Co-Constructing Models in High School Physics: Comparing Degrees of Teacher and Student Participation in Whole Class Discussions

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Abstract

In this study, we analyzed the participation of teachers and students during their co-construction of explanatory models for concepts in circuit electricity in two high school physics classes. While students in both teachers' classes experienced comparable levels of impressive pre to post-instructional test gain differences over controls, analysis of class discussions showed that considerable differences existed between the two groups in the ratios of student-to-teacher contributions to the development of explanatory models. Applying a new cognitive framework for the analysis of classroom dialogue (Williams & Clement, 2015), teacher and student contributions at the *non-formal reasoning* level were coded into model construction process categories of: referring to observations (O), generating explanatory models to explain phenomena (G), evaluating models currently under discussion (E), and making modifications to these models (M). This analysis based on the OGEM modeling processes made it possible to categorize each teacher and student contribution and to describe the specifics of how the model co-construction process was shared in each classroom. Ratios of teacher to student contributions in each category differed markedly between the two teachers. We conclude that teachers may vary in their styles and degrees of participation in model co-construction processes and still produce similar gains in conceptual understanding. We hypothesize that what remains most important is their ability to foster students' engagement in the four key processes of modeling.

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Study Purpose

In this study, we analyzed the participation of teachers and students during the co-construction of explanatory models for concepts in circuit electricity in the classes of two experienced high school physics educators. This analysis compared teacher and student contributions to whole-class discussions in an attempt to determine whether different forms and degrees of model co-construction could support student learning.

Our research questions were:

1. Can teachers in model-based science classes participate in whole-class discussions in different ways and in varying degrees and still foster high levels of student participation and understanding?

2. How can we describe differences between the teacher's styles? Are they both types of co-construction?

3. Are there aspects of the discussion-based model co-construction process that appear to be similar between the teachers in this study?

Ultimately, this research seeks to contribute to a coherent theory of model-based teaching and learning through increased understandings of both the common elements and unique strategies that teachers employ in supporting their students' model-building activities.

Theoretical Framework

In this study, we examined the teaching strategies utilized by two experienced high school physics educators involved in the process of model co-construction with their students. As used here, model based, teacher-student co-construction is a process by which the teacher and the students both contribute ideas during the building and evaluation of explanatory models (Clement, 2002). It is a process that may be considered a middle ground between purely teacher-generated and purely student-generated models in the classroom.

The focus of this study is on whole-class discussions. Some research suggests that whole-class discussions can be an effective means for facilitating the construction of scientific knowledge and that teaching with a focus on discussion can improve students' scientific reasoning ability and foster conceptual change (Hogan et al., 2000; Windschitl et al., 2008; Lehesvuori et al., 2013). Schwarz et al. (2009) suggest that such conversational interaction among teachers and students provides a means for students to collaboratively construct increasingly sophisticated approximations to scientific concepts through cycles of developing, explaining, evaluating and revising explanatory models.

The term model has many uses; however, 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; Johnson-Laird, 1983). Models are central to an understanding of underlying mechanisms in science. This includes concepts such as planetary motion, human respiration & circulation, erosion and continental drift, cellular reproduction, chemical reactivity, magnetic fields, electric circuits, etc.

Model-based teaching is instruction designed to support the development and evolution of learners' explanatory models. Explanatory models can be described as mental representations of causal or functional mechanisms that are often hidden and that can explain why phenomena in a system occur (Clement, 1989; Williams & Clement, 2015). Model-based science instruction intends to be student-centered, inquiry-based, and constructivist in its approach, differing from what may be referred to as "traditional" science teaching which tends to be more teacher-centric, didactic, and confirmatory in nature.

In traditional science instruction, models, if used at all, tend to be pre-developed, external representations of accepted ideas and theories that are used to show students how things work. In model-based science teaching, the teacher takes students' prior knowledge into consideration, guides the collaborative co-construction of explanatory models with students; both in the shared social space and in the students' minds, and encourages students to generate, evaluate and modify their explanatory models for accuracy and completeness, much in the way science extends our understanding of the world around us.

Most traditional electric circuit instruction emphasizes the application of the Ohm's Law equation $I=V/R$ for the solution of workbook problems. By contrast, in a model-based approach to electricity instruction, students are generally encouraged to focus first on the causal reasoning behind what is happening with the elements of charge, current, resistance, and voltage. The mathematical quantification of these phenomena is usually left until later in the instruction, where it serves to further verify and support the qualitative models. It is thought that this emphasis on the conceptual nature of circuit behavior can be beneficial in addressing the many well-documented misconceptions that students bring to the study of circuits (Çepni & Keles, 2006; Korganci et al., 2015)

A conceptually-grounded model-based learning approach is used in Steinberg et al.'s (2004) CASTLE (Capacitor Aided System for Teaching and Learning Electricity) curriculum that was 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 that exist throughout the circuit. By using the analogy of voltage as a type of "pressure" that exists 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. The CASTLE curriculum employs the extensive use of analogies, diagrams, and discrepant events to engage students and their teachers in the incremental co-construction of explanatory mental models for circuit electricity. It is this cooperative conversational classroom process, the different cognitive levels at which different teacher contributions are made, and the ratio of contributions made to it by teachers and students in these model-based learning situations that comprise the focus of this study.

Study Rationale

In the initial phase of the research (Williams, 2011), we examined high school physics students' experiences learning about electric circuits through model-based instruction. An experimental group of approximately 270 high school physics students who were learning about electric circuits through the model-based CASTLE curriculum and 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 instructional, which lasted from 6-8 weeks. Both groups had approximately equal distributions of male and female students.

