LARGE SCALE SCIENTIFIC MODELING PRACTICES THAT CAN INFLUENCE SCIENCE INSTRUCTION AT THE UNIT AND LESSON LEVELS [1]

By

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Abstract

In this study we articulate a multi-level scientific Modeling Practices Framework derived from expert studies on model based teaching strategies in classrooms and examine its usefulness in an actual classroom context. In addition, we develop vocabulary and diagrams to describe a multi level model based teaching processes. We are particularly interested in examining: (1) Is there a pattern of model construction processes that occurs over a large time scale of 3-6 lessons? (2) Is there a pattern of model construction processes that occurs over a medium sized time scale of 5-20 min cycles within lessons? (3) If present, how are these patterns connected? And (4) Do these patterns suggest a set of model development strategies for teachers? We conducted a detailed case study of a three-lesson cluster through which middle school students build an explanatory model about how the glucose goes from the small intestine to the blood and to the cells. The main findings of the study are included in a Classroom Dialogue Diagram that describes six Major Modeling Modes occurring at a large scale over 3 lessons and several smaller Model Construction Processes occurring at a medium sized time scale. The diagram provides a more detailed description of the modeling processes than those included in the NGSS. In addition, we found that the medium sized Model Construction processes are nested within the larger Major Modeling Modes, and act as subprocesses for them. Furthermore, we hypothesize that the six Major Modeling Modes could be understood as a "repeated Mode sequence" to guide instruction in the classroom. We hypothesize that this flexible modeling sequence can be used to teach different topics and subtopics, as a way of aiming for deeper conceptual knowledge along with learning modeling practices.

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Introduction

While researchers have been pursuing the description of major large scale modes of learning in science (such as how a unit or topic in the curriculum should be taught in a structured way) for a considerable time, only fairly recently have some incorporated mental models into their descriptions. Educators have also been trying to bring scientific thinking practices into the classroom for some time, but only fairly recently have these included modeling practices. Having students participate strongly in model construction may require a change in the way we think about planning lesson clusters or units-- there are important questions about how the structure of a science education unit such as the circulatory system should reflect the scientific practices associated with modeling. For example, should there be separate activities for model generation that precede model evaluation activities? How should we allow for the variety of models that students may generate?

In addition, the recent guidelines of NGSS (2013) that urge the building models during science instruction pose at least three challenges for science educators and teachers. Firstly, teachers need a better characterization of the content structure of models in science and their explanations that they are going to teach to the students. Secondly, they need more accurate descriptions of key modeling practices relevant for experts and relevant for classrooms in order to support students in conducting those practices within the classroom. Finally, they need to find a way of organizing model-based instruction at a large time scale that spans over many days.

The purpose of this paper is then to conduct a case study of large scale and medium size modes of modeling in an actual classroom context. To do this we will start from new descriptions of expert large scale and medium size modeling practices in the literature and use those new descriptors to make an initial analysis of classroom practices, which we will then augment and refine. This will allow us to articulate a multi-level scientific perspective on model based teaching strategies in classrooms. Another purpose is to develop the vocabulary and diagrams needed to describe such multi level cognitive teaching processes. To do this we will also need to look at the content structure of models in science for the classroom.

Theoretical Framework

In the next sections we will first examine different scholarly traditions that we think may contribute to providing a (1) a perspective on the content structures and (2) a perspective on modeling processes.

Structure of Science Content

Science as Multi-layered Mechanisms

Machamer et al (2000) propose the language of mechanisms that use "entities" and "activities" to explain biology in terms of multi-layered explanations. These authors claim that biological sciences such as neuroscience and molecular biology were built through the gradual and piecemeal construction, evaluation and revision of multi-layered mechanism schemata. They also indicate that higher-layer mechanisms are essential to understand lower layer mechanisms, just as much as those lower layers are essential for understanding those at higher layers.

Traditionally science educators have organized the subject to be taught by dividing the topic and organizing the curriculum frameworks into “units.” A unit is content driven and it is usually characterized as a body of knowledge that is the target of a sequence of lessons and that is conceptually and temporally separated from other topics.

But a unit can still be a large topic area that is composed by several subtopics. For instance, lets examine the circulatory system unit. It is composed of several subtopics such as blood, blood vessels, heart, and nutrients exchange at the capillary level. Likewise each of these subtopics can be divided into smaller subtopics. Then, the blood topic can be divided into two parts: cells and plasma and functioning of blood. Likewise blood cells can be divided into red blood cells, white blood cells, and platelets and so on. As result, the topics included in the circulatory system unit have the multi-layered (nested) structure as described by Machamer et al (2000).

It is important to help science educators and teachers to support their students in gaining an understanding of science as composed of nested mechanisms because it helps them to conceptualize the concepts to be taught as well as the organization of the instruction. We also consider it important to connect modeling practices to the organization of curriculum units because it is the traditional way that the curriculum frameworks are divided and teachers are trained to organize classroom work.

Multi-layered Qualitative Explanatory Models

A closely related topic is the nature of scientific qualitative explanatory models. Clement (2002) argues that an explanatory model is a special kind of model that represents hidden, unobserved mechanisms that can be used to explain either observable properties of phenomena, or to explain a function within a higher layer such as the functioning of the heart being explained by the chambers, muscles, valves, and electrical “pacemaker” cells . An explanatory model is a fundamentally different type of knowledge than a condensed summary of a pattern of observations. An explanatory model involves thinking about a system in terms of hidden material elements that are thought to be working as causal or functional agents within the system. In other words, a qualitative explanatory model explains how a system works and answers “why” questions about where its observable behavior comes from. Based on Machamer et al.'s (2000) account of mechanisms and Clement (2002) account of explanatory model, we think that an explanatory model of, say, the circulation system will have entities and activities that are not initially observed by the modeler. The model may have nested layers that include (1) a model of the blood flowing in vessels, including the heart as the pump; (2) a model at a lower layer that describes the mechanism inside the heart that causes the blood flow.

Scientific Modeling Practices in Experts

Understanding the model construction practices of scientists can be done from at least two perspectives: a philosophy/history of science view and a cognitive science view. We do not claim that these are the only perspectives on this important topic but they are the most relevant to our study.

Kuhn and Toulmin

In his book *The Structure of Scientific Revolutions*, Kuhn (1970) indicated that scientific knowledge construction is the result of a revolutionary process by which an older theory or paradigm is rejected and replaced by an incompatible new one. The new paradigm is the result of cycle that consists in: finding anomalies in the older theory; this produces and crisis in the scientific community; and one group then works together in originating a new paradigm. But then, the scientific community has more than one theory to explain the same data, yielding a competition process between them. Kuhn argues that these paradigms compete until one survives because either most of the researchers are converted to the other paradigm or because the supporters of the opposite paradigm die.

On the other hand, Toulmin (1972) indicated that more often, scientific knowledge construction is the result of an evolutionary process that is comparable to Darwin's natural selection theory. The process involves two steps: Innovation and selection. Starting from an existing model, the innovation part involves originating new conceptual variations while the selection part involves a process of competition and debate until leaving in place the best concept that will replace the older conception. Thus Kuhn's view in his book was more revolutionary, whereas Toulmin's view was more evolutionary.

Cognitive studies

Clement (1989, 2008a), Nersessian (1995, 2008), and Tweney (1985, 2010) have conducted research studies of the modeling practices of experts. They claim that experts use different non-formal reasoning processes such as analogies, discrepant events, and thought experiments that are coupled with high level processes such as generative abstraction, abduction, and cycles of evaluation and modification to build scientific knowledge. These descriptions tend to be primarily evolutionary in character, although Clement (2008c) also used a metaphor of 'punctuated evolution' to account for sudden insights in scientific thinking.

However, we observe that there is a huge challenge for teachers that want to conduct modeling practices in their classrooms because there are unsolved questions raised by philosophy of science and cognitive traditions in explaining scientific knowledge creation: What kinds of expert reasoning processes should science educators and teachers use in conducting modeling practices in their classrooms?

We need better descriptions of model construction practices from experts in order to provide science educators and teachers with clearer vocabulary, descriptions, and examples about how to build models with their students.

