such 'micro' strategies could be seen as *sub-strategies* for one of the four 'macro' OGEM strategies; e.g. the above micro strategies can both be seen as contributing to the larger 'G' strategy of generating a model. Another way to say this is that that the macro strategies refer to the goals/objectives of the actions taken by teachers while the micro strategies refer to the specific actions taken.

In order to help us identify and keep track of strategies at these different grain sizes, we worked to develop detailed diagrammatic representations of the teacher–student discourse patterns. These diagrams (a) present the spoken contributions of teachers and students, (b) track the evolution over time of the explanatory models being discussed, and (c) differentiate several strategy levels that can explain the teacher statements (Figures 2 and 3). There the above two cognitive strategy levels are distinguished from the third level of non-cognitive, dialogical strategies described in the 'Theoretical Framework' section. The diagrams show how a single teacher

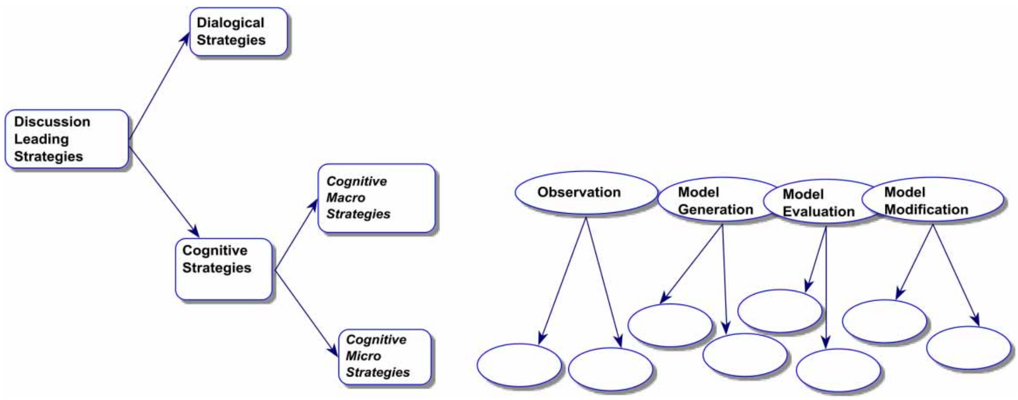

Figure 1. Taxonomy of three levels of teaching strategies, including dialogical strategies, and two levels of cognitive strategies (ovals refer to the individual macro and micro cognitive strategies present).

statement can often be seen as contributing simultaneously to a strategy at each of the three levels. These diagrams are further described later in the article.

Because we started with fewer ideas in our framework than for the macro strategies, the micro strategies required many more cycles of criticism and revision to arrive at a consensus on a set of stable categories that were judged by both authors to be sufficiently coherent, unambiguous, general, and unconfounded. Initially, we identified a considerable number (39) of cognitive micro strategies in the repertoires of the two teachers, each of which appeared to contribute to a larger goal of one of the four cognitive macro strategies. A hypothesized taxonomic relationship between these two levels of cognitive strategies, as well as the dialogical strategies described previously, is portrayed in the tree diagram in Figure 1. The ovals to the right of the tree diagram represent individual macro and micro cognitive strategies, with the macro strategies each having several micro strategies as sub-processes that can help implement a macro strategy.

The purpose of this qualitative study was to generate hypotheses about the content and structure of teachers' cognitive strategies for discussion leading. As such, the study is exploratory and hypothesis generating. The constructs being coded were about high-level and complex phenomena, and as a result of this the codes are high inference. Given the high inference nature of the strategy constructs, we did not feel at this early stage of hypothesis generation that coding by totally independent multiple judges was appropriate or feasible. Rather the investigators worked collaboratively for a considerable period of time to formulate, and repeatedly critique and refine the coding categories in order to heighten their coherence and generality.

Realizing that 39 micro strategies at the cognitive model construction level was too large a number to expect science teacher educators to address and teachers to remember and make meaningful use of in classrooms, we sought to amalgamate these into a more manageable number. In doing so, the list of 15 key cognitive strategies described in Table 2 was created.

Table 1. Classroom transcript with teacher cognitive macro and micro strategies identified.

Turn	Transcript	Macro strategy	Micro strategy
1	T: In what way do you think bulbs influence charge in a circuit?	Model Generation	Requesting the initiation of model construction
2	S1: The bulbs, they take up some electricity from that part of the circuit so it leaves less for the next filaments		
3	T: Take up electricity. Anybody have another idea?	Model Generation	Requesting the initiation of model construction
4	S2: We just thought that every time we did it (added a bulb), it (charge) would just become slower and slower, so by passing through more bulbs it probably just takes a longer time.		
5	T: Longer time. Okay. So it takes a longer time because?	Model Generation	Requesting new detail or elaboration of the model
6	S3: I would say that since the wires are so thin, then that way the charge flows through but when there's a filament, some of the charge gets lost in the bulb so it goes slower and takes longer.		
7	T: So where does it (charge) go in the bulb? What happens to it when it gets to the bulb?	Model Generation	Requesting new detail or elaboration of the model
8	S3: It's getting used.		
9	S4: It goes up to the filament and then goes back down so it's still connecting.		
10	T: It's still connecting.		
11	S5: Electricity is infinite.		
12	S1: It's not infinite. It's a circuit.		
13	S3: It's being used up.		
14	S4: It gets more charge from the battery and goes around again		
15	S6: If it was infinite then we wouldn't be having gas problems!		
16	T: Okay, so do you think that the charge gets changed?	Model Generation	Requesting new detail or elaboration of the model
17	S7: No.		
18	S3: Probably.		
19	S2: I think it slows down.		
20	S8: It uses up energy.		
21	S5: It probably lowers.		
22	T: So you think it's less.	Model Generation	Requesting new detail or elaboration of the model
23	S2: Yeah, it goes slower.		
24	S5: I think it slows down much more because it has to light more stuff.		
25	S9: Like, as it gets to the end of the circuit there's slower charge.		

