CHAPTER 4

CO-CONSTRUCTING MODELS THROUGH WHOLE CLASS DISCUSSIONS IN HIGH SCHOOL PHYSICS

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We identified modeling practices during whole class discussions of electricity concepts in the classes of two exemplary high school teachers. Four major model construction practices were shared between the teacher and the students referring to observations (O), and generating (G), evaluating (E), and modifying (M) explanatory models. Both groups achieved similarly impressive gain differences over a control group, and high rates of student contributions to modeling, indicating it is possible to achieve the latter. The teachers exhibited substantially different frequencies of scaffolding the practices. We conclude teachers may vary in their level of scaffolding but still experience equally strong student participation in modeling and gains in conceptual understanding. Importantly though, both teachers were focused on fostering the four modeling practices. We provide micro-analyses of classroom transcripts and representative diagrams to illustrate their process of teacher-student co-construction.

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Keywords: model-based teaching, co-construction, classroom discussion, scientific practices, scaffolding strategies, physics learning

The paradigm of physics teachers as disseminators of abstract conceptual content unlocking the mysteries of the universe by passing on their knowledge through lectures and notes is being challenged by current physics education research. In this study, we analyzed the contributions of both teachers and students during the construction of explanatory models for concepts in circuit electricity in the classes of two exemplary high school physics educators. This analysis attempts to document whether students can contribute significantly to such discussions with model construction practices. We also compare two exemplary teachers on the different degrees of scaffolding they employed for these practices and their corresponding levels of student participation and learning gains. We are interested in this type of student-centered, constructivist physics teaching because it challenges the paradigm of traditional didactic, lecture-based knowledge dissemination often associated with physics teaching and learning.

THEORETICAL FRAMEWORK

One of the core scientific and engineering practices identified by the Next Generation Science Standards (NGSS) (NGSS Lead States, 2013) to help learners construct understandings of difficult concepts is the development and use of models. More detail, however, is needed on the nature of modeling practices. The focus of this study is on student modeling practices visible in whole class discussions and the teacher scaffolding strategies supporting them. (Because the modeling practices we are looking at here are all mental processes, we will use the terms modeling practice and modeling process interchangeably.) A number of researchers have advocated whole class discussions as an effective means for facilitating the construction of scientific knowledge and teaching with a focus on discussion can improve students' scientific reasoning ability and foster conceptual change processes (Hogan, Nastasi, & Pressley, 2000; Lehesvuori, Viiri, Rasku-Puttonen, Moate, & Helaakoski, 2013; Windschitl, Thompson, & Braaten, 2008). Such conversational interaction among teachers and students is thought to provide a means for students to collaboratively construct increasingly sophisticated scientific models through cycles of developing, communicating, evaluating and revising them (Schwarz, Reiser, Davis, Kenyon, Achér, & Fortus, 2009).

In the context of this study, a model is considered to be a simplified representation of a system, which concentrates attention on specific aspects of the system (Ingham & Gilbert, 1991). Models are central to an understanding of underlying mechanisms in science. In the study of physics, in particular, models of various types (physical models, diagrams, equations, graphs, simulations, etc.) can be helpful for supporting students' understanding of abstract concepts (Brewe, 2008; Hestenes, 1987; Wells, Hestenes, & Swackhammer, 1995). These include concepts such as planetary motion, magnetic fields, and electric circuits. We focus on explanatory models, which can be described as mental representations of often hidden causal or functional mechanisms that can explain why phenomena in a system occur (Clement, 1989; Williams & Clement, 2015).

Most traditional electric circuit instruction emphasizes the application of the Ohm's Law equation I=V/R for the quantitative solution of circuit problems. By contrast, model-based learning approaches can be useful for fostering students' development of deeper conceptual understandings of the relationships between current, voltage and resistance within circuits (Borges & Gilbert, 1999; Dupin & Joshua, 1989; Steinberg & Wainwright, 1993). A modeling approach is used in Steinberg et al.'s (2004) Capacitor Aided System for Teaching and Learning Electricity (CASTLE) curriculum employed by the model-based teachers in this study. The CASTLE curriculum utilizes the introduction of large non-polar capacitors into basic electric circuits as a means for focusing students' attention on the transient states of potential differences existing throughout the circuit. By using the analogy of voltage as a type of pressure existing in the compressible electric fluid of a circuit, students are encouraged to generate explanatory models of dynamic pressure changes occurring throughout the circuit as these capacitors go through their charging and discharging cycles. It is thought this emphasis on the conceptual nature of circuit behavior can be beneficial in addressing the many well-documented misconceptions students bring to the study of circuits (Çepni & Keles, 2006; Korganci, Miron, Dafinei, & Antohe, 2015). The CASTLE curriculum employs the extensive use of other analogies, diagrams and discrepant events to engage students and their teachers in the incremental construction of explanatory mental models for circuit electricity. It is this intended conversational classroom process, the different cognitive levels at which teacher contributions are made, and the actual degrees of contributions made to it by teachers and students in these model-based learning situations that comprise the focus of this study.

STUDY BACKGROUND AND RATIONALE

In an earlier phase of our research (Williams, 2011), we examined an experimental group of approximately 270 high school physics students who were learning about electric circuits through the model-based CASTLE curriculum. They, along with an equally sized control group who learned through traditional instructional methods, completed a 20 question, conceptual, non-quantitative pre-test to gauge their understanding of and reasoning about electric circuits. An identical post-test was administered after the period of instruction, which lasted from 6–8 weeks. Both groups had approximately equal distributions of male and female students. A sample question from the test is included in the Appendix section of the chapter.

The purpose of this paper is not to evaluate the curriculum (see Steinberg, 2008). Nevertheless, we need to briefly present results from this testing in order to describe our reasons for choosing two exemplary teachers for an in depth study of their methods. Understanding more about their scaffolding and discussion leading strategies, and the nature of the student-teacher co-construction process in

TABLE 4.1. Pre and Post Test Conceptual Understanding Scores by Treatment Group

	Control Group n = 262		Experimental Group n = 282	
	Raw Score	**Percentage**	**Raw Score**	**Percentage**
Mean Pre Test Problem Solving Scores	6.59 / 20	32.9%	6.70 / 20	33.5%
Mean Post Test Problem Solving Scores	7.75 / 20	38.8%	11.61 / 20	58.1%
Mean Normalized Problem Solving Score Gains	1.17 / 13.41	8.8%	4.91 / 13.30	36.9%

their classrooms, is the main purpose of the present study. A repeated measures analysis of variance (ANOVA) with an alpha value of 0.05 determined that the students in the model-based learning group experienced significantly greater normalized gains (36.9%) in their levels of conceptual understanding over the course of instruction than their traditionally instructed counterparts (8.8%) as displayed in Table1. Calculations of Cohen's (1992) ***d*** indicate the effect size of the experimental treatment (model-based instruction of electricity concepts) on students' circuit problem solving outcomes is 1.293; a relatively large effect based on Cohen's scale.