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 gains (24.6%) in their levels of conceptual understanding over the course of instruction than their traditionally instructed counterparts (5.9%) as displayed in Table1 and Fig. 1 below.

	Control Group n = 262		Experimental Group n = 282	
	Raw Score	Percentage	Raw Score	Percentage
Mean Pre-Test Problem Solving Score	6.59 / 20	32.9%	6.70 / 20	33.5%
Mean Post-Test Problem Solving Score	7.75 / 20	38.8%	11.61 / 20	58.1%
Mean Problem Solving Score Gain	1.17 / 20	5.9%	4.91 / 20	24.6%

Table 1 - Pre/ Post Test Conceptual Understanding Scores by Treatment Group

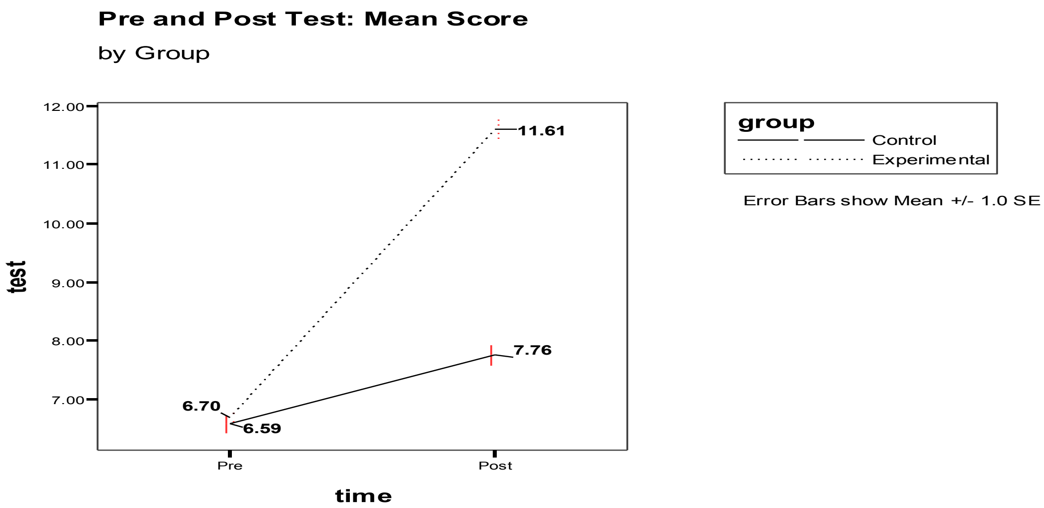

Fig.1 – Pre/ Post Test Conceptual Understanding Scores by Treatment Group

The success of the model-based learning experience in developing students' conceptual understandings of electricity supported our belief that it was important, in the present study, to focus on analyzing the participation of teachers and students during the co-construction of explanatory models in these classes.

Study Context & Setting

The study was conducted over a two year period during which two of the six teachers from the model-based group taught the electricity unit three separate times with different groups of students, each time spending approximately seven weeks. We wanted to analyze teachers with somewhat different student populations in order to increase the range of teaching situations represented in this comparative study. While both teachers utilized the same model-based curriculum, basic constructivist teaching philosophy, and general classroom structure, there were differences that existed between the two groups.

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 & 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.

Both teachers utilized class formats that had students alternating 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. It was these post-experimental classroom conversations and the teachers' subsequent reflections on them that we focused on in this study.

Data Collection & Analysis

While the goal of this study was to analyze the participation of teachers and students during the co-construction of explanatory models for concepts in circuit electricity in the classes of two experienced high school physics educators, it is important to note that considerable qualitative analysis of the data was conducted before the relatively simpler quantitative comparisons could be made.

First, segments of post-experimental whole-class conversations during which each of the teachers and their students appeared to be engaged in the co-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. For both teachers, whole-class discussion segments were analyzed from three different classes in an attempt to reduce the effects that any one group of students might have on the results. Segments 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 teacher strategies, we employed an interpretive analysis cycle 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, g) returning to the data again, and so on. (Clement, 2000)

Initially, this process allowed us to identify a fundamental similarity that existed between the instructional methodologies of the two educators. We observed that 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 that 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 kinds 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 that promotes and encourages 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 researchers cited above on this page as well as Minstell and Stimpson (1996) and Hammer (1995), also identified several cognitive strategies such as the use of analogies, inductions, and discrepant questions. Meanwhile researchers within our own group (Rea-Ramirez & Nunez-Oviedo, 2002; Khan, 2003; Nunez-Oviedo & Clement, 2008; Williams, 2011) began to focus on teacher/student model co-construction in a variety of science learning environments and describing teacher and student statements as contributing to the development of model elements through a variety of cognitive processes. We have described these phases 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 (GEM) originally grew out of observations of scientifically trained experts thinking aloud about explanation problems (Clement 1989, 2008)). Using this OGEM process framework, we developed the following criteria to code student and teacher statements during whole-class modeling discussions into four categories:

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.

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.

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 . . . , that makes sense . . . , I also believe it . . . , but that doesn't explain why . . . , do you think that is the way it works. . . , etc.

Modification (M): The statement either asks for or provides a suggested change, revision, adjustment, or modification to a theory, explanation, or explanatory model that is 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 . . . , etc.

We will utilize these categories in the diagram analyses beginning with Figures 2 and 3. 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'. Then a larger number of teacher ‘micro strategies’ were identified at a smaller grain size, such as ‘Teacher provides an analogy’ or ‘Teacher requests (that students generate) a model element’. We call these micro strategies 'Non-formal Reasoning' strategies. We found that each of these ‘micro’ strategies could be seen as sub-strategies for one of the four ‘macro’ OGEM strategies; for example, the above micro strategies can both be seen as ways of contributing to the larger ‘G’ strategy of Generating a model. Another way to view 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.