In conclusion, there is a need for researchers to find a way to organize science instruction that will address simultaneously the two challenges posed above: fostering the learning of multi-layered explanatory models as content along with fostering multi-level modeling practices. In the next section, we will discuss efforts conducted by researchers in unpacking and revealing the complex processes that take place during model-based teaching and learning in the classroom. After that, we will revisit the question of developing a new framework for model based learning processes based on expert studies.

Modeling practices in science classrooms and curricula

Several researchers have developed model-based curricula to teach qualitative explanatory models such as particle theory, electricity, mechanics, and energy in the human body at different school and age levels. These curricula emphasize content learning via model construction and revision processes. They emphasize understanding causal mechanisms, not just static structure, of qualitative explanatory models. But from the student's point of view these models are quite complex, and learning them can involve many conceptual steps. As result, studies of all these curricula have the following common characteristics: (1) depart from students' ideas and move toward a conceptual target; (2) instruction was conducted by combining small and large group discussions; (3) students' learning was measured through pre and post-tests; (4) students increased their understanding from pre to post at a statistically significant level; (5) the curricula were field tested in classrooms for one or more years; (6) teachers contributed to the development and testing of the curricula.

In the following paragraphs, we introduce the curricula in chronological order and we briefly describe each curriculum as well as the major steps they use to foster modeling practices in the students. At the end, we will comment about similarities and differences that we observe between them.

The CASTLE Curriculum

In the early 1980s Melvin Steinberg, a physics professor at Smith College, and a group of high school and college physics teachers developed the Capacitor-Aided System for Teaching and Learning Electricity (CASTLE) to respond to students' conceptual difficulties in electricity. The aim of this curriculum is to move students' initial naïve ideas toward an expert understanding of electrical phenomena. Throughout the curriculum students are stimulated to model mobile charges as a compressible fluid and electrical potential as "pressure" in the fluid. In addition, they learn that a pressure difference is what causes charges to move through a resistor. Case studies by Steinberg & Wainwright (1993) and Clement & Steinberg (2002) describe the processes that students are asked to engage in, as in the example in Table 1 .

1. Record their observations	The student's initial idea is that a battery is the "initiator" of current" and that charges move in the same direction everywhere. The student then works with the same circuit but with a capacitor. She predicted that bulbs will not light because they are both connected to different thin pieces of mental that never touch (the capacitor plates) and the current is going to stop. But she was surprised to observe bulb lighting.
2. Articulate their interpretations	Teacher suggested that the student to use the compass to investigate the direction of movement in each wire during charging. The student realized that charges were coming from the capacitor and that mobile charge is a normal constituent of batteries and aluminum foil of which the capacitor plates are made.
3. Criticize their existing model	The teacher removed the battery of the circuit and the student observed a new round of transient bulb lighting. By using a compass, the student realized that the current was moving in an opposite direction.
4. Construct a new model	The teacher introduced the "tire analogy" in which a puncture tire let -pressurized air escape. The student realized that something like pressure is the causal agent that makes charge move in the wires. This suggests that she had arrived at a compressible fluid-like model with pressure as causal agent. It is the pressure difference in the wires that can actually cause charge movement. The resulting student understanding is that a battery is a device that maintains above-and below-normal pressure values in its terminals to cause charge flow in the unified circuit. The teacher then introduces a color code for designating relative pressure values in the metal parts of circuits.
5. Apply the new model	The student then applies her new model to different types of circuits and depicts the charge levels in the wires by using the color code introduced by the teacher

Table 1. Sample Sequence from The Castle Curriculum

Preconceptions In Mechanics

A beginning of the 1990s a group of researchers in physics education, and teachers developed a set of units for dealing with students' persistent alternative conceptions in nine topics in mechanics. The text is a collection of lesson plans that targets some of the most difficult areas in mechanics, such as relative motion, Newton's Third Law, and gravitational forces. The method used attempts to have students build up their understanding at a qualitative, intuitive level before mastering quantitative principles. It also encourages students to become aware of their own alternative conceptions, to actively criticize them, and to develop new conceptions. The lessons use instructional techniques such as constructing visualizable explanatory models, class discussions, and bridging analogies. The technique described by Clement (1993) provides an overview of a lesson used to address the alternative conception of "static objects as barriers that cannot exert forces. It includes six steps. Here in the early steps he is describing the use of analogies. But a broad definition of modeling can include the use of analogies and in that view this table then looks similar to the other model based curricula (see Table 2).

1. Target problem for the students to discuss.	The students first discuss and "vote on" models for a target problem (one that draws out a misconception in many students) of whether a table exerts an upward force on a book placed on the table.
2. Analogous Anchoring example to draw out an anchoring conception	The students are asked whether a spring pushes up on one's hand when the hand is pushing down on the spring to draw out the students' intuition that is largely in agreement with physicists.
3. A strategy that fails	Students are presented with the hands-compressing-spring anchor and the book-on-the-table problem as analogous situations. Unfortunately this simple strategy does not often work. Thus there is a need for an additional effort to help students see how the analogy between the spring and the table can be valid.
4. Bridging analogies	The strategy consists in finding one or more intermediate third cases (e.g., a foam or a thin flexible board) that shares features with both the original case (book-on-the-table problem) and the analogous case (hand-compressing-spring). Students are asked to discuss how the bridging cases might be similar to or different from the anchor and the target examples.
5. Microscopic explanatory model	Students are introduced to a springy model for solids. They are asked to consider that a solid table is made of atoms connected by bonds that are somewhat like springs. Students are asked to explain how a table can exert an upward force.
6. Demonstration	At the end of this lesson the teacher made a demonstration in which he stands on the lecture table. It is observed that a laser beam reflecting from a small mirror near the center of the table deflects when the teacher steps near the mirror.

Table 2. Sample sequence taken from Clement (1993)

Children's Learning In Science (CLIS) Research Group Curriculum

Driver & Scott (1996) gives an account of a curriculum development initiative undertaken by the Children's Learning in Science (CLIS) Research Group at the University of Leeds in the UK. The project lasted over three years where they developed teaching materials for three topics: energy, elastic particle theory, and plant nutrition. The three topics were selected because they focus on concepts that have proved to be difficult for students and yet are central to an understanding of large areas of the sciences. The study provides a teaching schema for teaching particle theory that includes six phases (see Table 3).

1. Orientation and eliciting of pupil ideas.	Pupils are asked to describe and explain simple phenomena related to the properties of matter. In this way, their own ideas are made explicit and open for inspection.
2. The nature of scientific theory	Pupils are introduced to the nature of scientific theory and theory making through simulations and discussions, this being in preparation

and theory making	for Section 4 of the scheme. Two exercises were conducted —a simple rule-guessing game and "clues" to a murder mystery and are invited to find out "whodunit"— as analogies to understand the nature of scientific theory and theory making. In addition, students were asked to reflect on how they were able to "spot the rule" and "solve the murder".
3. A pattern of properties of solids, liquids, and gases.	Pupils work to identify and develop a pattern of observable properties in the behavior of solids, liquids, and gases.
4. Pupil theory making	Pupils develop their own theories as to the nature of solids, liquids, and gases. They are encouraged to base their theory making upon the pattern of properties identified in Section 3.
5. Review, reflection, and movement toward accepted theory.	Pupil theories are compared and evaluated by members of the class. The teacher introduces activities and information to guide pupils toward the accepted scientific point of view.
6. Application of accepted theory.	Pupils are given opportunities to apply the accepted theory about the nature of matter in familiar and novel situations.

Table 3. Table Extracted from Driver & Scott 1996, p. 99

Energy In The Human Body Curriculum

Rea-Ramirez (1998; 2004) Rea-Ramirez, Nunez-Oviedo, & Clement (2004) developed the Energy in the Human Body Curriculum (EHBC) that discusses the organization of the body and how it produces energy. Rea-Ramirez piloted the teaching sequence with eight individual students by using clinical interviews and with a small group experiment. Nunez-Oviedo (2001) and Nunez-Oviedo, Rea-Ramirez, Clement, & Else (2002) analyzed teacher and student interactions and provided initial descriptions of the modeling processes that took place during the small group experiment. Their main findings were that learning is not the result of a sudden insight but the result of different size reasoning cycles. In addition, Nunez-Oviedo described a cycle of instruction conducted by Rea-Ramirez that includes six phases that were used to organize later versions of the curriculum. The curriculum contains eight chapters and each of them is divided into up to five sections called "investigations". Each of the chapters and their investigations are organized by following the same cycle of instruction originating a multi-layered or nested structure. Finally, the conceptual steps followed by this cycle of instruction were described in terms of the teacher's activities as well as the thinking processes that they might produce in the students (see Table 4. Energy in the Human Body Curriculum (EHBC)).