Traditional approaches expect students to learn by listening and absorbing content. The CASTLE curriculum intends for teachers to hold discussions where students can engage in scientific learning processes (practices) involved in constructing models. We selected the two experimental teachers with the largest normalized gains (as shown in Table 4.2) for deeper case study analysis in order to study their scaffolding methods. In this sense we refer to them as exemplary. Their gains were notably higher, but not significantly higher at the p=.05 level, than the rest of the experimental group's gains. Additional prior research is best described in the context of our data analysis section below. Some research has identified the need for teachers to use cognitive discussion leading strategies and questioning strategies, but there has been insufficient research done on what those strategies are, and whether they can elicit student model construction processes.

TABLE 4.2. Pre and Post Test Conceptual Understanding Scores by Case Study Teachers

	Teacher A		Teacher B	
Mean Pre Test Scores	6.45/20	32.3%	6.73/20	33.7%
Mean Post Test Scores	11.80/20	59.0%	12.13/20	60.7%
Mean Normalized Test Score Gains	5.35/13.55	39.5%	5.40/13.27	40.7%

Our research questions were:

1. Can we document whole class discussions in which high school physics students contribute significantly with model construction practices, in addition to the teacher's contributions?
2. Can teachers in model-based physics classes participate in whole-class discussions by using a larger or smaller number of scaffolding moves and still foster high levels of student participation and understanding?
3. Can we describe qualitative differences and similarities in the discussion-based strategies used by the two teachers? Can they both be considered types of co-construction?

STUDY CONTEXT AND SETTING

The study was conducted over a two-year period during which the two selected teachers taught the model based electricity unit three separate times with different groups of students, each time spending approximately seven weeks. Both teachers utilized the same model based curriculum, basic constructivist teaching philosophy, and general classroom structure. Group A consisted of a teacher and his students at a small private suburban high school in New England. Of the 39 students, 28 were enrolled in one of two ninth grade general science classes and 11 were students in an eleventh grade physics class. Of the predominantly Caucasian students, 19 were male and 20 were female. Group B consisted of a teacher and his 69 students at a large public suburban high school in the Midwest. Each of the 69 students, of which 35 were male and 34 were female, was enrolled in one of three ninth grade physics classes. The group was a mix of Caucasian, Asian, Hispanic, and African American students. As shown in Table 4.2, the pretest scores indicated the two groups were closely matched on their average level of prior conceptual knowledge of basic electric circuits.

Both teachers utilized class formats in which students alternated between working in pairs on assembling and testing circuit experiments, completing readings and responses in their student workbooks, drawing color-coded analogical pressure-based diagrams of the circuits and their functions, and participating in whole-class discussions moderated by the teacher. In this study, we focus on the whole-class discussions.

DATA COLLECTION AND ANALYSIS

We first conducted microanalyses of discussions from each teacher to identify the major scaffolding strategies used by the teachers and the major model construction processes used by the students. This analysis was a challenging and lengthy qualitative research task. First, passages of whole-class conversations during which the teachers and their students appeared to be engaged in the construction of explanatory models of electricity were video recorded and later transcribed. In total, approximately 5.5 hours of whole-class discussion for each teacher were analyzed from three different classes in an attempt to reduce the effects any one group of students might have on the results. Passages were chosen from each group that featured whole-class discussions during which students were forming explanatory models for observations made in immediately preceding circuit experiments.

In an effort to develop viable descriptions of the strategies and processes used, we employed a construct development cycle (Miles & Huberman, 1994) leading to the progressive refinement of hypotheses about individual teaching strategies and modeling processes (Engle, Conant, & Greeno, 2007). This consisted of: a) segmenting the transcript into meaningful teacher and student statements as the primary units of analysis, b) making observations from each segment, c) formulating a hypothesized construct for or classification of the strategy behind the statement, d) returning to the data to look for more confirming or disconfirming observations, e) comparing the classification of the statement to other instances, f) criticizing and modifying or extending the hypothesized category to be consistent with, or differentiated from, other instances, and g) returning to the data again, and so on. Triangulation from multiple indicators in transcripts and from checks on the ability to use the same constructs across problems and subjects were used to improve and support validity.

Initially, this process allowed us to identify a fundamental similarity existing between the instructional methodologies of the two educators. Each teacher appeared to employ strategies of two distinct types; a *Dialogical* type in which strategies are intended to support students' general engagement in scientific conversation, and a *Cognitive Model-Construction* type with strategies intended to foster students' construction of explanatory mental models. Research by van Zee and Minstrell (1997), Hogan and Pressley (1997), and Chin (2007) has primarily identified what we refer to as dialogical 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.

We describe such dialogical strategies as not aimed at specific processes of conceptual learning, but rather as intended to support conversational interaction in general, encourage increased student participation in the discussion, and foster a classroom culture promoting and encouraging student input. While these dialogical strategies certainly help to develop necessary foundations for effective whole-class discussions, we will not discuss them further in this paper since our interest in this study is to explore the Cognitive Model Construction level where we attempted to identify a collection of specific cognitively-focused teaching strategies, not just for promoting participation, but for promoting reasoning and conceptual understanding through model construction.

The three researchers cited just above as well as Minstrell and Stimpson (1996) and Hammer (1995), also identified a few cognitive strategies such as the use of analogies, inductions, and discrepant questions. Meanwhile, researchers within our own group (Clement & Rea-Ramirez, 2008; Clement & Steinberg, 2002; Khan, 2003; Williams, 2011) began to focus on teacher and student model co-construction in a variety of science learning environments; describing teacher and student statements as contributing to the construction of model elements through a variety of cognitive processes. We have described these processes as being centered on the fundamental modeling practices of experimental observation (O), model generation (G), model evaluation (E), and model modification (M) (Williams & Clement, 2015). Three of these categories (G, E, M) originally grew out of observations of scientifically trained experts thinking aloud about explanation problems (Clement, 1989, 2008). Using this OGEM process framework, we engaged in the construct development cycle described above to develop the following criteria to code both student and teacher statements during whole-class modeling discussions into four categories.