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 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 presented above the teacher statements, and 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 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 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.

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) 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.

Immediately below the teacher statements is a brief description of the hypothesized teaching moves at the micro level of Non-formal Reasoning strategies. (This is also referred to as Level 2, as part of a larger 4 Level framework we utilize in our studies). 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) at what we refer to as Level 3.

For example, in Figure 2, the 2nd through 6th teacher statements all serve the goal of having students Generate (G) a model. However, one can differentiate between the micro strategies of Requesting Initiation of Model Construction, Requesting an Analogy, and Requesting Elaboration of the Model. These three different micro strategies all 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. The fact that this instance of the Generation (G) macro process 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 processes.

Above the students' statements on the diagrams, we have attempted to describe their micro level processes (in green) in contributing to the Model Construction processes at the top (in blue). As is the case for the teacher strategies, we attempted to link (via arrows) each of these student contributions to the macro level OGEM phases of the model co-construction process at Level 3.

Such diagrams were not created for all 5.5 hours of the whole class discussions that were analyzed from each of the teachers' classrooms, but rather were developed as representative visual portrayals of selected portions of the model co-construction process to help illustrate the nature by which teachers and students can contribute to the evolving explanatory models. Diagrams and brief descriptions for two such episodes are included below.

Episode #1 – Teacher A

In the experiment prior to the whole-class discussion in Episode # 1, the ninth grade students in Teacher A's class were using magnifying glasses to closely examine the filaments of two different types of miniature light bulbs that they were using in the CASTLE circuit building kits. By observing the physical differences in the filaments 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 the patterns in their Observations (O) of the light bulb filaments. Once they identify the key physical differences in filament wire thickness, he asks them if they could develop an analogy that would account for differences in the resistance to charge flow between the two bulb types. Therein begins the model Generation (G) phase. 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 that often confuses the distinction between charge flow rate and charge 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 that is very often confused or not discriminated by students learning physics and one that makes the use of analogies to describe charge flow in wires challenging without proper teacher guidance. In an attempt to clarify any possible confusion, Teacher A requests elaboration of the model regarding the issue of flow rate vs. flow speed and later provides elaboration of the model concerning the total amount or volume of air (charge) flowing in the straws (filaments).

What results is a rich conversation between three students who dispute the accuracy of the highway analogy. Again, it appears that 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 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.