1. Introduction	Teacher provides the students with an overview of the topic that they are going to study. Here students may recall useful schemata for learning.

2. Detection of students' ideas	Teacher asks an explanation question that may help the students to build their initial model (M1). The students answer the question by drawing and making comments.
3. Building on students' ideas	Teacher helps students repair their ideas and helps them to build an improved model (M2). In this phase, the teacher may use experiments, discrepant events, and analogies to help students move closer to the scientist model.
4. Introducing the scientific model	Teacher introduces the students to the scientific model with the aim not of memorization but of fostering in the student a comparison to and possible dissonance with their previous ideas (M2). This initiates new repairs and building in order to build an even better model (M3).
5. Adjusting the student model	Teacher asks the students the initial question again and then encourages students to compare their answer before and after instruction (comparing M3 & M1).
6. Application	Teacher asks the students to solve a problem or situation that was beyond the scope of the original topic.

Table 4. Energy in the Human Body Curriculum (EHBC)

Common patterns within model-based curricula

While examining these curricula we have realized that there common steps in supporting students' modeling that Clement (2008c) summarized broadly in the following four sections: Introducing problems, Building Model Parts, Synthesis, and Application. In the Introduction Problems section, all curricula detect students' ideas to introduce a problem or situation where the students either describe a pattern or encounter an anomaly situation that they explain and they expose their initial understanding of the situation. In the Building Model Parts' section, all of the curricula address students' ideas by building intermediate versions of the target model by either conducting experiments or using analogies. In the Synthesis section, all curricula somehow consolidate the scientific model and move toward the accepted view. In the Application section, all curricula apply the new model to new situations and some of them review explicitly students' initial conceptions.

Even though these four curricula have made considerable advance in understanding and fostering modeling processes we think that their descriptions and explanations are still too rough for guiding teachers in conducting modeling practices. For instance, "building on students' ideas" or "Review, reflection, and movement toward accepted theory" or "Construct a new model", what exactly do they mean? What are the processes that a teacher should conduct within each of these phases? In other words, these phases do not provide a detailed description of the modeling processes that are taking place within each of these conceptual steps. In addition, it is necessary to find a common vocabulary and description to name similar modeling practices that occur across topics and age levels in these curricula and in future model-based curricula.

Findings on modeling practices in the classroom

Throughout the years the cognitive research group at the University of Massachusetts, Amherst, has collaborated in conducting multiple case studies to examine the learning and teaching modeling processes that takes place within three of the above curricula. These case studies have documented different size modeling practices such as: micro strategies (analogies and thought experiments) (Else, Clement, & Rea-Ramirez, 2003; A. L. Stephens & J. Clement, 2010; A. L. Stephens & J. J. Clement, 2006; A. L. Stephens & J. J. Clement, 2007; A. L. Stephens & J. J. Clement, 2009, 2010; Stephens & Clement, 2012) and two macro strategies called model competition (Nunez-Oviedo & Clement, 2003a, 2008c) and model evolution (Nunez-Oviedo & Clement, 2003b; Nunez-Oviedo, Clement, & Rea-Ramirez, 2008). In addition, other studies have also described modeling practices that appear to have a large time scale of 2-6 lessons (Driver & Scott, 1996; Windschitl, et al., 2012) as well as smaller model evolution cycle patterns that seems to occur in 5-20 minutes cycles in classrooms (Schwarz et al., 2009).

Moreover (Minstrell, Anderson, & Li, 2011) have identified two kinds of teachers: teachers focused on teaching and teachers focused on learning. The first kind of teacher uses formative assessment to gather data to determine the amount of information that the students had learned. If the teacher considers that the students have learned enough, she moves forward in her teaching. The second kind of teacher, use formative assessment to assess students' learning in relation to the learning goal. This teacher is interested in students' thinking and the experiences that they need to deepen students' learning. These two kinds of teachers illustrate two enactments of formative assessment that suggest fundamental differences in teacher's belief on the nature of teaching and learning. The first kind of teacher considers learning as an accretion mode. The second kind of teacher considers learning as process of constructing and reconstructing knowledge in new contexts or in new situations. Minstrell et al (2011, p. 3) states:

> At the heart of the effective formative assessment lies the need to access and build upon student thinking as it develops from naïve to more sophisticated. This is particularly vital in the area of conceptual learning in STEM where feedback to students and next steps in instruction cannot rely upon exemplars and repeated practice as can be done more readily in teaching skills and procedures. Research has shown that students need learning experiences as interactions with phenomena and ideas to test and revise their own initial or developing ideas so that they can eventually arrive at those goal science ideas themselves.

As result, the authors ask how to integrate formative assessment into a responsive classroom practice. They conceptualize assessment and instruction as one entity within a larger paradigm of learning. Minstrell et al (2011) developed a "Building on Learner Thinking" (BOLT) framework for assessment in instruction. Minstrell et al (2011) argues that students do not learn when they see the scientific model even if the teacher goes step by step. Learning only takes place when teaching takes into account learners' thinking difficulties in order to move it forward to the desirable learning goal. BOLT has developed tools (diagnoser.com) for making students' thinking more visible and identifying problematic aspects to help evolving students' ideas. These are essential and valuable ideas. But there is a need for a more detailed account of learning processes and teaching strategies at different levels.

In this study, we would like to start from observations of large scale and medium size learning modes in experts to generate a framework of detailed modeling strategies (e.g. Competition, Evolution, Analogies, Thought experiments, and cycles). It will be interesting to see whether our findings in this case study resonate with the studies reviewed above.

Efforts in developing a multi level framework

Clement (2008c) made an attempt to develop a larger organizing framework for the modeling and teaching techniques identified by the case studies conducted using the Preconception's in Mechanics, CASTLE, and Energy in the Human Body curricula. He argues that they have in common two general instructional techniques that cut across disciplines and age levels: (1) Common Goal Structure and (2) Common Teaching Strategies.

Regarding Common Goal Structures, Clement (2008c) argues that these three curricula uncover and take into account students' preconceptions, including both useful ideas and misconceptions. But current US science standards just specify target concepts or models at best but they fail to specify the "learning pathway" that teachers need to follow in order to support students in reaching target concepts. These three model-based curricula attempt to provide the missing learning pathways regarding electricity, mechanics, and energy in the human body. These curricula include a detailed description of goals and the planned progression of the students' understanding that goes from common misconceptions, to intermediate models, and target models. This is called "planned learning pathway." However, the planned learning pathway needs to be adapted in classrooms where it becomes an "implemented learning pathway" that results from using the plan with real students adaptively.

Regarding Common Teaching Strategies, Clement (2008c) argues that these three model-based curricula include the strategies: Model Evolution, consisting of Model Evaluation and Modification processes, and Co-construction. "Model evolution" is different from model presentation. Teaching via model evolution means fostering a series of "model criticisms and revisions" to the parts of the students' models that are partly correct and partly faulty by using dissonance producing techniques and analogies. The teacher attempts to use these strategies at the right place and at the right moment to foster successive model element revisions until most students' ideas reach the target concept. At the center of each step of the model criticism and revision process there is a generation, evaluation, and modification **(GEM) cycle** that allows a model to improve as it evolves. GEM cycles are medium size processes that were identified in expert reasoning and appear to be central in student learning as well. Teaching via model evolution seems to be made possible by the teacher's and students' contribution of ideas through a process called "teacher-student co-construction." As result, the co-

construction process also reflects simultaneously social and cognitive perspectives for explaining science education. These curricula include multiple strategies within a single lesson and this may be due to the need for several different kinds of conceptual change at different stages within a lesson (Clement, 2008b).

Based on the previous findings Clement (2008c) discuss an overall framework of strategies called "Multiple Time Scale Levels of Organization." He argues that multiple levels of organization can help us understand the extremely complex activities of teaching and learning. The time scale includes six levels that correspond to a particular time scale, ranging from those strategies operating over months to those operating over seconds. He also argues that curriculum planning, lesson planning, and teaching in science, when taken seriously, is a complex multi-level process through which lower level strategies are nested within higher level strategies (see Table 5).