(*Continued*)

Table 1. Continued

Turn	Transcript	Macro strategy	Micro strategy
26	T: Okay so a couple of people have said it slows down. So that's why the compass needle doesn't move as far?	Model Evaluation	Requesting students to run their model for evaluation
27	S6: Do we know if the compass measures speed or charge? We don't know that yet.		
28	T: Oh, well so far it measures charge flow rate. So the charge flow rate is different with one bulb and three bulbs do you think?	Model Modification	(a) Providing differentiation between two elements of the model
		Observation	(b) Requesting observations

To conserve space, we provide an example of the cognitive strategy levels analysis for just one 3-minute episode of whole-class discussion from one of Teacher A's classes, shown in Table 1. This episode was chosen since it was a clear example and easy to comprehend without extensive electricity knowledge.

Background for Episode

The overall aim of the curricular unit containing this episode was to develop a concept of electrical resistance in circuits. Just before the whole-class discussion that took place in this episode, the students 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 bulbs' 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 and increased vs. decreased needle deflection) which they require to engage in the construction of explanatory models for the effects of light bulbs on the behavior of electric charge in circuits.

Analysis of the episode

What is perhaps initially most apparent about the episode in Table 1 is the teacher's ability to involve his students in extended periods of discussion with minimal participation on his part; *student-to-student* interaction as opposed to the more common *student-to-teacher* discourse. The teacher in this episode appears to be fostering a wide range of student engagement with the scientific ideas. Through this type of *dialogical* interaction, students feel comfortable in proposing and challenging ideas without the necessity for teacher intervention. What may not be initially apparent, however, is the work that the teacher is doing at the *cognitive model construction micro strategy* level. Throughout the description that follows, cognitive micro strategies will be identified in *italics*.

There is an implicit Observation phase before the whole-class dialog shown in the Table 1, since the students have just come from doing laboratory observations in pairs. The teacher then begins the discussion with a question by *requesting the initiation of model construction* of the effects of light bulbs on charge movement in electric circuits. Turn 1—'In what way do you think bulbs influence charge in a circuit?' This is done to engage the students in the model Generation process and begin brainstorming ideas about what might be going on inside the wires as bulbs are added to the circuit. When the first student response (Turn 2) suggests the commonly misconceived explanatory model of light bulbs taking up or consuming some of the electricity, the teacher is careful not to evaluate the reply as being incorrect. Instead, the teacher utilizes the dialogical strategy of paraphrasing the student's response to honor it and make sure all other students in the class heard it, and then opens the floor to other explanatory models by using a different iteration of the cognitive micro strategy of *requesting the initiation of model construction*. Turn 3—'Take up electricity. Anybody have another idea?'

Although one student suggests an explanatory model of reduced charge flow that partially aligns with the scientifically accepted model, it is clear that the notion of charge being used up, lost, or consumed in the light bulbs is still very much on the minds of many others. The teacher elects to facilitate continued discussion rather than taking it over and allows the students to express their opinions, all the while paraphrasing key points and *requesting elaborations to clarify the proposed models*. Turn 5—'So it takes a longer time because . . . ?' and Turn 7—'So where does it (charge) go in the bulb?'

After fostering the generation of four separate explanatory models for the condition of the electric charge: (a) consumed by bulb, (b) passing through filament, (c) infinite, and (d) replenished by battery, the teacher makes a simple statement, which considers the general nature of all of the suggested models stating, Turn 16—'Okay, so do you think that the charge gets changed?' This appears to set the students off on a series of evaluations of the existing models and the generation of some additional ones.

After hearing a variety of student suggestions, the teacher elects to focus attention on one student's statement by paraphrasing it into a clarifying question, Turn 22—'So you think it's less?' This serves as a combined dialogical strategy; keeping the conversation moving and a cognitive model construction micro strategy; *requesting further elaboration of the model* of reduced charge flow.

The teacher then groups together and paraphrases the student responses that are concurrent with the target model of reduced charge flow rate that he is aiming for. Next, he employs the strategy of *requesting students run their model for evaluation* in hopes that the students will begin to evaluate their model, based on what they saw the light bulbs and compass needles do. Turn 26—'Okay, so a couple of people have said it (charge flow) slows down. So that's why the compass (needle) doesn't move as far?'

The segment ends with a question by a student concerning precisely what a compass needle's deflection indicates about charge movement in the wires it is placed nearby.

The teacher first addresses the issue by *providing differentiation between two elements of the model* regarding what is measured and then turns the discussion back over to the students by *requesting observations* by asking whether charge flow rate is different with varying numbers of bulbs in the circuit. Turn 28–'Oh well, so far (in our model) it measures charge flow rate. So the charge flow rate is different with one bulb and three bulbs, do you think?' This serves to re-focus the discussion on the processes of generating and evaluating explanatory models for charge movement in bulbs and wires.

Diagrammatic Representations of the Modeling Discussions

We developed a diagramming notation to represent the co-construction processes that the teachers and their students engaged in during these classroom discussions. In their simplest form, the diagrams are horizontal versions of the classroom transcript with student statements on the top row and teacher statements on the bottom row, with time running from left to right. For this reason, the diagrams tend to be wide, and in this case, necessitated being split into two parts—a and b. The horizontal strip across the middle of the diagram contains short written phrases which describe evolving explanatory models. These phrases represent our hypotheses for the teacher's conception of what a student's addition to the model was at a given point in the discussion, based on the student's statements. It was assumed that the teachers were aiming to foster model construction based on their view of the student's model at that time, and how it differed from the target model.

In Figure 2 arrows pointing from both teacher and student statements toward the explanatory model descriptions in the center strip indicate shared contributions to the changes or additions in the models. At other times, arrows from the models are directed toward teacher statements, indicating the influence of the current model on the teacher's next query or comment. The very general form of this role for the teacher is described by Hogan, Nastasi, and 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 this is a skill that both educators in this study displayed in their teaching.