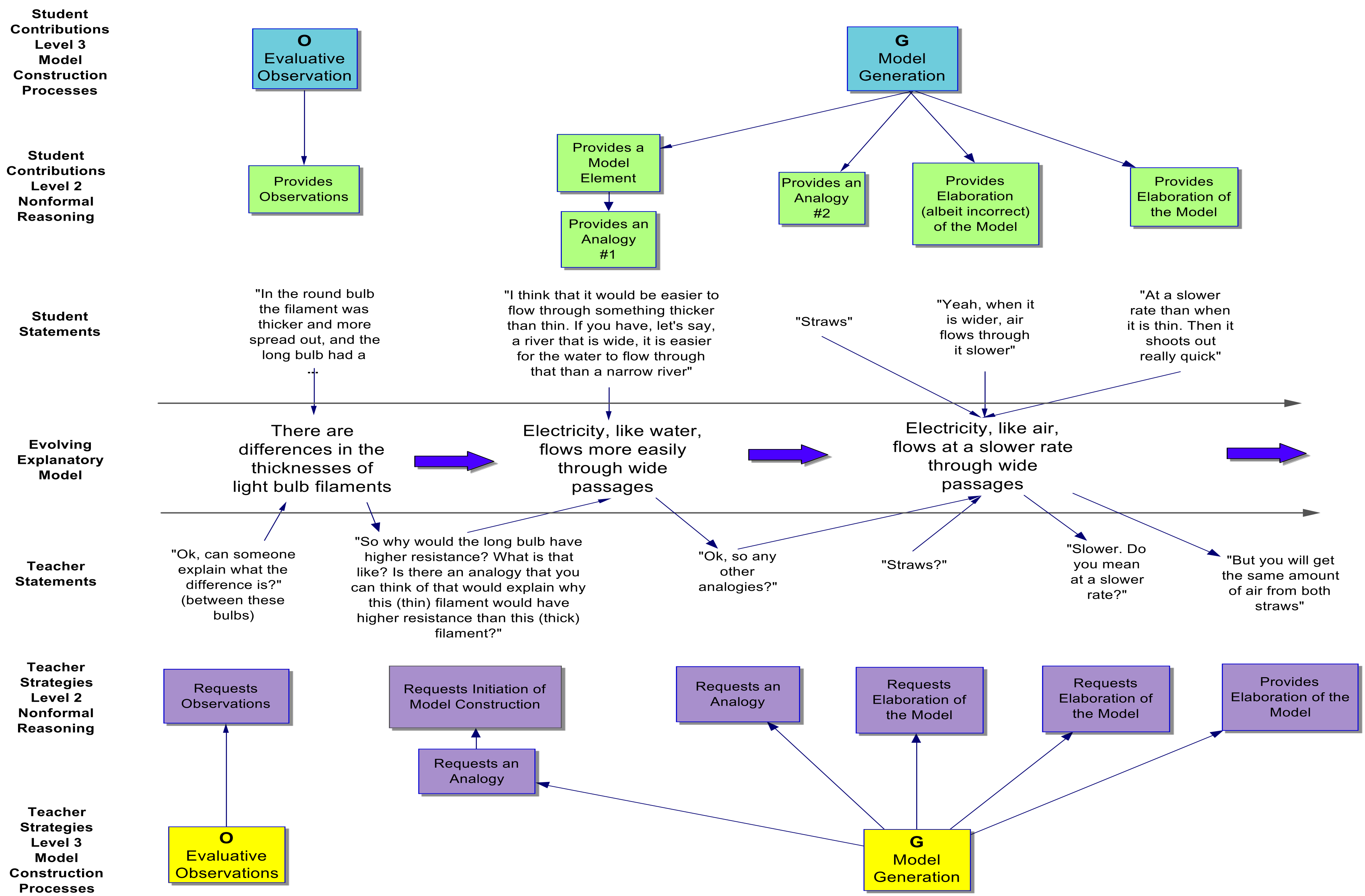

Fig. 2 - Whole Class Model Co-Construction Diagram # 1 for Teacher A – Part A

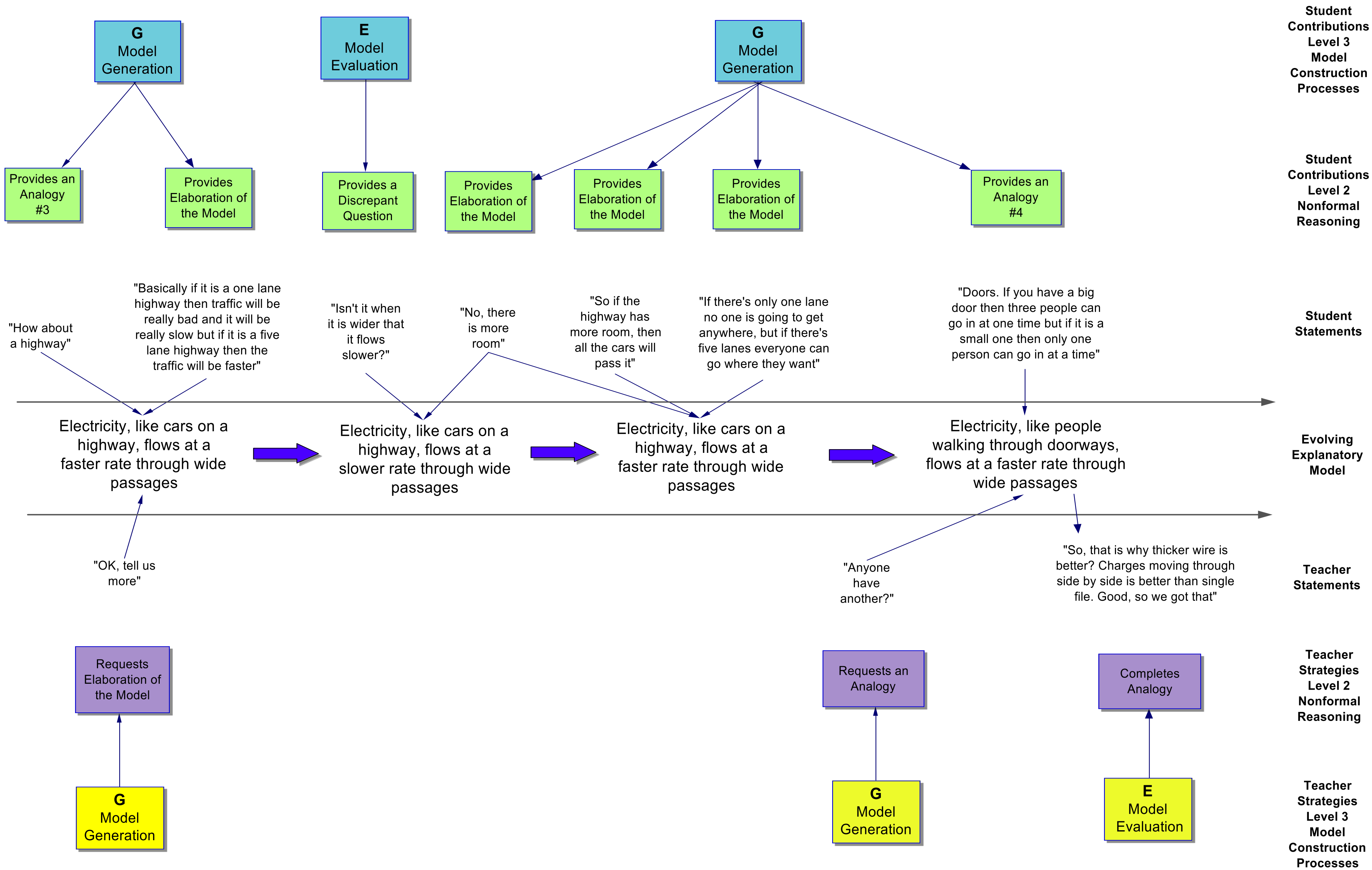

Fig. 3 - Whole Class Model Co-Construction Diagram # 1 for Teacher A –Part B

An interesting feature of Episode # 1 is Teacher A's encouragement of the students to utilize analogies to support their construction of explanatory mental models for charge flow in wires. By using analogies to map a set of relationships from known domains (the *bases*) into the new domain (the *target*), the students can construct explanatory models that can generate inferences in the target domain. In this episode, the ninth grade students in Teacher A's class generated four distinct analogies for charge flow in light bulb filaments. Specifically, they referred to water in rivers, air in straws, cars on roadways, and people walking through doorways as known domains (bases) from which they mapped relations from each into the target domain of electric charge travelling through a conducting wire.