Level F	Curriculum integration strategies
Level E	Unit-sized modeling strategies
Level D	Lesson strategies
Level C	Single model element strategies
Level B	Individual cognitive strategies
Level A	Dialogical strategies

Table 5. Multiple Time Scale Levels of Organization

Clement (2008c) suspects that instructional design must include all six levels to be optimally effective for teaching for meaningful conceptual change leading to integrated knowledge that can be applied flexibly. In addition, the idea of time scale levels may potentially help teachers to sort out different levels for planning and for structuring discussion.

Introducing Modeling Practices Framework

So we believe that it is necessary to build an overall framework grounded on expert and classroom data that somehow organizes the identified strategies. But we think that this framework should go into detail about what substrategies are present within each level. By subprocesses we mean what tactics (subprocesses) at Level D, for example, should serve to contribute to one of the larger strategies or goals at level E. We attempt here to unpack and expand details at Level E, with some reference to tactics at level D that constitute supporting substrategies. In this way we hope to contribute to a full framework to support science educators and teachers in developing model-based learning pathways.

The cognitive learning in science group at the University of Massachusetts, at Amherst, has been working in developing multi level frameworks grounded in case studies. For example, Williams & Clement (2015) describe cognitive strategies; Nunez-Oviedo and Clement (In preparation) describe teacher student interaction patterns; Stephens, Clement, Price, and Nunez-Oviedo (2017) examine the role of imagery during model-based discussions; Clement (2008a; 2017) develops a multi level Expert Modeling Practices Framework. The latter work on science experts has involved analyzing data from videotaped protocols of experts thinking aloud about unfamiliar explanation problems. We will use it as a departure point for the present study in the hope that comparisons to expert reasoning can sharpen our ways of describing the scientifically relevant reasoning of students and teachers during discussions, and help in describing important teaching strategies for supporting such reasoning.

Expert Modeling Practices Framework

In this case study, we will start from part of an Expert Modeling Practices Framework (Clement, 2017) that contains four different levels of modeling practices derived from expert reasoning studies (Clement, 2008a) as well as from several classroom case studies (Brown, 1987, 1989; Brown & Clement, 1987, 1989; Brown & Clement, 1992; Clement, Rea-Ramirez, & Steinberg, 1999; Clement, Steinberg, Stephens, & Williams, 2005; Else, Clement, & Rea-Ramirez, 2008; Khan, 2005, 2008; Nunez-Oviedo, Clement, & Rea-Ramirez, 2002; Nunez-Oviedo, Rea-Ramirez, Clement, & Kahn, 2005; Rea-Ramirez & Clement, 1997; A. L. Stephens & J. J. Clement, 2007; A. L. Stephens & J. J. Clement, 2009; Stephens, Clement, & Nunez-Oviedo, 2006; L. Stephens & J. J. Clement, 2006, 2007, 2009; E. G. Williams, 2006, 2011).

Two levels of the expert Modeling Practices Framework (see Figure 1) will be taken as an initial hypothesis or model of what large scale and medium size scientific knowledge construction processes could look like in the classroom. That is, we are going the use the expert framework as a starting point to look for teaching strategies and we will then try to improve it or expand it as needed. This part of the framework includes two nested levels of different size modeling strategies. Level 4 includes four Major Modeling Modes and Level 3 includes medium size Model Construction Phases of Generation, Evaluation and Modification, collectively termed GEM processes or a GEM cycle. Level 3 also includes methods for assessing competing models. In the full framework these are fostered by Level 2 Nonformal Reasoning Processes that likewise are fostered by Level 1 Imagistic processes, but we do not have room to discuss those here. Strategies at Level 2 and Level 1 are the topics of other studies (Stephens et al., 2017; E. G. Williams & Clement, 2017).

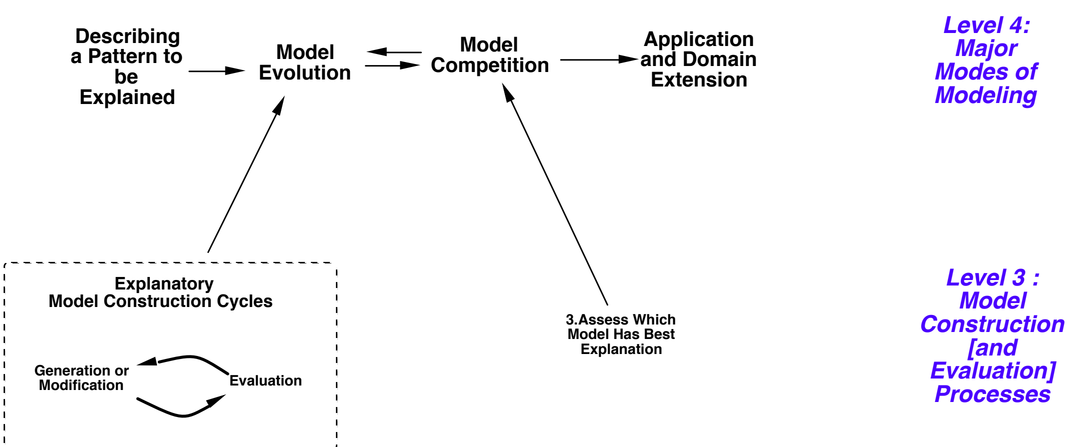


Figure 1. Part of Modeling Practices Framework

Figure 1 shows Two Nested Levels of Processes in Explanatory Model Construction. Each process also identifies a corresponding teaching strategy of scaffolding that particular process**.** We are continuing to evaluate and improve this framework in the course of applying it to classroom video transcripts.

Research Questions of this study

The challenge for this case study is to articulate a multi-level scientific perspective on model based teaching strategies. Part of this challenge is to develop the vocabulary and diagrams needed to describe such a multi level cognitive teaching processes.

Building from new descriptions of the multi layered nature of scientific topics and from descriptions of expert and science educators modeling practices found in the literature we want to examine the following research questions:

- Is there a pattern of model construction that occurs over a large time scale of 3-6 lessons?
- Is there a pattern of model construction that occurs over a medium sized time scale of 5-20 min cycles within lessons?
- If present, how are these patterns connected? For example does one pattern describe subprocesses within the other pattern?
- Do these patterns suggest a set of model development strategies for teachers?

Goals of this study

This case study has three goals:

Firstly, to **articulate a multi-level scientific perspective** on modeling processes occurring in an actual classroom context;

Secondly, to **provide vocabulary and diagrams to describe cognitive strategies at multiple levels**, and

Thirdly, to suggest a set of **large scale strategies for teachers**.

Method

Context

In this paper we address the above questions by presenting an in-depth case study of a teaching episode that took place in a racially mixed middle school classroom located in a northeastern suburban town in the USA. We focus on whole class discussions during three lessons of the Energy in the Human Body Curriculum (EHBC).

The teacher had nearly 20 years of teaching experience, very good content domain and classroom management skills, and conducted her teaching by having the students share with her in making model construction contributions. Students were organized into groups or "tables" of four-six students. The teaching episode took place almost at the end of the school year and consisted of three 45 minutes lessons that were videotaped and transcribed verbatim. Transcripts are slightly condensed here to maintain the transparency of the flow of the conversation. The students worked out their ideas either in their curriculum workbook or on their small group whiteboard.

The topic of the cluster of lessons was "how the glucose goes to the cells through the blood stream". In particular, students examined the processes and structures that allow the glucose absorption in the small intestine. The lessons took place during Sub-investigation (6.4b) of Chapter VI and Investigation (7.3) of Chapter VII of the fourth version of the EHBC (see Figure 2). For examining the same episodes, see Investigation 6.5 and Investigations (7.2) and (7.3) of the online version of the EHBC curriculum (https://srri.umass.edu/node/673/).

Figure 2 shows that the EHBC is composed of eight chapters and each of them includes Investigation and Sub-Investigations. The dashed arrow depicts the two segments of the curriculum connected at the end of the teaching episode that is being analyzed. In order to provide context for the reader we will first describe briefly the main aspects that took place during the preceding Chapters VI and VII and the Investigations and Sub-Investigations that pertain to the teacher episode.