1. 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 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, or it may be a request or suggestion for designing or doing a future observation(s). Examples of key phrases that help identify observation strategies: "did you see . . . ," "what did you notice…," "tell us about your observations . . .," "what was detected . . .," "what would we see if. . ."etc.
2. Generation (G): The statement either asks for, or provides, a theory, explanatory model or model element, conception, or model based 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: "why do you think that happened. . .," "what do you think is happening . . .", "what explanation can you think of for . . .", "I think that maybe what's going on is . . . ," "I think it does that because. ."etc.
3. Evaluation (E): The statement refers to a theory, explanatory model, conception, or model-based 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 . . . ," "what do you think

of that explanation….,” “that makes sense . . .,” “I also believe it could be. . .,” “but that doesn’t explain why . . .,” “do you think that is the way it works. . . ,” etc.

4. Modification (M): The statement either asks for, or provides a suggested change, revision, adjustment, or modification to a theory, explanation, or explanatory model under evaluation. This may involve only a minor alteration, variation, or addition or could introduce a substantially 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 referring to an explanatory model 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 . . .”, “how could we fix the model so that it considers …”, etc.

In the present study, statements made by the teachers and students during whole class discussions were first examined to see if they fit into the OGEM process pattern, at a macro level we call model construction strategies. Criteria for those strategies were developed and refined. Then, a larger number of teacher micro strategies were identified at a smaller grain size, such as “Teacher provides an analogy” or “Teacher requests (generated by students) a model element.” We call these micro strategies nonformal reasoning strategies. We found that each of these micro strategies could be seen as a sub-strategy for one of the four macro OGEM strategies; for example, the above micro strategies can both be seen as ways of contributing to the macro strategy of generating a model (G). Another way to view this is the macro strategies refer to the goals or objectives of the actions taken by teachers while the micro strategies refer to the specific actions taken.

RESULTS

Diagrammatic Representations of the Modeling Discussions

In an attempt to visually portray the interplay between the micro-level strategies and macro-level OGEM processes, we developed a diagramming notation to represent the construction processes teachers and students engaged in during these classroom discussions. We constructed such diagrams for a representative subset of the discussions. In their simplest form, the diagrams are horizontal versions of the classroom transcript with student statements presented above the teacher statements, and time running from left to right. For this reason, the diagrams tend to be wide, and for presentation here, necessitated being split into two parts: a and b. The horizontal strip across the middle of the diagrams contains short written phrases which describe the 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 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.

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 model descriptions 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, p. 405) 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." This is a skill both educators in this study displayed in their teaching.

Immediately below the teacher statements is a brief description of the hypothesized teaching moves at the micro level of nonformal reasoning strategies. These include such strategies as: teacher requests observations, teacher provides a model element, teacher requests the running of a thought experiment, and teacher provides concept differentiation. Arrows to these micro level strategy descriptions point upward to illustrate their being driven by one of the four macro processes (observation, generation, evaluation, or modification). In Figure 4.1, for example, the 2nd through 6th teacher statements all serve the goal of having students generate (G) a model. One can differentiate, however, between the micro strategies of requesting initiation of model construction, requesting an analogy, and requesting elaboration of the model. These three different micro strategies appear to be contributing to the macro process of model generation (G). The macro level or model construction process layer portrays the larger time scale goals of the teacher in engaging the students in the process of generating an explanatory model. This instance of the generation (G) macro process points to different types of micro strategies portraying the relation specific micro strategies serve a smaller number of more general and longer-duration macro processes.

Above the students' statements on the diagrams, we analyzed each statement to describe their micro level processes in contributing to the model construction processes at the top. As is the case for the teacher strategies, we attempted to link (via arrows) each of these student contributions to the macro level OGEM processes of the model construction process. In what follows, we give an analysis of a discussion led by each teacher, using these model evolution diagrams.

Episode 1: Teacher A

In the experiment prior to the whole-class discussion in Episode 1, the students in Teacher A's class were using magnifying glasses to examine the filaments of two different types of miniature light bulbs they were using in the CASTLE