<u>Episode #2 – Teacher B</u>

Just prior to the whole class discussion featured in Episode #2, the students in Teacher B's ninth grade science class had conducted an investigation in which they first assembled an electric circuit (referred to in the transcript as Circuit A) containing two light bulbs connected in series with a previously discharged 1 Farad non-polar capacitor as shown in Fig. 4 below.

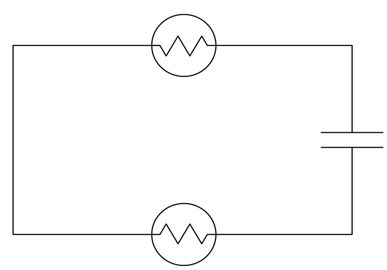

Fig. 4 - Circuit A – Two bulbs in series with a discharged capacitor

The purpose of this investigation was for the students to establish that a neutralized or discharged capacitor placed in a circuit without a battery would not result in the lighting of the bulbs. The second part of the investigation involved the insertion of a battery pack into the circuit as shown in Fig. 5 below.

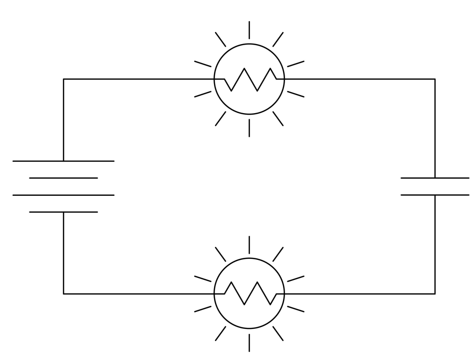

Fig. 5 - Circuit B – The same as Circuit A but with a battery pack inserted in series

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

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 that the light bulbs did come on but then he quickly turns the discussion over to the students by requesting that 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 that they provide a model element to explain the behavior of the electric charges in the circuit. After encouraging the 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 on their earlier memories of the compass needle deflection, Teacher B refocuses on model Generation (G) activity by again requesting that the students suggest explanatory models based on their observations. Since the first student response is not as developed as is required, the teacher requests that 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 that 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 that 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 that were 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.