Chapter VI begins reminding the students that in previous chapters they had learned that cells need oxygen and glucose to get energy in the form of ATP by conducting a process called cellular respiration. The teacher asked the students to show the path followed by oxygen and sugar to the big toe and show how the carbon dioxide gets out of the big toe. Students drew individually their ideas on an empty outline diagram of the human body. The teacher then asked the students to share their individual drawing in their small group and then come up with a group drawing that they draw on their student workbook and on their whiteboard. The teacher then conducted Investigations (6.1), (6.2), and (6.3) (see Figure 2**Error! Reference source not found.**).

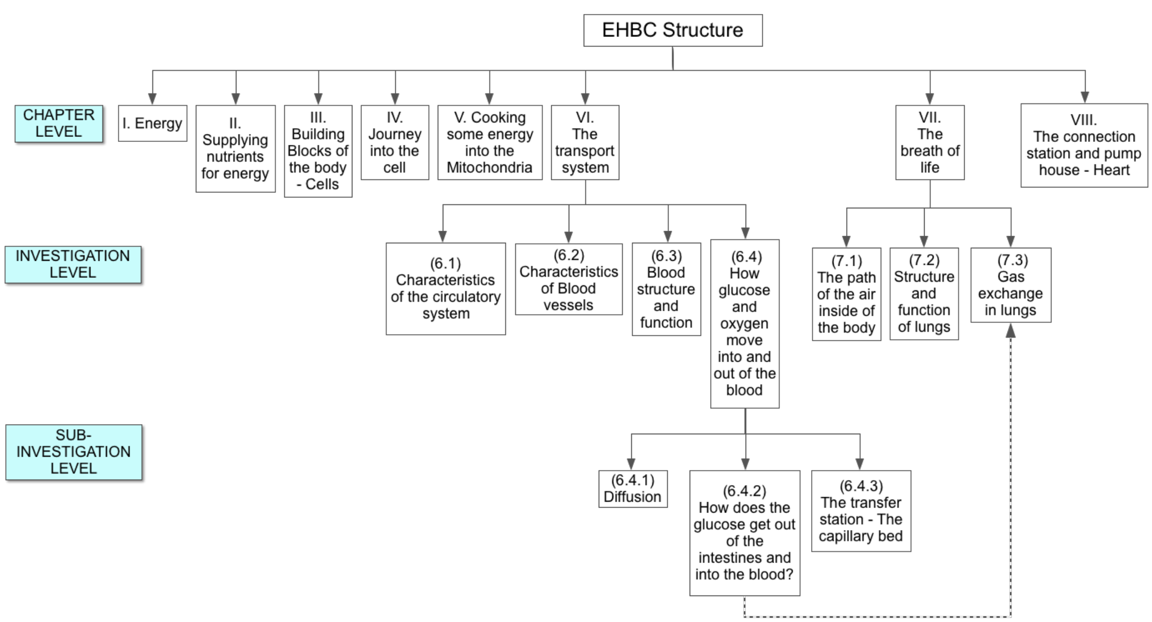


Figure 2. EHBC Structure

Overview of the teaching episode

During Chapter VI, Investigation (6.4) the teacher asked the students to think about their previous investigations about digestion and remember where the glucose came from. Next the teacher asked them to think about how the glucose goes to the cell through the blood stream and asked them to draw their ideas in the workbook. The teacher then asked the students to share their individual ideas with their group and with the rest of the class. She then told the students that in this investigation they will only study how the blood gets glucose from the intestines to be carried into the cells and that later they will examine how the blood gets oxygen to be carried to the cells. The teacher then conducted Sub-Investigation (6.4.1.) about diffusion processes and then continued teaching Sub-Investigation (6.4.2.) and Sub-Investigation (6.4.3) (See Figure 2**Error! Reference source not found.**).

This study focuses on Sub-Investigation (6.4.2) where the teacher taught the students about how glucose goes from the small intestine into the cells by conducting the following activities: (a) She asked the students to draw individually and show in their drawings a small portion of the intestine and the position of the capillaries there to get maximum absorption of nutrients. Students then shared their ideas within small group and came up with a group drawing, and then shared their ideas in large group. (b) The teacher then drew on an overhead placed on an overhead projector an outline of the villi of small intestine. She asked the students to come up individually and draw their ideas about the position of the capillaries with respect of the villi directly into the overhead so that everybody in the class could see them. The teacher then supported the students in evaluating and modifying the students' ideas until they were very close to the scientific view. They also discussed the importance of villi as an exchange site of nutrients. (c) The teacher then showed the students an overhead that depicted the scientific view of the villi structure. (d) Finally, the teacher asked the students to go back and modify what they have drawn before.

At the end of the present transcript, the teacher made a connection to Chapter VII. Chapter VII begins reminding the students that in previous chapters they had learned that cells need oxygen and glucose to get energy in the form of ATP by conducting a process called cellular respiration. In order to conduct Investigations (7.1) and (7.2), the teacher asked the students to draw individually on their workbook the path followed by oxygen molecules until reaching the cells, drawing this on an empty layout of the human body. The teacher then asked the students to share their individual drawing at the small group and then come up with a group drawing that they drew on their student workbook and on their whiteboards. Then students shared their ideas in large group. By examining drawings and students' large group sharing, the teacher realized that the students had a fairly good model of the physical structure of the respiratory system. The students had studied this topic before and Investigations (7.1) and (7.2) constituted an activity to recall those ideas.

As result, the teacher skipped Investigations (7.1) and (7.2) and began to conduct Investigation (7.3) where she asked the students (a) to remember what the exchange site of the digestive system was (villi) that they had just studied and to think about the site of exchange in lungs. A student said that lungs might have a kind of villi inside. (b) The teacher then showed the students an overhead depicting a bunch of grapes with a string attached to it. This suggested the overall layout of the alveoli in lungs and originated a short discussion between teacher and students about its structure and function. (c) The teacher showed the students an overhead depicting the scientific view of the respiratory system and alveolus structure. This originated an exchange between teacher and students about the richness in oxygen and carbon dioxide of the blood depicted in the drawing, its source and where it is going. (d) The students modified their initial drawings (not shown in the video).

Social processes

In addition, the EHBC included social processes that were tailored into the EHBC. Along with teacher student interactions, students had to work individually or in pairs and write down or draw their ideas in the curriculum workbook. Other times, students had to share, compare, and discuss their ideas within their small group until reaching consensus. The students also had to share and defend their ideas in large group discussions. Finally, the students had to think back about their initial mental models and reflect about how it may have changed through instruction.

Data analysis

Starting from the initial framework of expert processes shown in Figure 1, we attempted to identify larger (Level 4) and smaller (Level 3) reasoning patterns that were occurring throughout instruction in this lesson cluster. The identified reasoning patterns were then diagramed, evaluated, revised, and checked and re-checked against the transcripts and the videotaped lessons multiple times until reaching a more stable diagram shown in Figures 3, 4 and 5. This involved adapting and expanding the expert framework in some cases. Social grouping decisions are also noted in Figures 3, 4 and 5. The students' and teacher's utterances have been condensed somewhat there to keep the size of the diagram manageable.

Results

In this section we will first describe the two major levels of teaching processes that we found by presenting a Classroom Dialogue Diagram. In the second section, we provide a detailed description and interpretation of the case study transcript, using our newly developed constructs and vocabulary for teaching processes.

First Part: Summary of the Processes Identified

Classroom Dialogue Diagram

One result of this study is depicted in Figures 3, 4, and 5. They show an overall description of the modeling practices detected at Level 4 and Level 3 during this three-lessons cluster. They may act as an advanced organizer for the study to guide the reader in the analysis of the classroom dialogue. In addition, Figures 3, 4 and 5 show a diagramming notation and vocabulary to illustrate the teacher student co-construction process. Williams & Clement (2015) describe such classroom dialogue diagrams in the following way.

> In their simplest form, the diagrams are horizontal versions of the transcript with student statements on the top row and teacher statements on the bottom row, with time running from left to right (see Figures 3, 4, and 5). The horizontal strip across the middle of the diagram contains short written phrases to describe the evolving explanatory model. These phrases represent our hypotheses for 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 students' model at that time, and how it differed from the target model… arrows point from both teacher and student statement toward the explanatory model descriptions in the center strip indicate shared contributions to the changes or additions in the models. At other times, arrows from the models are directed toward teacher statements, indicating the influence of the current model on the teacher's next query or comment (p. 13).