In the next iteration of the diagram in Figure 3(a) and 3(b), we focused on the teachers' strategies. After a long period of construct development, we were able to code them at three levels: *dialogical strategies* (shown immediately below the teacher statements—Level 1), *cognitive micro strategies* (Level 2), or *cognitive macro strategies* (Level 3). The diagram depicts a number of our hypothesis based on these codings. For example, it shows each of the teaching strategies at the cognitive micro level as contributing to one of the four macro strategies (Observation, Generation, Evaluation, or Modification). For example, in Figure 3(a) the first four teacher statements serve the goal of having students generate a model. However, one can differentiate between the micro strategies of *requesting initiation of model construction* and *requesting elaboration of a model* by referring to extending the generation of a model element students have already talked about. These two micro strategies both appear to be contributing to the macro strategy of model Generation. The cognitive macro strategy layer

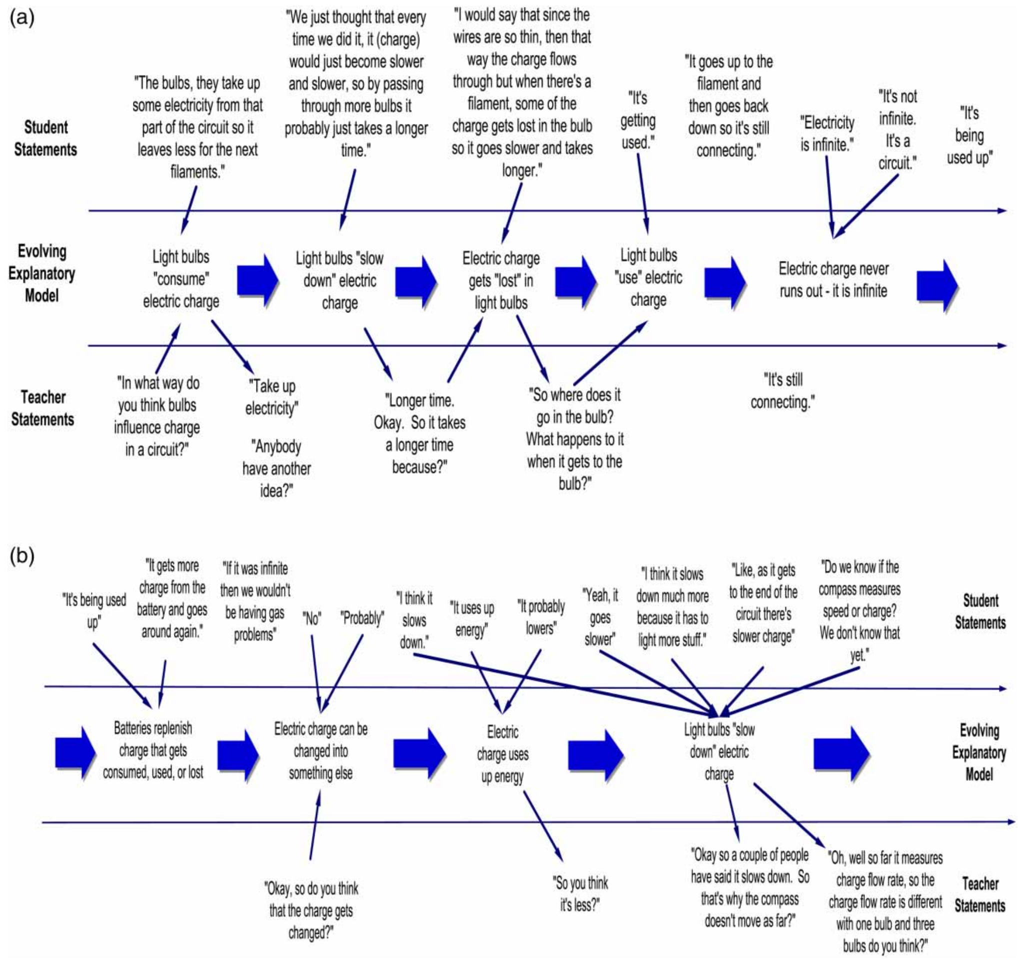

Figure 2. Model co-construction diagram (a) transcript and model evolution—Part A and (b) transcript and model evolution—Part B.

portrays the larger time scale goals of the teacher in engaging the students in the process of generating an explanatory model. The fact that the first instance of the Generation macro strategy points to different types of micro strategies portrays the relation that specific micro strategies serve a smaller number of more general and longer-duration macro strategies. And the fact that strategies at all three levels can be associated with a single teacher statement depicts the hypothesis that these three levels of strategies can operate in parallel.

Findings on Cognitive Strategies

Table 2 is distilled from all of the whole-class model-based discussions that occurred in the videos collected; approximately 6 hours in total, and shows 15 cognitive model