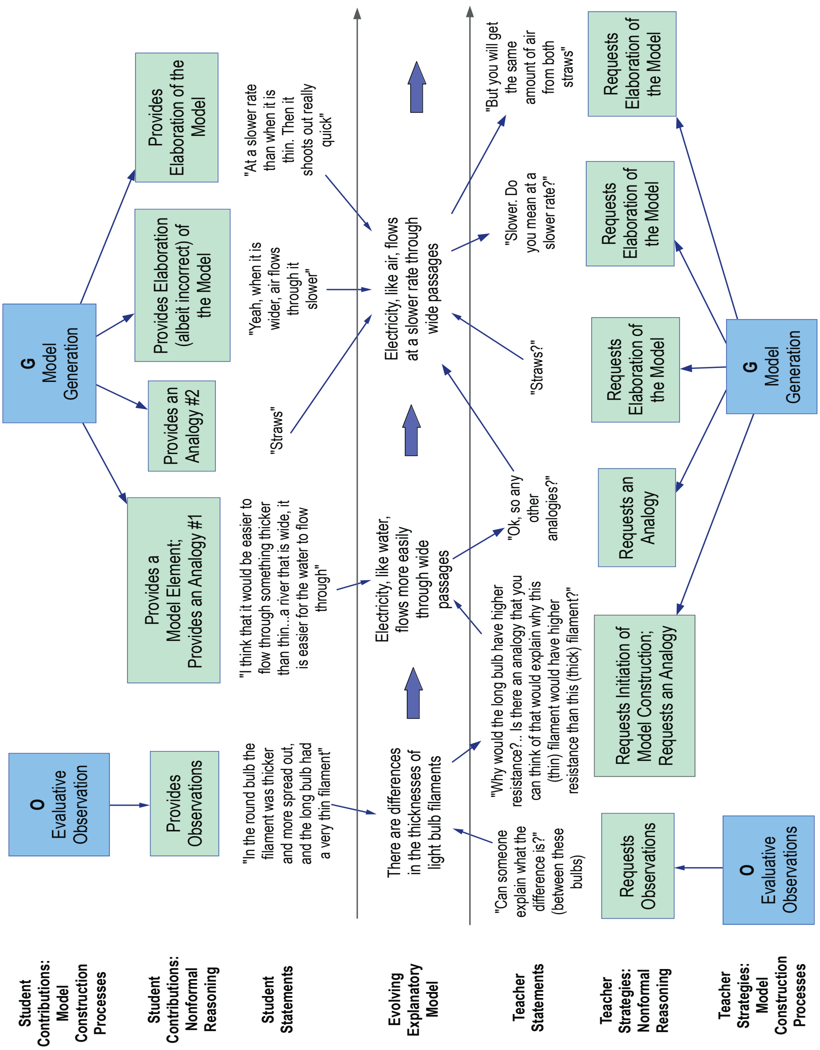

FIGURE 4.1. Whole-Class Model Construction Discussion—Episode 1—Part A

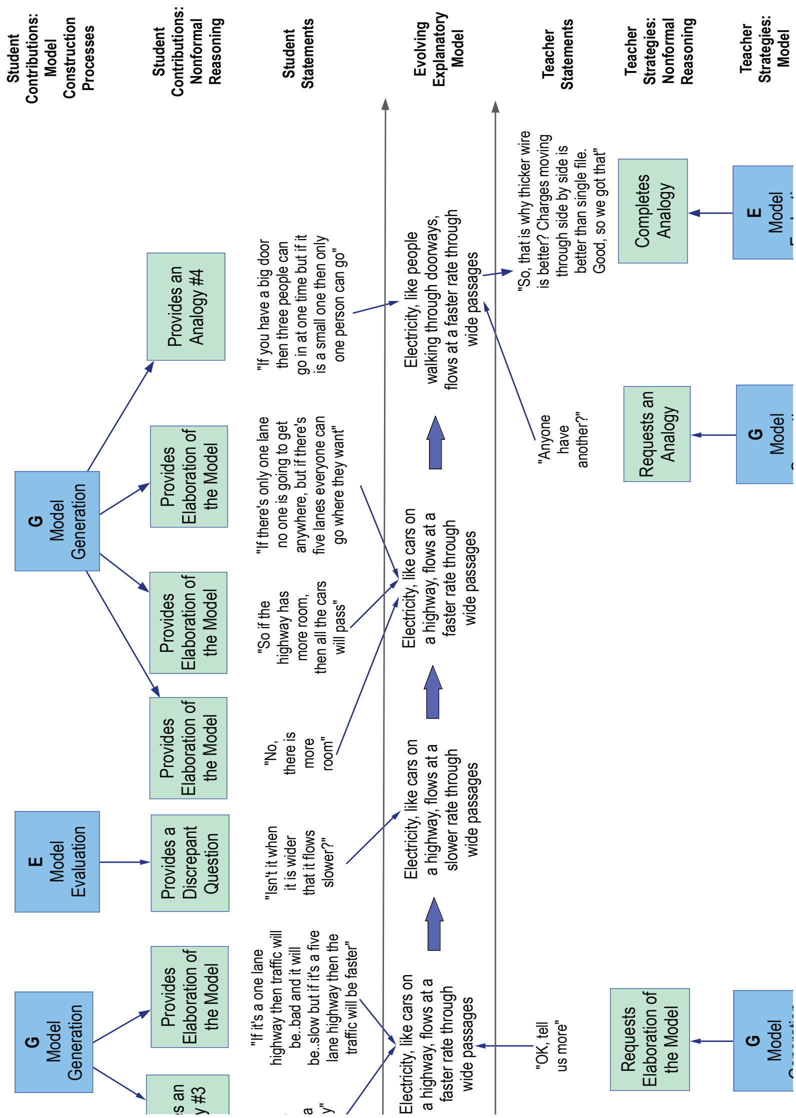

FIGURE 4.2. Whole-Class Model Construction Discussion—Episode 1—Part B

circuit building kits. By observing the physical differences in the filaments (one thick and the other thin) of these bulbs, it is intended that students will develop explanatory models to account for differences in their behavior and effects on the circuit. The curriculum draws on students' previous experiences to support the development of analogies that can aid in their understanding of charge movement in light bulb filaments.

The episode begins with Teacher A asking the students to share their observations (O) of the light bulb filaments, as shown in Figure 4.1. Once they identify the key physical differences in filament wire thickness, he asks them if they could develop an analogy to account for differences in the resistance to charge flow between the two bulb types. Therein begins the model generation (G) process. After a student responds with the first suggestion of a possible analogy, the teacher encourages additional contributions. This is likely done to further explore the notion of easier flow through wider passages, a concept often confusing the distinction between charge flow rate and charge flow speed.

This issue of flow rate vs. flow speed surfaces through another student explanation of blowing through drinking straws as a suitable bulb filament analogy. Flow rate refers to the total number of air particles (or electric charges) flowing past a certain spot in the straw (filament) in a given period of time. Flow speed refers to the velocity of any one air particle (or electric charge) as it travels through the straw (filament). This is a concept very often confused or not discriminated by students learning physics and one making the use of analogies to describe charge flow in wires challenging without proper teacher guidance. Another issue concerns the initial conditions of the thought experiment in an analogy, such as whether the speeds in different width straws are being compared with the same pressure source, or with the same flow rate source. In an attempt to clarify, Teacher A requests elaboration of the model regarding the issue of flow rate vs. flow speed and later provides a concrete clarification of the model concerning the number of particles (charges) flowing through the straws (filaments).

What results is a rich conversation between three students who dispute the accuracy of the highway analogy. Again, it appears they may be getting caught up on the distinction between flow rate (total number of cars passing by per second) versus the flow speed of each car (in, say, meters per second). The teacher neither requests nor provides any further elaboration of the model at this point. Instead, he asks if there are any other analogies. The analogies here all appear to be attempts to help generate (G) a model for the circuit. Teacher A wraps up the discussion by using the student-suggested doorway analogy to integrate the concepts of passage width and flow rate as applied to charge movement in wires.