The lower part of Figures 3, 4, and 5 contain labels for two levels of strategies: at Level 4 called Major Modeling Modes and at Level 3 called Model Construction (GEM) Processes.

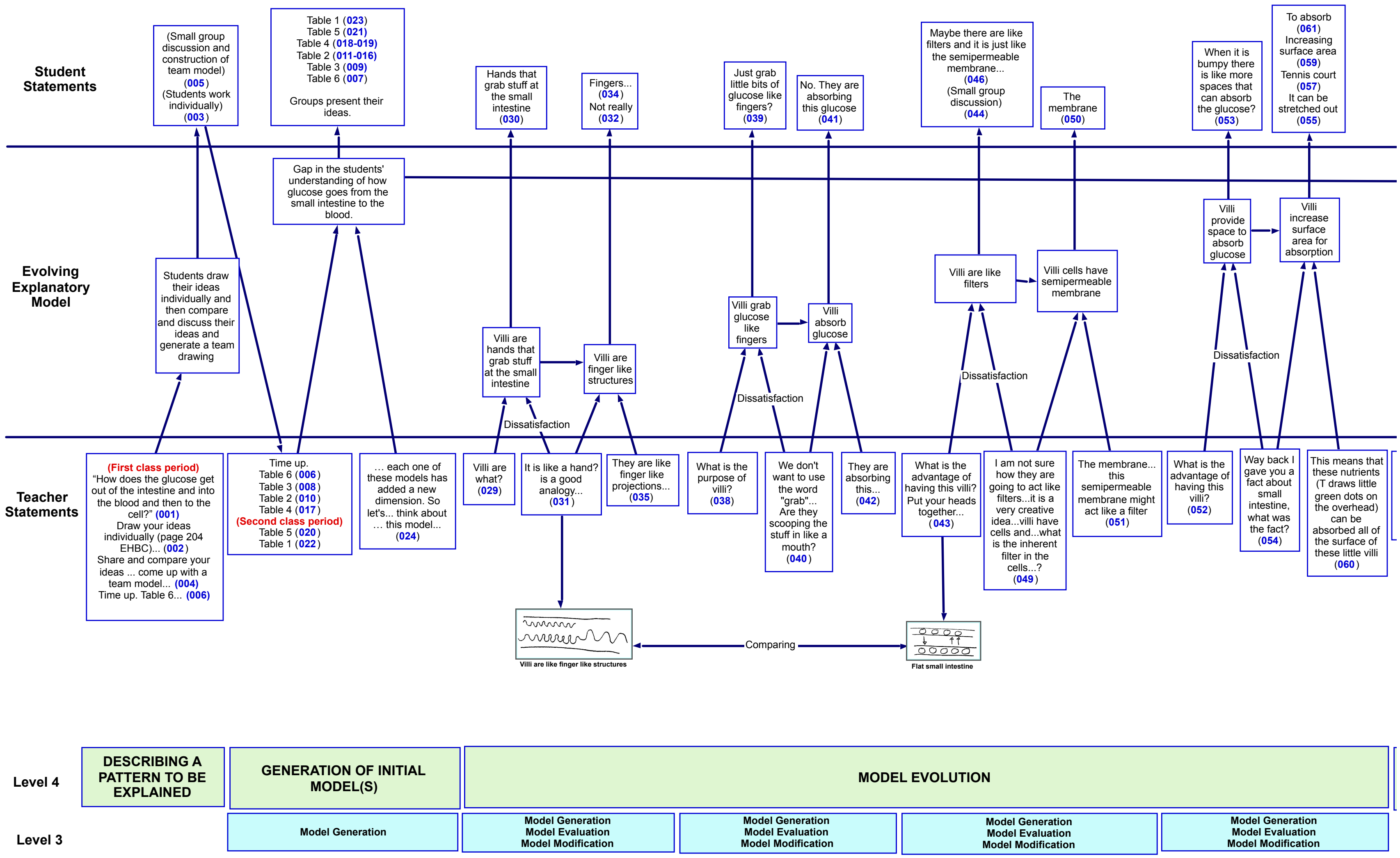


Figure 3. Classroom Dialogue Diagram, First Part

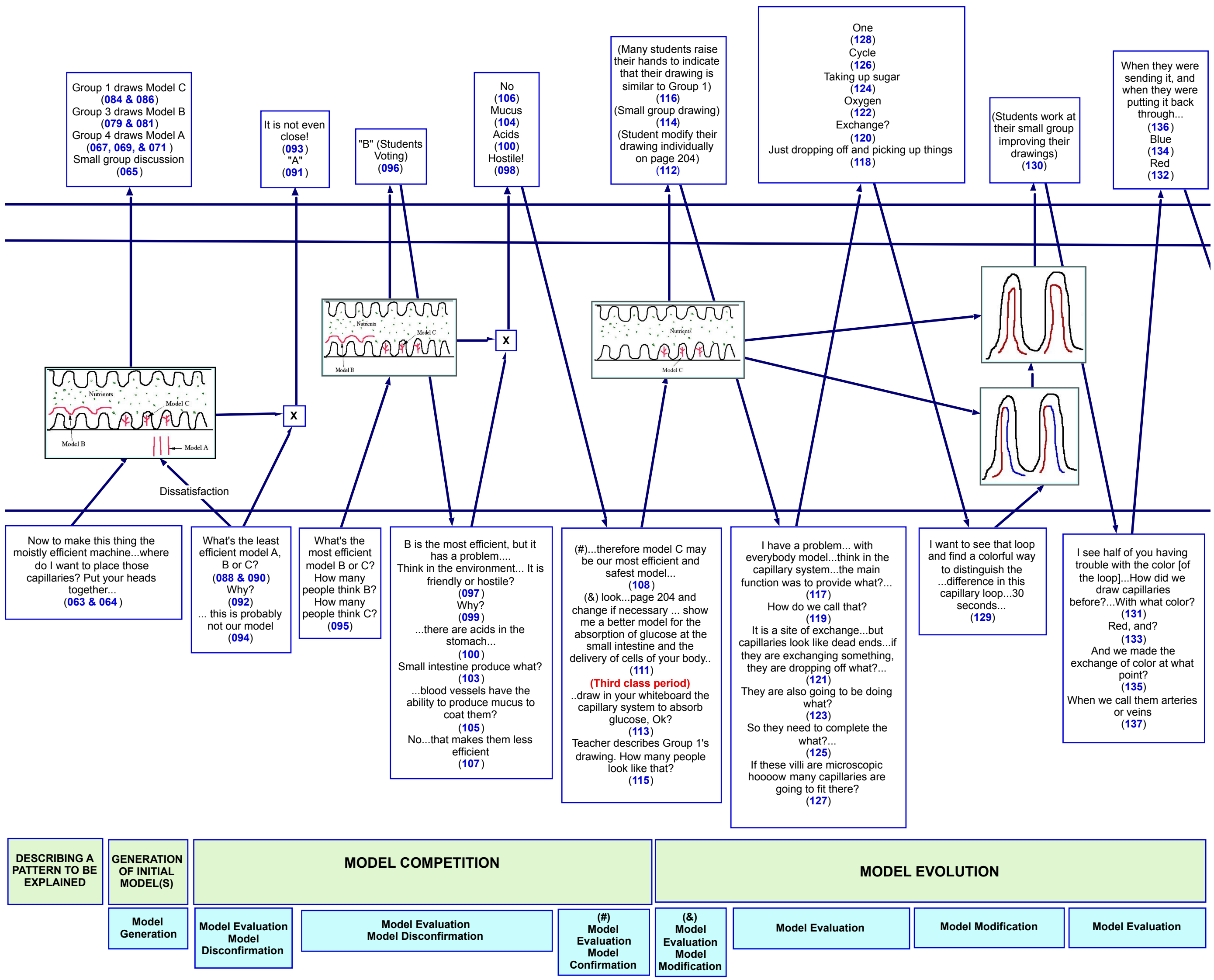


Figure 4. Classroom Dialogue Diagram, Second Part

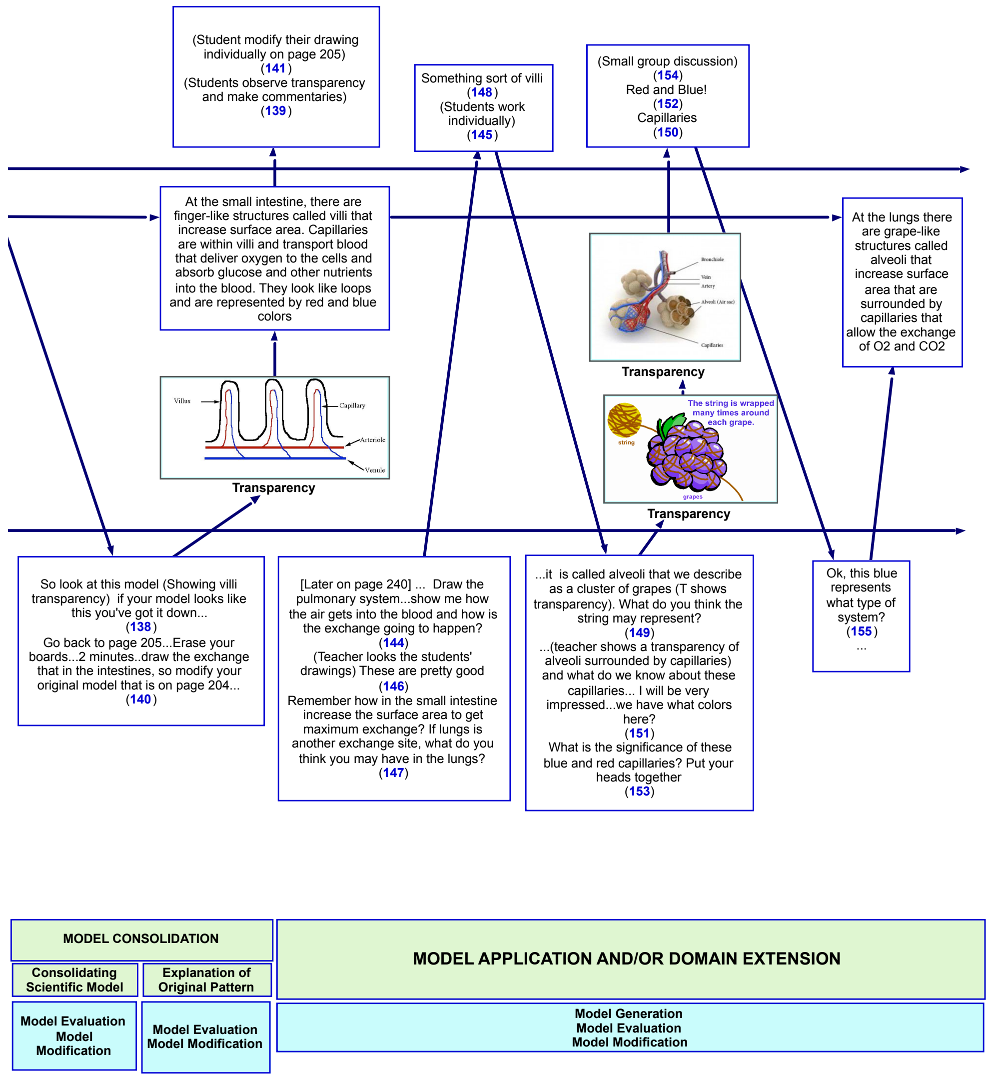


Figure 5. Classroom Dialogue Diagram, Third Part

Major Modeling Modes

Table 6 shows the Major Modeling Modes and their working descriptions that were identified in the transcript analysis. These modes are derived from studies in expert reasoning shown in **Error! Reference source not found.**Level 4, but we found two modes —Generation of Initial Models(s) Mode and Model Consolidation Mode— that were not observed in expert protocols.

Major Modeling Modes		**Description**
Describing a Pattern to be Explained Mode		Students make observations leading to a pattern to be explained. Or the teacher describes or asks the students a question ("How does the glucose gets out of the intestine and into the blood") about a pattern that needs to be explained. This might also be done through a demonstrations or film.
Generation of Initial Model(s) Mode*		To generate the explanatory model, the teacher supports the students in combining individual and small group work. After this the students report their ideas in large group. Students' ideas may include misconceptions, alternative conceptions, useful conceptions, and gaps.
Model Evolution Mode		The teacher focuses on one students' idea at the time and supports them in evaluating and modifying elements of the explanatory model. The process is repeated as many times as needed.
Model Competition Mode		The teacher focuses on two or more competing models and supports the students in reviewing and comparing them to decide on the model with the best explanation. This may include disconfirming one model at a time. The process is repeated as many times as needed leaving in place the most promising model.
Model Consolidation*	Consolidating Scientific Model	Once the students' explanatory model gets closer to the target model, the teacher helps make any final repairs, summarizes the scientific model.
	Comparison to Original Model	The teacher asks students to go back to their initial model and review and modify if necessary.
Model Application and Domain Extension		The teacher supports the students in applying their new model to another domain.
* These modes were not observed in the expert protocols but they appear to be important parts of the classroom modeling processes.		

Table 6. Major Modeling Modes

Model Construction Processes

Table 7 shows three Model Construction processes involved in GEM cycles (see **Error! Reference source not found.**Level 3) and their working definitions that were also identified in the transcript analysis. These processes are derived from studies about expert reasoning.

Model Construction Processes	Description