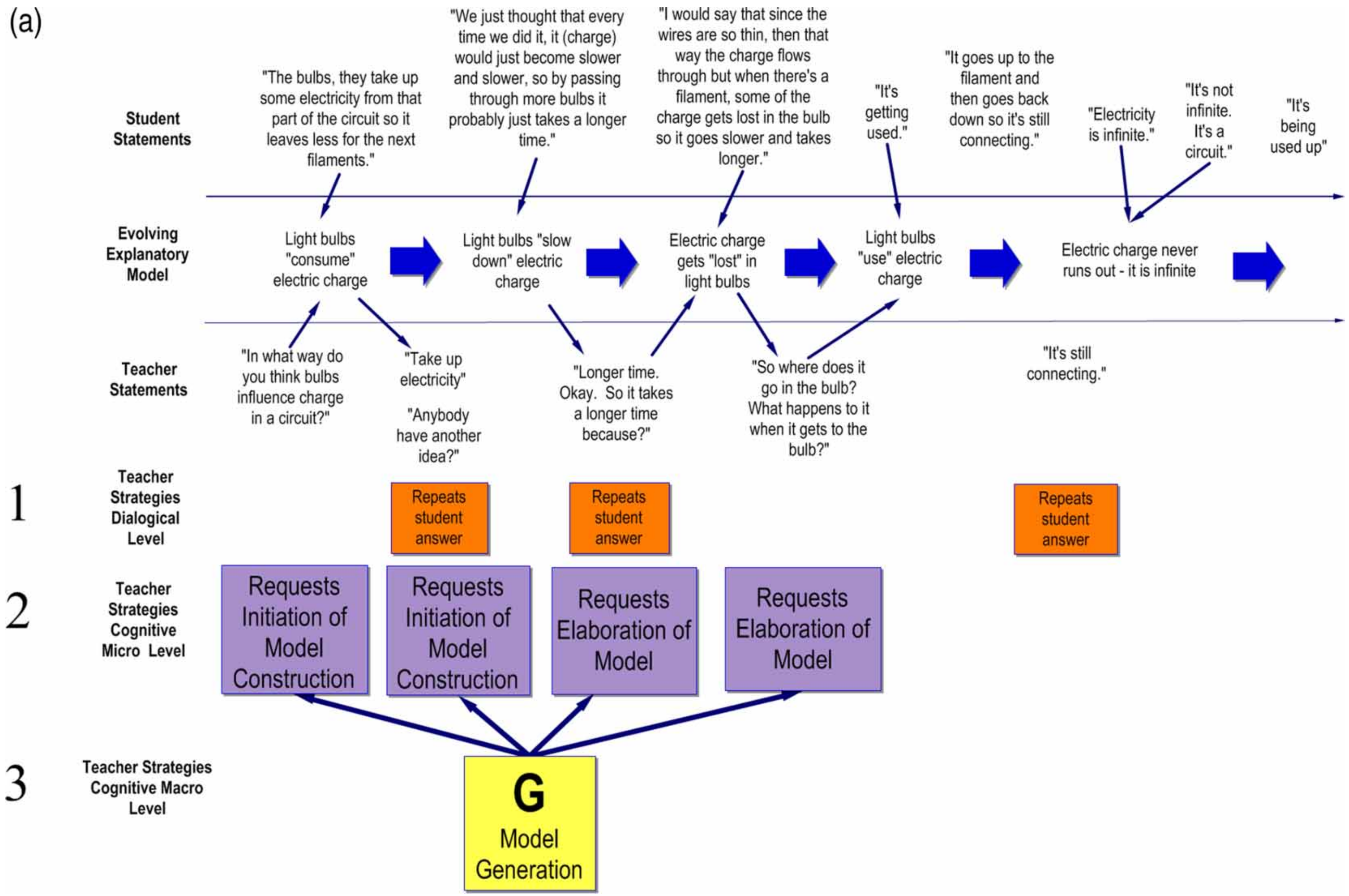

Figure 3a. Model co-construction diagram (a) three levels of strategies—Part A.

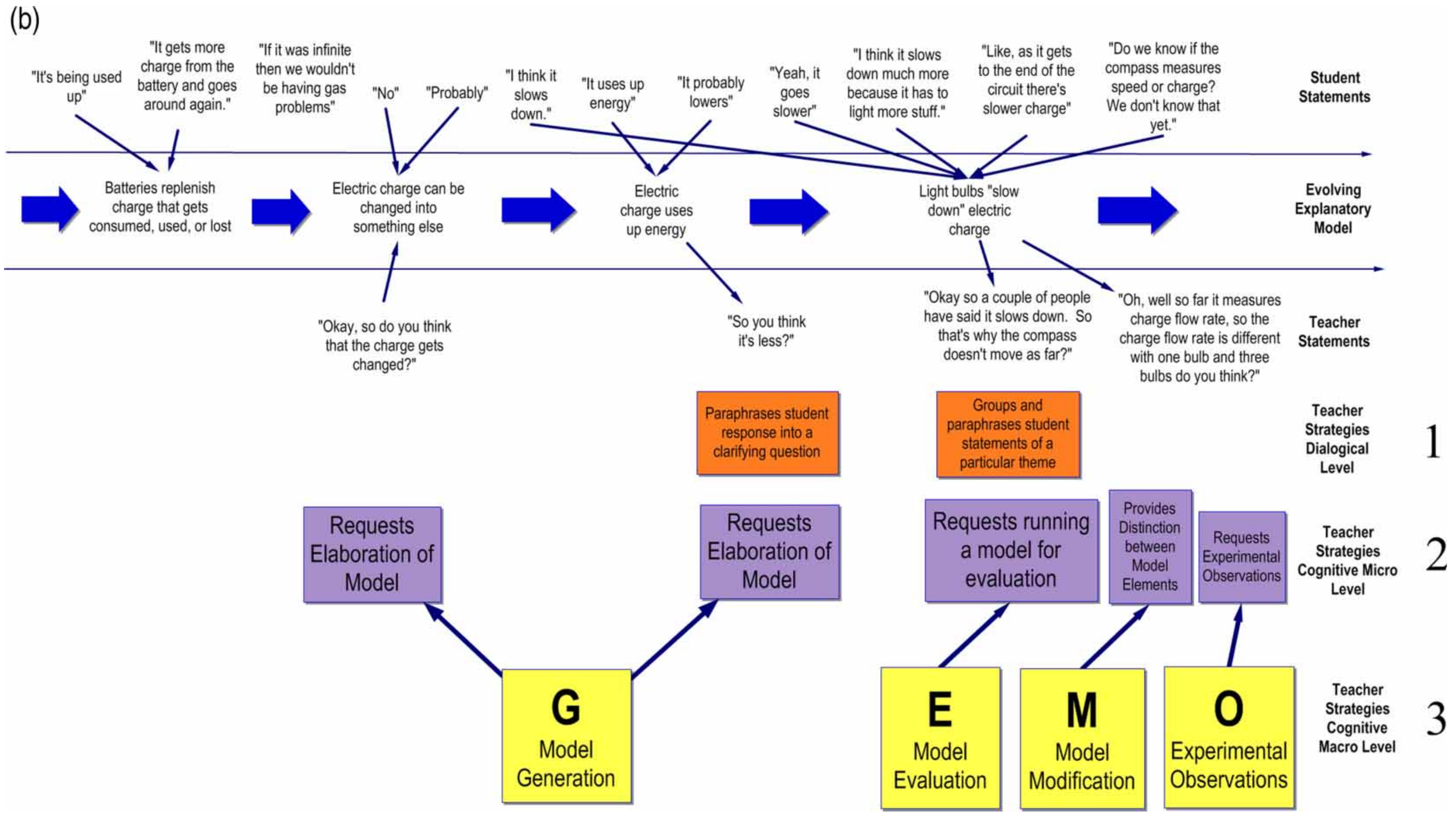

Figure 3b. Model co-construction diagram (b) three levels of strategies—Part B.