Not all ideas put forward are correct. But, what is impressive to us in this episode is the incorporation of student ideas, and the gradual evolution of the models; with evaluations and modifications, yielding competing ideas and subtractions from the model as well as additions, as opposed to a monotonic build-up from instruction. The former process is more like real science than is the latter. While the teacher clearly facilitates this process through the strategic use of scaffolding questions, it is largely the students who are making contributions to this developing model. This is a significantly different process than the traditional teacher-centric approach of information promulgation often occurring in physics classes.

Episode 2: Teacher B

Just prior to the whole class discussion featured in Episode 2, the students in Teacher B's class conducted an investigation in which they first assembled an electric circuit (referred to in the transcript as Circuit A) containing two light bulbs connected in series with a previously discharged 1 Farad non-polar capacitor as shown in Figure 4.3. The purpose of this investigation was for the students to establish that a neutralized or discharged capacitor placed in a circuit without a battery would not result in the lighting of the bulbs. The second part of the investigation involved the insertion of a battery pack into the circuit as shown in Figure 4.4 (Circuit B).

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

After students have investigated both circuits A and B, Teacher B begins the post exploration discussion by having the students reflect on their observations (O) of the circuit building activity. First, he provides an observation by reminding them the light bulbs did come on but, then he quickly turns the discussion over to the students by requesting they provide their own observations, specifically of the duration and brightness of the bulb lighting. When one student reports that the bulb brightness was not constant, Teacher B supports the class's engagement in the model generation (G) process by requesting they provide a model element to explain the behavior of the electric charges in the circuit. After encouraging the

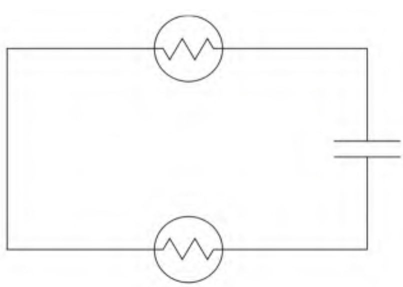

FIGURE 4.3. Circuit A

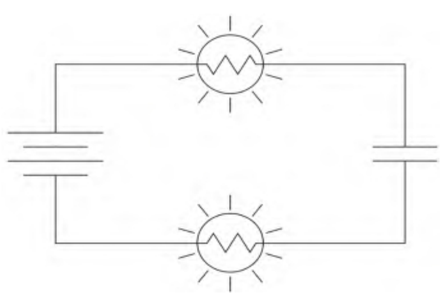

FIGURE 4.4. Circuit B

students to further describe their explanatory models of charge movement, the teacher requests additional observations (O), this time from an earlier exploration. This is likely done for the purpose of making a connection between bulb lighting and compass needle deflection as two types of evidence for charge movement in circuits.

Once the students report their earlier memories of the compass needle deflection, Teacher B refocuses on model generation (G) activity by again requesting the students suggest explanatory models based on their observations. Since the first student response is not as developed as is required, the teacher requests the students evaluate (E) and modify (M) the model under discussion and ultimately add to and improve it, bringing it more in line with the scientifically accepted target model.

At this point in the discussion, Teacher B again focuses his students on the act of model generation (G) by requesting they propose explanatory models based on their observations of Circuit B. Specifically, he guides the students through the logic chain that if a) compass needle deflection occurs when charge is flowing in wires, and that if b) bulb lighting occurs simultaneously with compass needle deflection, then c) when bulbs light, charge must be flowing. Teacher B then supports the students' evaluation (E) of their model by requesting they run a thought experiment predicting what would occur if compasses were used to evaluate the movement of charges in Circuit B where a battery back joined the two light bulbs and capacitor already present. The episode concludes with the generation (G) of a model in which capacitors, in conjunction with a battery, can affect the rate of charge flow in electric circuits. This is an important step toward developing a more generalized explanatory model of differing regions of charge density or electric pressure as causing the movement of charge.

What is most salient about Episode 2 is Teacher B's ability to guide his students in generating explanatory models by developing inferences from their own experimental observations. This activity represents a constructivist approach to learning about charge flow in electric circuits as compared to a more traditional one in which students are first taught the theory then conduct experiments to confirm it. What is also important in this episode are the scaffolding strategies Teacher B utilizes when students' attempts at constructing explanatory models are not as developed or sophisticated as are required to adequately move the process in the direction of the target model. In particular, in part B, the teacher asks the students for experimental evidence to extend the initially proposed explanatory model and secondly, requests refinement of the model by asking for a repair to the language describing the model. These are important strategies because they help the students understand any shortcomings in their own models without directly telling them that they are wrong, serving to encourage them to continue with the model construction process and to see model building is a process of continual evaluation and modification.

We developed the co-construction diagrams above to provide; 1) a visual representation of the interplay between students and teachers in co-constructing explanatory models for scientific phenomena; and 2) a means of interpreting the strategic role of the teacher in scaffolding the observation, generation, evaluation and modification processes of model construction. Vygotsky (1962) referred to the gap between the thinking students can do on their own and what they can do with support from others as the Zone of Proximal Development. Teacher supports helping to bridge this gap are often referred to as scaffolding. In particular, in this chapter, by scaffolding we mean guiding and supporting a discussion with questions, comments, and occasionally ideas contributing to student model construction. Partly because we focused on discussions rather than sections where the teacher gave a presentation, the great majority of the teacher contributions predominantly took the form of questions. The diagrams also 3) portray the relationship between the teacher strategies and student statements at the micro nonformal reasoning level and the macro OGEM model construction processes level.

Student and Teacher Model Construction Participation Ratios

During the 11 hours of whole class discussions facilitated by these two teachers, the students contributed more than 800 instances of these OGEM practices. Students in the transcripts were identified as follows: the first to speak was coded Student 1, and his or her subsequent utterances were attributed to Student 1, the second to speak was coded Student 2, etc. On average, 74% of the students in Teacher A's classes and 66% of the students in Teacher B's classes participated in any one discussion. These values were determined by noting the percentage of students contributing during each discussion session for Teacher A (e.g. 17 out of 24 students present or 70.8%), adding the percentages together, and dividing by the total number of sessions for that Teacher; and similarly for Teacher B.

Students contributed to each of the observation, generation, evaluation, and modification categories. Considerable differences existed between teachers in the raw counts of their conversational statements and in the ratios of the student to teacher contributions. Results for ratios of student and teacher contributions are shown in Tables 4.3 and 4.4. While multiple student or teacher statements at the micro level may contribute to a single OGEM process at the macro level, each of the individual micro-level contributions was counted separately as either an O, G, E or M in the data collection process.