Model **G**eneration	In the ***Generation*** **(G)** the teacher or student statement either asks for or provides a theory, model, conception, or explanation. This can be done with varying degrees of speaker confidence in the correctness of the statement and can be done in either a declarative or interrogative manner. Examples of key phrases that help identify Model Generation strategies: What ideas do you have about…, what do you think is happening…, What explanation can you think of for…, I think that maybe what's going on is…., etc.
Model **E**valuation	In the ***Evaluation*** **(E)** phase of the GEM cycle the teacher or student statement refers to a theory, model, conception or explanation that has previously been or is currently under discussion. The statement either asks for or provides an evaluation, judgment, refutation, criticism, support, or endorsement of a particular explanatory model. Examples of phrases that help identify Model Evaluation strategies: Do you agree with …, That makes sense…, I also believe that…, Are you sure you can have…, Do you think that is the way…, etc.
Model **M**odification	In the ***Modification*** **(M)** phase the teacher or student statement either asks for or provides a suggested change, adjustment, or modification to a theory, explanation or addition or could introduce a completely revised model with little resemblance to the original. Sometimes the modification statement comes with little verbal evidence that an evaluation process has been underway as students often engage in this process internally. If the statement appears to make little or no reference to the previous model, it is instead considered to be in the Generation category above. Examples of phrases that help identify Model Modification strategies: Does anyone see it a different way…, Would anyone suggest changing…, Maybe if we explained it like this…, Could it be more along the lines of…, etc.

Table 7. Model Construction Processes (Williams & Clement 2015, p. 88-89)

Second Part: Transcript Analysis: Modeling Processes in the Classroom

In the next paragraphs we will examine three-lesson transcripts to provide examples of Major Modeling Modes (see Figure 1, Level 4) and Model Construction Processes (see Figure 1, Level 3).

DESCRIBING A PATTERN TO BE EXPLAINED MODE, First Episode

Describing a Pattern to be Explained Mode occurs when the teacher asks a question or calls the students' attention to a particular situation, pattern, phenomenon that requires an explanation. The situation may be an empirical observation pattern —a set of observations that exhibit a regularity— or a may be an explanatory model of a system that is accepted and calls for an underlying explanation or mechanism at a different level (see Table 6). Alternatively, the students make observations and uncover such a pattern in their observations. Next, we will describe the processes conducted by this teacher in developing this Describing a Pattern to be Explained Mode.

How the glucose goes into the blood at the small intestine?

The Describing a Pattern to Be Explained Mode began in the first lesson of this three-lesson cluster when the teacher asked the students to read an introductory paragraph in the student workbook that reminded them that glucose comes from food, and that it must get into the blood, and that this happens in the small intestine. The paragraph ended by asking the students:

> 001. (Students' workbook) How does it [glucose] get out of the intestines and into the blood and then to the cell…?