Table 2. Cognitive model construction discussion strategies: Macro and Micro levels

Macro level—Observation	
Micro-level strategies	*Classroom transcript examples*
Requests or provides 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?
Requests or provides diagram to help students recall results of an experiment	T: You had a compass under this wire (draws circuit), one under this wire, and one here. What did you notice about all three wires?
Macro level—model Generation	
Micro-level strategies	*Classroom transcript examples*
Requests or provides the initiation of model construction	T: In what way do you think bulbs influence charge in a circuit?
Requests or provides a model element to explain specific observation	T: Okay, so same amount (of measured current). So, what does that tell you about the rate of charge movement through these wires?
Requests or provides new detail or elaboration of the model	T: What happens to charge when it gets to the bulb?
Requests or provides spatial direction of effect	T: Tell me in which direction the charge is moving through the bottom half of that circuit S: Positive to negative. T: Charge is moving? S: From the bottom. T: On the bottom half. Would you all agree it's moving from right to left?
Requests or provides an analogy	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?
Macro level—model Evaluation	
Micro-level strategies	*Classroom transcript examples*
Requests or provides evidence to support or refute a model	T: She thinks that the top bulb (in this model) should be brighter than the bottom bulb or lit longer. Do we have some evidence that would either support that or refute that?
Requests or provides the design of an experiment or thought experiment	Example 1: T: Could we design an experiment to check which of those things that were just proposed is happening? Example 2: T: What if we were to test that model by placing a compass under the wire on either side of the bulb? Would that tell us whether the bulb consumes charge?
Requests or provides running a model for prediction or evaluation	Example 1: 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?

(*Continued*)

Table 2. Continued

	Example 2: T: OK, so a couple of people have said it (charge flow) slows down. So that's why the compass needle doesn't move as far?
Requests or provides a discrepant question or discrepant event	T: Your idea is that the flow rate (of charges) in the wire between the long bulb and the short bulb is different, depending on what order they are in. Is that right? S2: Yes. T: But this other group says that the compass needle deflected the same amount regardless of the order the bulbs were placed in. So, what do you think about that? S3: I don't know. Maybe it (flow rate) is the same.
Macro level—model Modification	
Micro-level strategies	*Classroom transcript examples*
Requests or provides additions or changes to the model	T: Can anybody think of a way to make the model better? –to account for the finding that not all bulbs light with the same brightness?
Requests or provides differentiation between elements of models.	T: That's probably true. But *is heat the same as charge*?
Requests or provides integration of two models or concepts	T: When we added a resistor to the circuit with one bulb, what did you notice? S: The bulb got dimmer. T: Like when you added a second bulb to the circuit? S: Yes –the same thing happened. T: So, that pretty much tells us that *a light bulb is a type of resistor*; at least in terms of their effects on other elements in the circuit.
Requests or provides repair to or refinement of the language describing the model	S: I think it (the light bulb) absorbed some of the charge. T: Absorbed some of the charge. Anybody have anything else? What's another word for absorbs?

construction micro strategies that resulted from the amalgamation and winnowing of the original 39 identified. We have lumped together strategies like the teacher *providing* a model element or *requesting* a model element. Most often these teachers would make a request rather than providing a new element or evaluation, but sometimes they provided them. Partly for this reason, we refer to the overall process as 'model co-construction' by both students and teacher. The table is organized hierarchically with the 15 micro-level strategies being sub-divided into the 4 general macro strategies that they contributed to. The strategies are worded at a general enough level to apply potentially not just to physics but to other science topics as well, and it will be interesting to see if other studies find them being used in other areas. Our previous studies have identified the use of a number of these strategies in middle school biology (Clement, 2008b; Nunez-Oviedo & Clement, 2008) but more comprehensive studies in such areas remain to be done.

Even after modifications to models have been made, they are not necessarily at the level of accuracy or specificity required for conceptual understanding. That being the case, we have observed that the model construction cycle of OGEM often continues until the quality and clarity of the model is sufficient. Also, in practice, several different modeling ideas can be generated early on, meaning that several overlapping OGEM cycles are playing out in parallel. This means that in a dialog like the one shown in the diagrams herein, the four macro strategies will occur in a variety of orders, not just in the order O,G,E,M.

Discussion

An overview of the relationship of this study to previous ones can be described with reference to Figure 1, after which we will consider the relationships in detail. Earlier research by others such as van Zee and Minstrell (1997) had primarily identified dialogical strategies, mixed together with a few cognitive strategies. Our own research group had focused on what we now call Cognitive macro strategies of GEM.

In this study in response to our first two research questions:

(1) What discussion-based strategies (dialogical and cognitive) aimed at fostering students' construction of explanatory models can be identified as being utilized by two experienced science teachers?
(2) Do the cognitive strategies exist on multiple levels?

we first attempted to see whether those macro strategies could be seen in classrooms of teachers trained in model-based instruction, and we found evidence for that and added a fourth macro strategy of Observation. In our analyses we tried to separate these cognitive strategies cleanly from dialogical strategies, as indicated in Figure 1. We then also identified a new layer of 15 cognitive micro strategies at a smaller grain size level than the macro strategies. Although these strategies may not have been named or in some cases even fully conscious in the minds of the teachers working on the fly at the time, they did agree with the teachers' interpretations in later interviews that the strategies captured their purposes in the instruction.

In order to speak to the third question:

(3) If so, what relationships can be described as existing between these levels?

we found that each of the strategies at the micro level could be interpreted as a sub-strategy or sub-process operating in the service of one of the OGEM processes at the macro level. Also, if the teacher used two or more micro strategies in a row that were on the same topic and that fit into the same larger macro strategy, we assumed that the series of micro strategies in that cluster were expressions of the same continuing macro strategy. (The first four instances of model Generation in Figure 3(a) fit this description.) In the Williams (2011) study, all eight of the discussions analyzed contained such clusters. For these reasons, we hypothesize that there is a process–subprocess relationship between the strategies at the macro and micro levels shown in Figures 1 and 3(a) and 3(b), and that specific micro strategies serve a smaller number of more general and longer-duration macro strategies. Furthermore, it was possible to do this hierarchically; that is, it was possible to interpret each micro strategy as being in the service of only one macro strategy throughout all of the discussions.