While the rate of student verbalization was only slightly higher in Teacher B's classes than in Teacher A's classes (434 turns compared to 411 turns in the same approximate time), the considerably higher rate of teacher contributions in Group B caused the comparative ratios of student to teacher contributions to be quite different. For example, as shown in Tables 4.5 and 4.6, for teacher A, students contributed 2.6 times as much to model development in the overall aspects of the OGEM processes as the teacher did whereas for Teacher B, students contributed only 1.2 times as much as their teacher did.

It is particularly interesting to compare the sub-category totals to see that, for generating models, students in Teacher B's classes provided roughly twice the

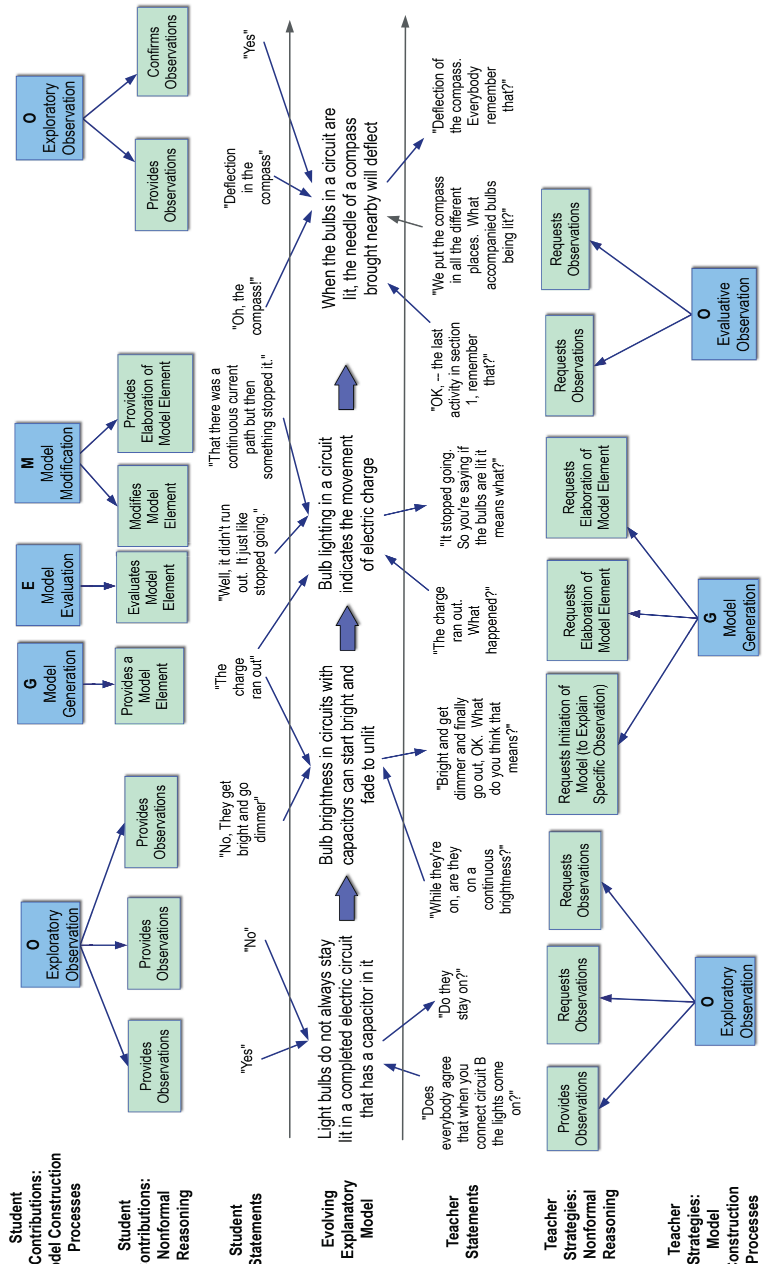

FIGURE 4.5. Whole-Class Model Construction Discussion—Episode 2—Part A

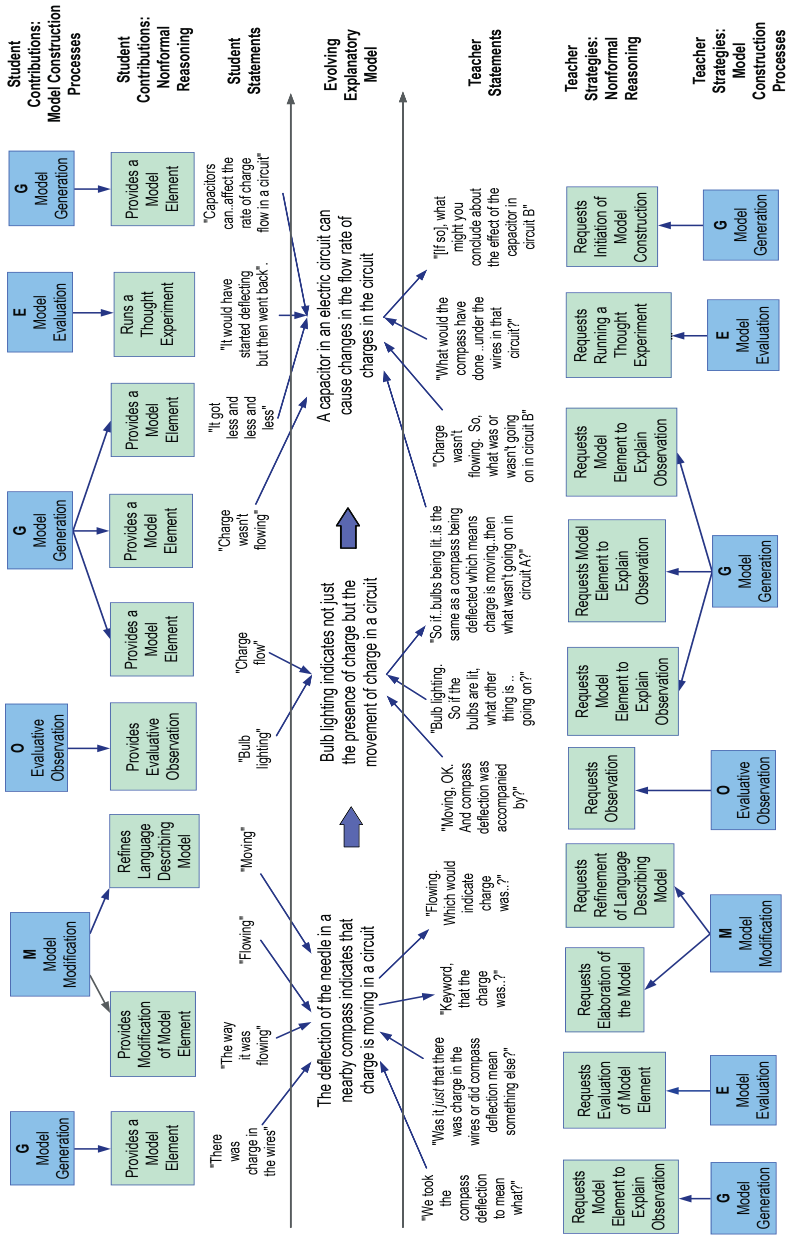

FIGURE 4.6. Whole-Class Model Construction Discussion—Episode 2—Part B

TABLE 4.3. Student and Teacher Contributions to OGEM Processes—Group A

Group A

	Students				Teacher			
Discussion #	**O**	**G**	**E**	**M**	**O**	**G**	**E**	**M**
1	21	69	17	4	5	10	16	2
2	24	18	8	4	2	8	10	1
3	11	21	6	2	4	7	6	0
4	17	27	10	3	6	9	8	2
5	22	38	14	6	7	13	15	3
6	19	33	12	5	7	11	7	2
OGEM Process Totals	114	206	67	24	31	58	62	10
Grand Totals	411				161			

number of contributions as the teacher, while in Teacher A's classes student contributions were considerably higher at 3.6 times what the teacher offered. When it came to evaluating models currently under discussion, in Teacher A's classes the student to teacher participation ratio was 1:1, however, in Teacher B's class, the teacher evaluated models 3 times as frequently as students did. As well, in Teacher A's class, students contributed to model modification 2.4 times what the teacher did while in Teacher B's class that same ratio was considerably lower at 1:1. For each of the four OGEM practices, it appears Teacher B chose to play a more active and engaged role in leading the co-construction process.

TABLE 4.4. Student and Teacher Contributions to OGEM Processes—Group B

Group B

	Students				Teacher			
Discussion #	**O**	**G**	**E**	**M**	**O**	**G**	**E**	**M**
1	5	50	9	4	10	26	35	2
2	15	61	3	2	7	18	23	2
3	17	49	7	3	11	23	18	4
4	12	33	8	5	9	27	22	4
5	20	54	11	2	8	29	20	3
6	14	37	9	4	6	21	28	4
OGEM Process Totals	83	284	47	20	51	144	146	19
Grand Totals	434				360			

TABLE 4.5. Student and Teacher Model Construction Contribution Ratios—Group A

	Raw Ratio	Simple Ratio
Observation	114 : 31	3.7 : 1
Generation	206 : 58	3.6 : 1
Evaluation	25 : 26	1 : 1
Modification	24 : 10	2.4 : 1
Overall	411 : 161	2.6 : 1

TABLE 4.6. Student and Teacher Model Construction Contribution Ratios—Group B

	Raw Ratio	Simple Ratio
Observation	83 : 51	1.6 : 1
Generation	284 : 144	2 : 1
Evaluation	47 : 146	0.3 : 1
Modification	20 : 19	1 : 1
Overall	434 : 360	1.2 : 1

DISCUSSION

Discussion of research question 1: *Can we document whole class discussions in which high school physics students contribute significantly with model construction practices, in addition to the teacher's contributions?