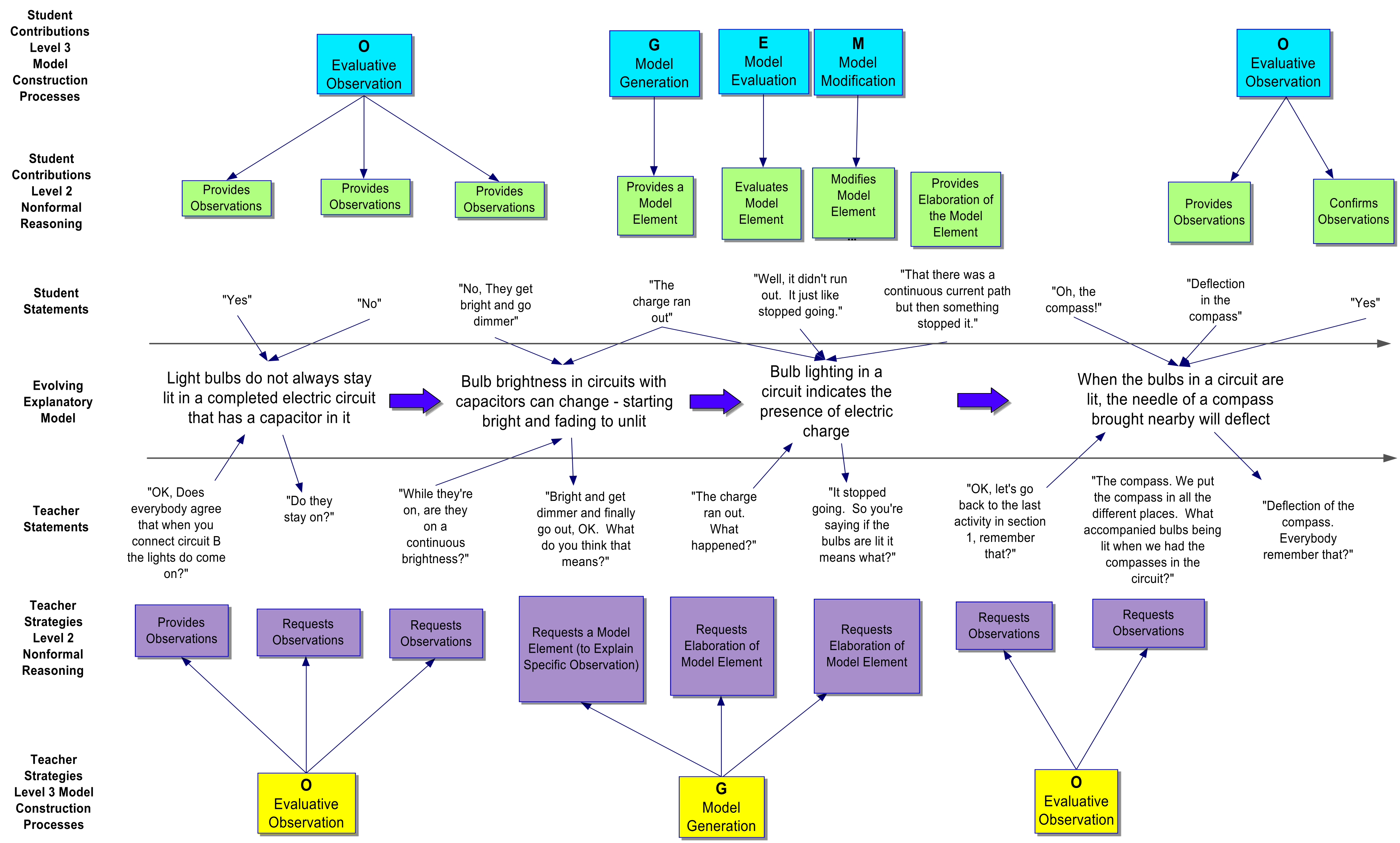

Fig. 6 Whole Class Model Co-Construction Diagram # 2 for Teacher B – Part A

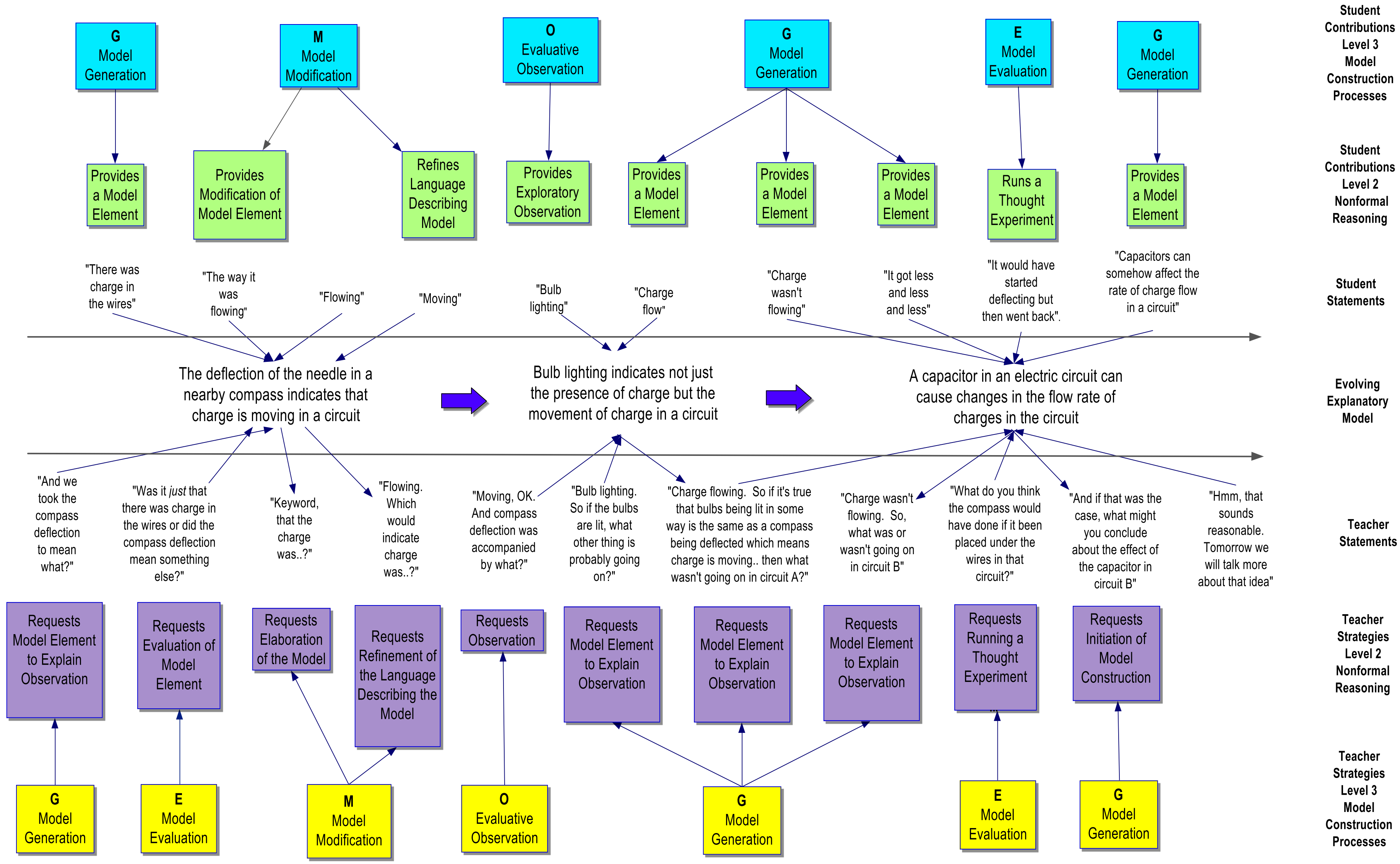

Fig. 7 - Whole Class Model Co-Construction Diagram # 2 for Teacher B – Part B

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 and then conduct experiments to confirm it. What is also important in this episode are the teaching strategies that Teacher B utilizes when students' attempts at constructing explanatory models are not as developed or sophisticated as are required to adequately move the process in the direction of the target model. In particular, in part B the teacher asks the students for experimental evidence to extend the initially proposed explanatory model and secondly he requests refinement of the model by asking for a repair to the language describing the model. These are important strategies because they help the students 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 that model building is a process of continual Evaluation and Modification.

We constructed the diagrams 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 utilizing whole-class discussions as an effective forum for leading students through the Observation, Generation, Evaluation and Modification phases of model construction. The diagrams also permit a visual portrayal of the relationship between the teacher strategies and student statements at the 'micro' Non-formal Reasoning level and the 'macro' OGEM Model Construction Processes level.

Student/ Teacher Model Construction Participation Ratios

Once students' and teachers' statements during the whole-class discussions were coded into the four macro-level modeling process categories and counts of these were compiled, the quantitative comparison of the contributions by ratio became a simple mathematical task and it became possible to describe specifics of how the model co-construction process was occurring in the classrooms of each teacher. It is important to note that, even though on the diagrams presented above multiple student or teacher statements at the micro level may point to a single OGEM phase at the macro level, each of the individual micro-level contributions was counted separately in the data collection process.