With regard to specific connections to previous studies, van Zee and Minstrell (1997), Hammer (1995), Roth (1996), Hogan and Pressley (1997), and Chin (2007) have also attempted to identify whole-class discussion-centered teaching strategies aimed at supporting students' scientific conceptual understanding. The study by Chin (2007) is of particular interest, having built upon the other studies, and due to its similarities in goals and its differences in methodology and results in comparison to the present study. Like the research presented here, Chin's study set out to investigate whole-class teacher-guided discussions and to develop a typology and coherent framework of teaching strategies organized by approaches or categories. However, there are also important differences.

For one, Chin focuses solely on teacher *questioning* whereas the present study also considers other types of teacher statements as factors in effective discussion-based teaching. Most of our strategies begin with the wording 'Requests or provides' to reflect the idea that the teacher sometimes provides input instead of questioning. Second, in the present study, the development of categories resulted from the creation of detailed diagrammatic representations of the teacher/student discourse as an intermediate step. We also added the step of acquiring input from the teachers involved on the accuracy of the diagrams, as a means of providing triangulated support for the development of strategy descriptions and hypotheses as to their effects on student learning.

Third, in terms of the products of the research conducted, Chin's work resulted in a list of 11 questioning-based teaching strategies organized into four main instructional approaches, namely, Socratic questioning, verbal jigsaw, semantic tapestry, and framing. The results of the present study organize teacher strategies into two levels; (1) those that support dialogical classroom interactions and (2) those that support cognitive model construction. The cognitive strategies are in turn divided into 4 macro strategies and 15 micro strategies. Chin's major category of Socratic questioning bears some resemblance to our category of dialogical strategies; both being general strategies for drawing out students in discussion. However, Chin's focus on general strategies for tying together facts, keywords, abstract concepts, and framing summaries is different from our focus on the cognitive macro and micro strategies targeting particular types of conceptual learning processes for developing explanatory models, and these may be complementary lenses for viewing instruction.

In an investigation of a high school chemistry teacher utilizing whole-class discussion to promote students' construction of explanatory models for solubility, Justi, Paganini Costa, and Braga Mozzer (2011) categorized the teacher's statements into five groups of actions. These actions were seen as supporting students'

(1) participation in the discussion, and supporting their expression and discussion of (2) their previous ideas, (3) their codes of representation, (4) empirical evidence, and (5) their current ideas and models. We see connections between the teacher strategies provided as examples in the five categories and the OGEM strategies we identified at the cognitive macro level in our study and, moving forward, it will be interesting to explore these connections.

Simon, Erduran, and Osborne (2006) and Louca, Zacharia, and Tzialli (2012) describe a number of strategies that teachers use to support argumentation, a different process than model construction, but one that may have some overlaps with it. In particular, they identified moves teachers made to support argument evaluation, such as encouraging the evaluation of an argument using evidence, overlapping with our strategy of model evaluation via experimental evidence. However, they looked at student evaluation of *arguments*, not necessarily *models*, and presumably because of the nature of their different focus on argumentation, such studies tend not to include strategies for model generation or modification.

Specific to investigating the role of classroom discussion in the development of students' explanatory models for scientific concepts, studies by our group, Rea-Ramirez (1998), Clement (2008b), Nunez-Oviedo & Clement (2008), Khan (2003), Price (2007), and Williams & Clement (2008), have explored cognitive teaching strategies at the macro or GEM level for topics in life science and chemistry classrooms. Using physics as the subject area, this study has contributed a fourth macro strategy (Observation), added a layer of 15 micro teaching strategies, and distinguished these from dialogical strategies.

In addition, diagrams were developed to track the complex interchange and possible connections between the contributions students make in discussions and the strategic statements and questions that the teacher generates 'on the fly'. Instead of simply reporting a single list of strategies observed, these diagrams embody hypotheses about the sub-goal structure of the relationship of cognitive micro-level strategies to cognitive macro-level strategies, as well as the parallel operation of dialogical strategies in a way that, to our knowledge, has not been previously described in science education.

Clement (2008b) asked the question, 'How do we describe the various strategies and skills used in "scaffolding"? Everyone recommends scaffolding but few say how to do it.' An attempt has been made here to develop a framework for describing scaffolding in model-based teaching that is organized as a structured set of strategies. A long-term goal here is to contribute to a growing model of how teachers can support students' conceptual learning processes through a process of scaffolding whole-class discussions.

Conclusion

Focusing on two high school physics teachers with the highest student pre-/post-test gains in a group of model-based educators, intensive case studies of these teachers were conducted in an effort to identify, describe, and categorize the discussion-based teaching strategies they utilized. We found evidence that in addition to previously documented *dialogical* strategies that the teachers utilized to engage students in communicating their scientific ideas, there were also *cognitive model construction* strategies aimed at fostering students' particular learning processes.

Within the *cognitive model construction* category, we identified 15 cognitive micro strategies, each of which contributes to one of 4 cognitive macro strategies (OGEM). We also developed a whole-class discussion diagramming system that portrays the connections between these cognitive micro and macro strategies, and shows dialogical strategies being used in parallel with the cognitive strategies. The theoretical idea that cognitive macro strategies may occur at a longer time scale duration than micro strategies was introduced along with the idea that micro strategies can serve as sub-processes for macro strategies (see also Clement, 2008e; Schoenfeld, 1998). The diagrams portray the teachers scaffolding student learning in a process of teacher–student co-construction.

Study Limitations and Suggestions for Future Research

The primary purpose of the preliminary quantitative study was not to generalize from the sample to a population, but to identify teachers worthy of further study because of the learning gains in their classes. This study was limited to investigations of the teaching strategies of two veteran educators who have honed their skills over several years of experience. This gave us the most fertile possible ground for more in-depth work on identifying and articulating teaching strategies. In the interest of determining learning progressions for the expert teaching strategies identified, it will be important to expand future studies to include teachers who are in earlier stages of their careers (Windschitl et al., 2008).

The factors that determine whether students gain conceptual understanding from a discussion are certainly more varied than those discussed in this article and include social dynamics, group purposes and motivation, and metacognitive factors. Here, we have focused on the teacher's cognitive strategies as an inadequately understood process, and distinguished these from dialogical strategies, and we hope this will complement research on other factors.