* with over 400 student contributions to model construction practices in a total of approximately 5.5 hours of recorded discussions for each teacher, it can be concluded students made a significant contribution to constructing the explanatory models for circuit electricity in these classes. While there were different degrees of scaffolding by the teachers, we are counting instances of relatively high order cognitive contributions on the part of the students, not just recitals of facts. For both teachers, the number of student contributions was greater than the number of teacher contributions. So, there is a body of evidence here that students contributed a significant number of ideas to the model construction process representing a sharp departure from the traditional paradigm of the teacher as the provider of knowledge and the student as the mere recipient. This result resonates with an early study by Hake (1998), in which he identified interactive-engagement approaches to instruction as a key feature successful innovative programs in physics instruction had in common, showing they outperformed others on standardized tests of conceptual understanding. In the present case, however, we also have evidence indicating that students were engaged in, and gaining practice in, the OGEM scientific thinking processes.

Regarding our second research question: *Can teachers in model-based physics classes participate in whole-class discussions by using a larger or smaller number of scaffolding moves and still foster high levels of student participation and understanding?* we also asked what the kinds and quantity of teacher scaffolding moves were for each of these four practices. The strategies identified in the bottom two rows of Figures 4.1, 4.2, 4.5, and 4.6 can be thought of as illustrating a more fine-grained view of scaffolding strategies in model-based discussion leading. For a more complete discussion of these strategies at both macro and micro levels, see Williams and Clement (2015).

If we take the tallied OGEM teacher contributions as instances of scaffolding, it is apparent in Tables 4.3 and 4.4 that Teacher B provided considerably more scaffolding than Teacher A, and this occurred as well within each of the four OGEM categories. The data support our initial impressions from the video recordings of Teacher B's very active involvement in the discussion compared to Teacher A's more reserved style. Although the two teachers' scaffolding styles (as indicated by their frequency of scaffolding OGEM practices) were quite different, they still led to high degrees of participation and learning in their students. This finding suggests there is not one best way to support students' effective engagement in constructing explanatory models for physics concepts.

In response to our third research question: *Can we describe qualitative differences and similarities in the discussion-based strategies used by the two teachers? Can they both be considered types of co-construction?* In all categories of the OGEM modeling process, Teacher A seemed to participate substantially less than Teacher B in doing so, having less than half the overall contributions (161) as compared to those of Teacher B (360) in equivalent time periods. When these are compared to the 400 plus student contributions for each group, we can infer Teacher B's discussions involved more alternating Teacher and Student contributions (TSTS...), whereas Teacher A's involved more Student-Student contributions (TSSSTSS...). Keeley (2008) suggests the analogies of ping-pong or volleyball to describe student and teacher discourse interactions involving TSTS…and TSSSTSS... exchanges respectively. This difference is aptly illustrated in Figures 4.1 and 4.2 vs. Figures 4.5 and 4.6. McNeill and Pimentel (2010) have studied both the advantages of leading discussions with SSS exchanges, and the difficulty of teaching this practice to teachers.