While it was determined that the students in both Teacher A & B's classes contributed readily to the development of model elements through their statements in each of the Observation, Generation, Evaluation, and Modification categories, considerable differences between educators appeared in the raw counts of their conversational statements and thus the ratios of the student to teacher contributions. Tables 2 to 6 below are representative of approximately 5.5 hours of classroom discussion for each of Groups A & B. In each of the OGEM process categories, the number of statements contributed by both students and teachers are tabulated.

Group A

	Students					Teacher			
Segment #	**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 Phase Totals	114	206	67	24		31	58	62	10
Grand Totals	411					161			

Table 2 – Student & Teacher Contributions to OGEM Categories – Group A

Group B

	Students					Teacher			
Segment #	**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 Phase Totals	83	284	47	20		51	144	146	19
Grand Totals	434					360			

Table 3 – Student & Teacher Contributions to OGEM Categories – Group B

Student : Teacher Model Element Development Ratios for 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 – Student & Teacher OGEM Contribution Ratios – Group A

Student : Teacher Model Element Development Ratios for 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

Table 5 – Student & Teacher OGEM Contribution Ratios – Group B

It appears that while the rate of student verbalization was only slightly higher in Teacher B's classes than 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, teacher A's students contributed 2.6 times as much to model development in the overall aspects of the OGEM processes as the teacher did whereas Teacher B's students contributed only 1.2 times as much as their teacher did. This data supports initial impressions from the video recordings of Teacher B's very active involvement in the discussion compared to Teacher A's more reserved style.

It is particularly interesting to compare the sub-category totals to see that, while in Teacher A's classes the ratio of student to teacher participation in referring to experimental Observations was 3.7 : 1 , in Teacher B's classes, the students references to the circuit investigations they conducted was only slightly higher than that of the teacher's. Likewise, in terms of Generating models, the students in Teacher B's classes provided roughly twice the number of contributions as their teacher, while in Teacher A's classes the students contributions were considerably higher at 3.6 times what the teacher offered. When it came to Evaluating models that were 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. In all cases, it appears that Teacher B chose to play a much more active and engaged role in leading the co-construction process, whereas Teacher A employed a style that favoured much more selective use of his participation.

Discussion

In response to our first research question:

1) *Can teachers in model-based science classes participate in whole-class discussions in different ways and in varying degrees and foster high levels of student participation and understanding?*

The students in both teachers' classes achieved approximately the same level of impressive gains on tests of conceptual understanding. This means that for these teachers, quite different styles of instruction and degrees of participation in the cognitive processes of model co-construction, still led to equally high degrees of participation and learning in their students. This implies that there is not one best way to support students' effective engagement in constructing explanatory models for science concepts.

In what follows, we attempt to describe similarities and differences between the two educators in this study from different perspectives in order to further our understanding of what constitutes the process of model based discussions and model co-construction.

Regarding our second research question

2) *How can we describe differences between the teacher's styles? Are they both types of co-construction?*

From the point of view of thinking about traditional instruction, regardless of the differences in their degrees of participation, both teachers were able to support high levels of student participation in whole class discussions with upwards of 400 student contributions to model development taking place over five and a half hours of observation. While both teachers fostered equal or greater levels of student participation than that of themselves in most aspects of model co-construction, it is apparent that in all categories of the OGEM modeling process, Teacher A seemed to participate substantially less than Teacher B in doing so. This is evidenced by the considerably fewer overall contributions of Teacher A (161) as compared to those of Teacher B (360) in equivalent time periods.

One factor that may have contributed to the lower frequency, of Teacher A's contributions to the class discussions was his use of lengthy periods of silence, often referred to as "wait time" or "think time". It was common for Teacher A to wait 10 seconds or more for students to respond to his questions or statements. Similarly, he would often not speak for considerable (30- 50 seconds) periods of time, allowing students to speak directly to one another without teacher narration, mediation or intervention.

Keeley (2008) suggests the analogy of ***volleyball*** to describe this sort of student-to-student interaction as opposed to the more common student-to-teacher discourse which is described as ***ping-pong***. Ping-pong represents a back and forth question-answer pattern: the teacher asks a question, a student answers, the teacher asks another question, a student answers, and so on. Volleyball represents a different discussion pattern; the teacher asks a question, a student answers, and other students respond in succession; each building upon the previous student's response. Discussion continues until the teacher "serves" another question or response. This form of discourse pattern can be observed in Fig. 3 where Teacher A is seen to remain silent while students respond to one another about analogies being suggested.

Through this type of "volleyball" discussion, Teacher A appears to be fostering a wide range of student engagement with the scientific ideas. This type of interaction is intended for students to feel comfortable challenging and clarifying ideas without the necessity for teacher intervention. Whether through wait time or think time, the teacher appears to have developed a whole-class discussion atmosphere in which students have come to learn that they will be provided ample opportunities to speak and that they shouldn't rely on the teacher to always mediate this.

In terms of ***scaffolding*** students' deeper conceptual understanding of science phenomena, in this case the behavior of hidden causal aspects of electric circuits, we view this as a process of helping students bridge the gap between what they currently know and what they need to know through the construction of viable explanatory models. Vygotsky (1962) referred to this gap in what students can do on their own and what they can do with support from others as the Zone of Proximal Development. In model-based teaching where whole-class discussions are used as a medium for collaborative reasoning and sense-making, we see the questions, responses, and requests for examples, analogies, predictions, and evaluations used by teachers like those in this study serving as supports for students to bridge the gap in their understanding. The strategies shown in the bottom two rows of Figures 2, 3, 6, and 7 can be thought of as illustrating a more fine-grained model of scaffolding in model-based discussion leading.