We suspect that the present hierarchical description of cognitive strategies at two levels may be a little too 'clean' since one can imagine possible exceptions, for example, instances of proposing an analogy that occurs not just within a model Generation phase but alternatively within a model Modification phase. However, there is merit in starting from a scheme that is simpler to understand and remember and the present scheme is consistent with the data analyzed in this study.

With a fairly large number of model construction supporting teaching strategies like those identified in this study, in preparing a manageable 'toolkit' of strategies for educators learning to use them, it will be important to continue working on distilling or chunking these into fewer categories for simplification of memory and application. The OGEM macro strategies give us one approach, since if teachers can learn to think about those, they may be able to 'chunk' a number of the second level of more specific micro strategies within them.

Here, we have focused in depth on the *identification* of cognitive strategies. Designing a future experimental study of the *effects* of such strategies would be desirable but difficult, since they should be used within a model-based curriculum. As reported, we and others found significant gain differences in exploratory studies of CASTLE model-based groups and control groups, but with sampling via volunteers and no means to separate effects of the curriculum and effects of the strategies. Now that an arguably coherent set of cognitive strategies have been identified, looking at student performance and teaching strategy behavior using a model-based curriculum like CASTLE before and after training on the strategies might accomplish this. And video tutoring studies where the tutor can elicit more substantial amounts of evidence on the effects of individual strategies could also contribute important information (Clement, 2002).

The teacher-guided discussion in Figure 3(a) represents an intermediate position on a spectrum of open to strongly guided inquiry approaches. The teacher maintains focus on the topic but he is rather open to any ideas within that as he draws students out at the beginning of the discussion. Then toward the end of the segment the strategies illustrated in Figure 3(b) represent specific ways in which the teacher begins to guide the discussion to encourage content learning. We only had room to present a short segment here, but such guided discussions can be longer and involve many more of the strategies shown in Table 2. Also, the teacher both elicits ideas from students and injects some language and ideas into the discussion, meaning that the discussion is at an intermediate position on a spectrum of student-generated ideas to teacher-generated ideas. We are not advocating this segment as an example of the only way to teach, but find it interesting to use the diagram as a way to raise these questions about various dimensions of guided inquiry as possible topics for future research (Lehesvuori, Viiri, Rasku-Puttonen, Moate, and Helaakoski, 2013; Louca et al., 2012).

Implications

Although the work at this stage is intended for researchers, we would like to eventually share results with pre-service and practicing science educators. We will need to do this in simplified form, by dividing the extremely complex act of science teaching into several basic sets of skills so that the sets can be learned and practiced one or two at a time. Recently, Windschitl (no date) has assembled a set of dialogical strategies and a few general cognitive strategies into a useful paper for pre-service teachers that can introduce them to discussion of leading tactics. The fuller set of two levels of cognitive strategies identified in this study may complement that collection. In addition, it is possible that greatly simplified versions of diagrams such as Figures 2 and 3 may be useful as a graphical representation of several important concepts, including model evolution, co-construction, and scaffolding (Clement, 2008d) as we work toward the goal of educators gaining a clearer understanding of how their discussion-leading strategies can foster the development of conceptual understanding.

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References

Campbell, N. (1920). *Physics: The elements*. Cambridge: Cambridge University Press. Republished in 1957 as The foundations of science. New York: Dover.

Chin, C. (2007). Teacher questioning in science classrooms: Approaches that stimulate productive thinking. *Journal of Research in Science Teaching*, *44*(6), 815–843.

Clement, J. (1989). Learning via model construction and criticism. In G. Glover, R. Ronning & C. Reynolds (Eds.), *Handbook of creativity: Assessment, theory and research* (pp. 341–381). New York, NY: Plenum.

Clement, J. (2000a). Analysis of clinical interviews: Foundations and model viability. In A. E. Kelly & R. A. Lesh (Eds.), *Handbook of research design in mathematics and science education* (pp. 547–589). Mahwah, NJ: Lawrence Erlbaum Associates.

Clement, J. (2000b). Model based learning as a key research area for science education. *International Journal of Science Education*, *22*(9), 1041–1053.

Clement, J. (2002). Protocol evidence on thought experiments used by experts. In W. Gray & C. Schunn (Eds.), *Proceedings of the twenty-fourth annual conference of the cognitive science society.* Mahwah, NJ: Erlbaum.

Clement, J. (2008a). *Creative model construction in scientists and students: The role of imagery, analogy, and mental simulation*. Dordrecht: Springer. 630 p.

Clement, J. (2008b). The role of explanatory models in teaching for conceptual change. In S. Vosniadou (Ed.), *International handbook of research on conceptual change*. Amsterdam: Routledge.

Clement, J. (2008c). Six levels of organization for curriculum design and teaching. In J. Clement & M. A. Rea-Ramirez (Eds.), *Model based learning and instruction in science* (pp. 255–272). Dordrecht: Springer.

Clement, J. (2008d). Student/teacher co-construction of visualizable models in large group discussion. In J. Clement & M. A. Rea-Ramirez (Eds.), *Model based learning and instruction in science* (pp. 11–22). Dordrecht: Springer.

Clement, J. (2008e). *Six strategy levels for model based teaching*. Proceedings of the 2008 Annual Meeting of the National Association for Research in Science Teaching, Baltimore, MD.

Clement, J. (2009). The role of imagistic simulation in scientific thought experiments. *Topics in Cognitive Science*, *1*(4), 686–710.

Collins, A., & Gentner, D. (1987). How people construct mental models. In D. Holland & N. Quinn (Eds.), *Cultural models in thought and language* (pp. 243–265). Cambridge: Cambridge University Press.

Duit, R., & Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning. *International Journal of Science Education*, *25*(6), 671–688.

Gilbert, J., & Boulter, C. (1998). Learning science through models and modeling. In B. J. Fraser & K. G. Tobin (Eds.), *International handbook of science education* (pp. 53–66). Dordrecht: Kluwer Academic Publishers.

Gilbert, S. W. (2011). *Models based science teaching: Understanding and using mental models*. Arlington, VA: NSTA Press.