In thinking about hypotheses to explain these differences, the above data resonated with some less formal observations we had made from the video recordings. We noticed Teacher A generally had longer wait time for students to answer after he asked a question, and would sometimes allow SSS exchanges for 30–50 seconds. Another factor discussed by others is the need for both divergent and convergent periods in discussions (Scott, Mortimer, & Aguiar, 2006). While both teachers solicited student ideas in a divergent way, Teacher A sometimes appeared to let this go on for longer periods, as illustrated in Figures 4.1 and 4.2. We also had the impression Teacher B not only used more questions but also used narrower, more specific questions to guide student thinking. As a metaphor, one might describe the teachers' questioning strategies as rungs on a ladder to be climbed, where A's rungs were further apart than B's rungs. For these reasons it is possible students in Teacher A's class were able to practice and learn more thinking skills—in the form of spontaneous model construction (OGEM) processes enacted with less teacher guidance—even though they evidenced the same content gains. We did not, however, have the resources to measure gains in thinking skills directly in this study, so that is an interesting question for future research.

There were some strong similarities between the two teachers. Each fostered equal or greater levels of student participation than that of themselves in most aspects of model co-construction and appeared focused on guiding the discussion enough to converge on target models. From a broader perspective, the two teachers were very close to one another on a spectrum of teaching approaches ranging from didactic and teacher-driven at one end to constructivist and student-centered at the other. As illustrated in Figures 4.1 and 4.2 and 4.5 and 4.6 for both Teacher A and Teacher B, the vast majority of their strategies were in the form of requesting students contribute to the model co-construction process rather than providing such pieces of the puzzle themselves. This is quite different than the discussions occurring in more traditional teacher centered classrooms.

Another shared characteristic of Teacher A's and B's model based instructional efforts is, while both were able to readily engage students in participation in all four of the OGEM processes, the number of student statements in the evaluation (E) and modification (M) categories were relatively low. One explanation for the lower rates of student participation in these aspects of the modeling process is they may have felt the tasks of evaluation (E) and modification (M) belonged in the hands of the teacher, as is typically the case. Another is they may simply had not had much experience with taking the lead on critically evaluating and suggesting revisions to models, posing a significant challenge.

We hypothesize the most important commonality though is both teachers exhibited the qualitative pattern of using OGEM support strategies and, primarily by asking questions, encouraged their students to participate in those same processes. Student model generation, evaluation, and modification processes are not encouraged in traditional instruction so both teachers were unusual in this way. The teachers rather than the students, for the most part maintained control of the direction of the discussion through guiding questions. As the teachers occasionally contributed ideas and terms where needed so, both students and teachers contributed to the discussions. In this way both teachers appeared to be fostering processes of teacher-student co-construction.

CONCLUSION

As we have discussed, results of an initial phase of this research (Williams, 2011) found students in model-based CASTLE classes recorded significantly greater pre- to post-test gains in conceptual electric circuit reasoning and problem solving outcomes than their counterparts who learned the concepts of electricity through more traditional, lecture and equation-based means. As a follow up to these results, we analyzed video recorded episodes from the classes of the two most successful model based teachers in an attempt to identify and describe the types of scaffolding strategies and student modeling practices being employed during large group discussions (Williams & Clement, 2015). There, through microanalysis of protocols, we identified two distinct types of cognitive methods in teachers' repertories; micro non-formal reasoning strategies, and macro model construction processes. At the macro level we identified four major OGEM practices or processes; observation, model generation, model evaluation, and model modification. The intention of the CASTLE curriculum was to foster student involvement in such practices and we asked whether this had in fact happened. We tallied student contributions to these four practices that were contributing to an evolving model.

Students made over 800 contributions of these four model construction practices in 11 hours of discussion, providing more contributions than the teachers in each case which can be a reasonable result as there was only one teacher per classroom. We conclude it is possible to elicit frequent student participation in model construction practices. We also asked what the level of teacher scaffolding was for each of these four practices. While both classes achieved similarly impressive gains, the teachers exhibited substantially different frequencies of scaffolding the practices. While Teacher B chose to be almost equally involved in the co-construction process by contributing as many OGEM moves as his students, Teacher A displayed a much more reticent and reserved style. We conclude teachers may vary in their amount of scaffolding and still experience equally strong student participation in modeling and gains in conceptual understanding. This gives us some insight into the range of teacher-student interaction profiles that can produce exemplary gains. We hope teachers will find these results relevant to decisions about types of scaffolding and the intensity or frequency of scaffolding they provide.

There were important similarities between these successful instructors. Both appeared to be scaffolding the broader processes of observation, model generation, model evaluation, and model modification. Students are typically not encouraged to use the latter three practices in traditional instruction so, we believe these classes were challenging the paradigm of teacher-centric instruction. Since both students and teachers contributed scientific model construction practices to the discussions, we characterize the overall process as one of teacher-student co-construction. This process may be considered a middle ground between purely teacher-generated and purely student-generated models in the classroom. We hypothesize what remained most important was the teachers' ability to foster students' engagement in the four key modeling processes of the activity, in the effort to help students construct meaningful explanatory models for scientific concepts.

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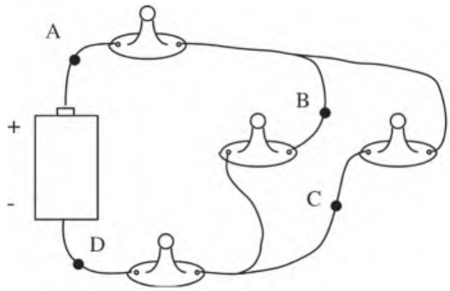
APPENDIX: ELECTRIC CIRCUITS PRE/ POST TEST

The following is a sample problem from the pre-post test.

In this circuit, *all four bulbs are identical*, and *all four bulbs are lit*, although they *may or may not all be the same brightness*.



Which of the following is true?

A. The current at point B is greater than the current at point C.
B. The current at point B is equal to the current at point C.
C. The current at point B is less than the current at point C.
D. There is not enough information to know the relative current at the two points

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