Using the analogy of a ***ladder*** as a device for bridging such a gap, in comparing the teaching styles of Teachers A & B, we see some differences in the type of ladder each provides to their students. With his frequent and ongoing conversational input, Teacher B's ladder of strategic support can be imagined as one with many rungs spaced closely together, providing students with small incremental steps to climb. Teacher A, in comparison, provides a ladder in which the rungs are further apart, requiring the students to take larger and possibly riskier steps in order to advance across the gap in their understanding. At some points on Teacher A's ladder, it could even be imagined that the gaps between the rungs he provides are so wide that there is little way the students can climb without offering support to one another. Regardless of the structure of the ladder that each teacher provides, it appears that the students in their classes manage to traverse the gap in understanding as evidenced by the substantial and essentially equal pre/posttest gains in electric circuit conceptual problem solving. Thus we believe that the work both teachers have done with their students qualifies as teacher-student co-construction.

In this study we did not have the resources to measure growth in students' general scientific reasoning skills (such as those in the top two rows of Figures 2, 3, 6, and 7) as an outcome after instruction. Since Teacher A fostered a higher ratio of student to teacher contributions within the scientific reasoning practices identified, it may be that his students had more practice with doing scientific reasoning in class. It could be that even though they had similar gains as Teacher B's students on electricity concepts, they may have had greater gains in general scientific reasoning skills. It would be interesting in future research to examine whether such differences in teacher scaffolding styles has any impact on such general scientific reasoning skills.

With respect to our third research question:

3) *Are there aspects of the discussion-based model co-construction process that appear to be similar between the teachers in this study?*

While it may seem that Teachers A & B are using substantially different discussion-leading styles and strategies in guiding their students through the construction of explanatory models of electric circuit behavior, it is important to realize that they are actually very close to one another on a spectrum of teaching approaches that ranges from didactic, confirmatory and teacher-driven at one end to constructivist, inquiry-based, and student-centered at the other. An example of their similarities that may not be obvious from the tables of raw counts of their contributions, but can be seen in the diagrammatic representations of the class discussion, is that for both Teacher A and Teacher B, the vast majority of their conversational strategies are in the form of ***requesting*** that students contribute to the model co-construction process rather than ***providing*** such pieces of the puzzle themselves. Our impression is that this is quite different than the discussions occurring in more traditional teacher-centered classrooms.

Another shared characteristic of Teacher A & B's model-based instructional efforts is that, while both were able to readily engage their 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. For example, neither teacher was able to foster student participation in the Evaluation (E) of explanatory models at a rate any higher than their own; in fact for Teacher B the students' contributions for this process were merely a third of his own. Levels of student contributions in the model Modification (M) category were the lowest of the four categories with only 24 and 20 statements pertaining to the revision of explanatory models from Teacher A and B's students over 5.5 hours of classroom discussion. While Teacher A did manage to support his students' participation in this aspect of the modeling process at a rate of 2.4 times greater than his own, it was only because he limited himself to a mere 10 contributions to the Modification (M) phase during the conversations.

One explanation for the low rates of student participation in these aspects of the modeling process is that they may have felt the tasks of Evaluation (E) and Modification (M) belonged in the hands of the teacher. Typically it is the teacher, in most instructional situations, who is charged with the responsibility of assessing and evaluating students' ideas and creations and deciding when revisions or corrections need to be made. It is quite possible that students in both teachers' classes had not had much experience with taking the lead on critically evaluating and suggesting revisions to their own or their peers' thinking in the past, so expecting them to be able to effectively do so in the model-based learning context may have posed an unreasonable challenge for them.

Another factor that may contribute to the low number of both student and teacher statements referring to model Modification (M) could be that considerable time and effort generally must be invested in the Generation (G) and Evaluation (E) of explanatory models before they are deemed needful of Modification (M). The teachers and students in this case study were observed to spend substantial periods of time coming up with and critically considering the explanatory models for various aspects of electric circuit behavior before they reached the consensus that adjustments in the models were required for them to properly explain the experimental observations. This poses an interesting question for future research.

We hypothesize that the most important commonality though is that both teachers exhibited the qualitative pattern of using OGEM strategies and, primarily by asking questions, encouraging their students to participate in those same processes.

Conclusion

Results of an initial phase of this research (Williams, 2011) found that 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 two of the model-based teachers in an attempt to identify and describe the types and levels of instructional strategies and learning processes 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 OGEM Model Construction Processes. Within the macro OGEM Model Construction Process level, we were able to organize strategies into four major OGEM processes or phases, evaluative Observation, model Generation, model Evaluation, and model Modification. We also observed and tallied student contributions to these four processes that were contributing to an evolving model.

A key finding in this study is that, while the two teachers featured both used strategies at the Non-formal Reasoning level of interaction with their students, they exhibited substantially different ratios of student/ teacher participation at this level.. 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, seemingly permitting his students to take the lead in the discussions and development of the explanatory models.

Regardless of these differences in the degrees of teacher participation and the resulting ratios of teacher / student contributions to the development of model elements, the students in both teachers' classes achieved approximately the same level of impressive gains on tests of conceptual understanding. Both educators appeared to be guided by the broader processes of evaluative Observation, model Generation, model Evaluation, and model Modification that had been previously identified as occurring in model-based science classes of a variety of topics and levels. Thus at this level we were able to detect a similar overall qualitative pattern of strategy use across different instructors using a model-based approach. We hypothesize that what remained most important was their ability to foster students' engagement in the four key phases of the activity, in the effort to help students construct meaningful explanatory models for scientific concepts.

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