Gobert, J., & Buckley, B. (2000). Introduction to model-based teaching and learning in science education. *International Journal of Science Education*, *22*(9), 891–894.

Hafner, R., & Stewart, J. (1995). Revising explanatory models to accommodate anomalous genetic phenomena: Problem solving in the 'context of discovery'. *Science Education*, *79*(2), 111–146.

Hammer, D. (1995). Student inquiry in a physics class discussion. *Cognition and Instruction*, *13*(3), 401–430.

Harre, R. (1961). *Theories and things*. London: Newman History and Philosophy of Science Series.

Hogan, K., Nastasi, B. K., & Pressley, M. (2000). Discourse patterns and collaborative scientific reasoning in peer and teacher-guided discussions. *Cognition and Instruction*, *17*(4), 379–432.

Hogan, K., & Pressley, M. (1997). Scaffolding scientific competencies within classroom communities of inquiry. In K. Hogan & M. Pressley (Eds.), *Scaffolding student learning: instructional approaches and issues* (pp. 74–107). Cambridge, MA: Brookline Books.

Ingham, A. M., & Gilbert, J. K. (1991). The use of analogue models by students of chemistry at higher education level. *International Journal of Science Education*, *13*, 193–202.

Johnson-Laird, P. N. (1983). *Mental models*. Cambridge, MA: Harvard University Press.

Justi, R., Paganini Costa, P., & Braga Mozzer, N. (2011). Key teacher's roles in supporting the co-construction of students' knowledge in modeling-based teaching contexts. In C. Bruguière, A. Tiberghien & P. Clément (Eds.), *ESERA 2011 Conference Proceedings: Nature of science, History, Philosophy, Sociology of Science* (pp. 57–63). Part [strand 5]. Lyon, France: ESERA.

Khan, S. (2003). *Model construction processes in a chemistry class*. Paper presented at the National Association of Research in Science Teaching Conference, Philadelphia, PA, March 23–26, 2003.

Khan, S. (2011). What's missing in model-based teaching. *Journal of Science Teacher Education*, *22*, 535–560.

Lehesvuori, S., Viiri, J., Rasku-Puttonen, H., Moate, J., & Helaakoski, J. (2013). Visualizing communication structures in science classrooms: Tracing cumulativity in teacher-led whole class discussions. *Journal of Research in Science Teaching*, *50*(8), 912–939.

Louca, L. T., Zacharia, Z. C., & Tzialli, D. (2012). Identification, interpretation—evaluation, response: An alternative framework for analyzing teacher discourse in science. *International Journal of Science Education*, *34*(12), 1823–1856.

McNeill, K. L., & Krajcik, J. (2008). Scientific explanations: Characterizing and evaluating the effects of teachers' instructional practices on student learning. *Journal of Research in Science Teaching*, *45*(1), 53–78.

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook*. 2nd ed., Newbury Park, CA: Sage.

Nersessian, N. (2008). *Creating scientific concepts*. Cambridge, MA: Massachusetts Institute of Technology Press.

Nunez-Oviedo, M. C., & Clement, J. (2008). A competition strategy and other discussion modes for developing mental models in large group discussion. In J. Clement & M. A. Rea-Ramirez (Eds.), *Model based learning and instruction in science* (pp. 117–138). Dordrecht: Springer.

Price, N. (2007). *Self-study of the evolution of a "deferred judgment questioning" discussion mode (sounding) in a middle school science teacher*. Paper presented at the 2007 Annual Meeting of the National Association for Research in Science Teaching, New Orleans, LA.

Rea-Ramirez, M. A. (1998). *Model of conceptual understanding in human respiration and strategies for instruction* (Unpublished doctoral dissertation). University of Massachusetts, Amherst.

Roth, W. M. (1996). Teacher questioning in an open-inquiry learning environment: Interactions of context, content, and student responses. *Journal of Research in Science Teaching*, *33*(7), 709–736.

Schoenfeld, A. H. (1998). Toward a theory of teaching-in-context. *Issues in Education*, *4*(1), 1–94.

Schwartz, D. L., & Black, J. B. (1996). Analog imagery in mental model reasoning: Depictive models. *Cognitive Psychology*, *30*, 154–219.

Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Acher, A., Fortus, D., ... Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching*, *46*(6), 632–654.

Simon, S., Erduran, S., & Osborne, J. (2006). Learning to teach argumentation: Research and development in the science classroom. *International Journal of Science Education*, *28*(2–3), 235–260.

Steinberg, M. S., Bryant, D. N., Cronin, S. M., Cunha, M. L., Drenchko, J., Ewald, G. L., . . . Wainwright, C. L. (2004). *Electricity visualized: The CASTLE project*. Roseville, CA: PASCO Scientific. 600pp.

Steinberg, M. (2008). Applying modeling theory to curriculum development: From electric circuits to electromagnetic fields. In J. Clement & M. A. Rea-Ramirez (Eds.), *Model based learning and instruction in science* (pp. 151–172). Dordrecht: Springer.

Vosniadou, S. (2002). Mental models in conceptual development. In L. Magnani & N. Nersessian (Eds.), *Model-based reasoning: Science, technology, values* (pp. 353–368). New York, NY: Kluwer/Plenum.

Williams, E. G. (2011). *Fostering high school physics students' construction of explanatory mental models for electricity: identifying and describing whole-class discussion-based teaching strategies* (Unpublished doctoral dissertation). University of Massachusetts, Amherst.

Williams, E. G. & Clement, J. (2008). *Co-constructing explanatory mental models in high school physics: Comparing ratios of teacher/student participation*. Proceedings of the NARST Annual Conference, Baltimore, MD.

Windschitl, M. (no date). *A primer on productive classroom conversations*. Retrieved from http://tools4teachingscience.org/

Windschitl, M., Thompson, J., & Braaten, M. (2008). How novice science teachers appropriate epistemic discourses around model-based inquiry for use in classrooms. *Cognition and Instruction*, *26*(3), 310–378.

van Zee, E., & Minstrell, J. (1997). Reflective discourse: Developing shared understandings in a physics classroom. *International Journal of Science Education*, *19*, 209–228.