We interpret this as the *Pattern to be Explained* for this section (Line 001). The teacher paraphrased the workbook question (Line 002) by saying:

> 002. T: So you are going to draw the journey after digestion… to show how the glucose leaves the intestine and then go out to the cells…so we are looking for two sites. One how the glucose is passing through the intestine walls into the cell and two how the glucose leaves the blood to go to the cell…seven minutes.
> 003. S: (Students work individually on page 204 of their workbook)

The teacher asked the students to write and draw their ideas individually for about seven minutes in silence (Line 003). The first Pattern to be Explained in this case study is a small explanatory model of the circulatory system that calls for an underlying mechanism to understand glucose absorption at the small intestine (see Figure 3**Error! Reference source not found.**, lower part, left side of the Classroom Dialogue Diagram). This mode is also present in the Expert Modeling Practices Framework (see Figure 1, Level 4).

Summary of the Describing a Pattern to be Explained Mode

In summary, in the first episode of Describing a Pattern to be Explained Mode the teacher asked the students to explain: "How does it [glucose] get out of the intestines and into the blood and then to the cell?" The question was included in the EHBC student's workbook. This Mode is depicted in the very left side of Figure 3**Error! Reference source not found.**.

The role of Observations

In order to begin with a simpler case, we are discussing a lesson that does not involve new observations from a lab or from real life. It is interesting that the class could do a considerable amount of model construction without acquiring new observations. This is reflected in our definition of a Pattern to be Explained as not only encompassing empirical patterns, but also previously accepted models of internal functioning (in this case the fact that sugar moves from the intestines to the blood is the pattern to be explained.)

A different scenario that would involve observations is having the students generate models of the structure of the throat. This is a challenging task for middle school students that leads to a large assortment of models with various tubes going to stomach, lungs, or a single branch going to both or nowhere. Once students generate initial drawn models, different everyday observations can be used to evaluate the models. Examples include: Can you breathe through your nose alone? Can you breathe while swallowing? What happens when you choke? Medical records show that people can get lung diseases from ingesting food or other material into the lungs, etc. This type of information could be used to evaluate problematic or incomplete models of where tubes go from the throat and the position of the epiglottis. Some could also be used to motivate model construction. As shown in Figures 6 and 7 such empirical information can play an important role as exploratory Observations or Evaluatory Observations, as part of either the Model Evolution Model or Model Competition Mode.

GENERATION OF INITIAL MODEL(S) MODE, First Episode

The Generation of Initial Model(s) Mode happens when the students generate an explanatory model to answer the Pattern To Be Explained question. The teacher asked the students to share and compare their individual students' ideas within the small group to originate a team model that then is disclosed in whole group presentation (See Table 6).

Would you share your ideas and come up with a team model?

Once the students finished answering individually the Describing a Pattern to Be Explained question, the teacher supported them in creating a team model (Line 004). The teacher asked the students:

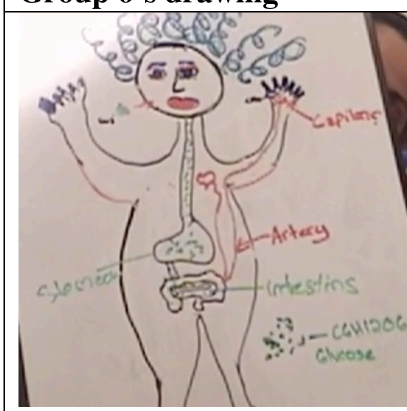
004. T: Ok, would you share your models with your teammates, would you…compare…and then I want you to…use the whiteboard…and see if you can come up with a team model, you have about seven minutes.
005. S: (Students work at their small group and come up with a team model)

The students shared and compared their individual ideas and then draw a team drawing on their whiteboard for about seven minutes (Line 005). While the students were drawing at their small group, the teacher walked around looking the team drawings. At the end of the seven-minutes period the teacher stopped the students' work (Line 006) and calling one of the groups to present their ideas. The teacher said:

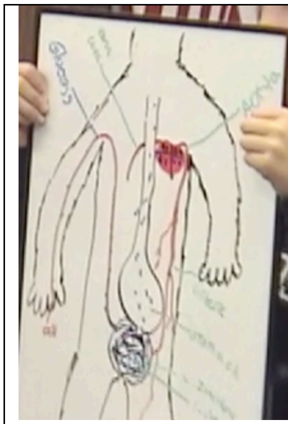
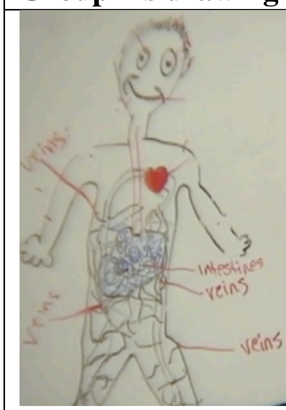
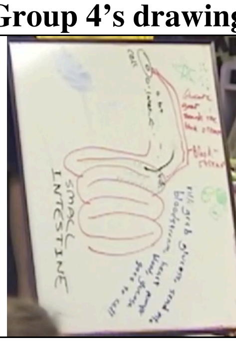
006. T: "Time up-- table 6."

The students from Group 6 (Line 007) placed their whiteboard in front of the class and shared their group ideas in large group. The students have experience in conducting this type of presentation and they listened to their classmates in silence. The teacher then called successively students from Group 3 (Line 009), Group 2 (Lines 011-016), and Group 4 (Lines 018-019) to present their ideas. After each presentation teacher and students tried to grasp the differences between group drawings. The teacher then asked the students not to erase the whiteboards to have them ready for the next class period (Line 019a). At the beginning of the second class period, the teacher asked Group 5 (Line 020) and Group 1 (Line 023) to present their ideas to their classmates. It is interesting to note that the teacher did not call the groups in order (1, 2, 3 and so on) to present their ideas. Instead we hypothesize that she first asked the groups whose models were farther from the target model to present and then asked the groups whose models are closer to the target model. Table 8 shows Screenshots of the groups' whiteboards along with the transcript of the group presentation.

As it can be seen on Table 8 and their transcripts none of the six groups of students had a full explanatory model of the transfer of glucose to the blood either at the small intestine or at the body cells. We consider that these group's drawings as well the as their descriptions are the students' open ended and divergent explanatory models that are the result of Generation of Initial Model(s) Mode (see Table 8).

Group 6's drawing	**Student's Description in large group**
	007. S: Ok, first the woman eats an apple and the apple goes down to the digestive system and then it goes into the intestine and the intestine use selective absorption that the villi get the glucose up. So the glucose goes up using an artery and then it mixes with the blood with the oxygen and all the other good stuff and then goes into the cell and it begins to branch out but this artery it is going to [inaudible] and then it branches out into small little capillaries and the cellular respiration occurs. (While the student was talking the drawing was facing the other groups and she was moving her hand on top of the drawing. After the presentation the group showed the drawing to the camera. The teacher did not provide any feedback about the group's presentation).

Group 3's drawing	**Student's Description in large group**

	008: T: table 3. 009. S: Ok, the person eats something and it goes down into the esophagus and into the stomach and it gets down into the small intestine and into the large intestine before [inaudible] and then the arteries from the small intestine and then it gets out all the glucose and minerals because there is where they are and minerals and other stuff and then glucose is carried through and then it branchs off and then all the glucose goes into the cell where cellular respiration starts. (While making the presentation, one of the the students was pointing to the drawing and the other was holding the drawing in front of the class).
Group 2's drawing	**Student's Description in large group**
	010. T: table 2. 011. S: Ok, first when you eat something and then it goes into your esophagus and then it goes into the intestine. 012. T: Ok so you have veins. That is the difference because you have capillaries and veins. 013. S: As the, villi absorb the glucose… (Inaudible)… It goes into the blood vessel and into the heart that pumps the blood into the lungs to get oxygen 014. T: Ok, I see actually one little difference in this model is that the glucose goes back where first? 015. S: To the heart. 016. T: We have two models it goes to the heart and then pumps from the heart to the rest of the body. Thanks, table 4 please.
Group 4's drawing	**Student's Description in large group**
	017. T: table 4. 018. S: Actually the glucose start in the small intestine and the villi and it grab it and sucks it (inaudible) it goes into the bloodstream by osmosis and then it diffuses into the cell through the cell membrane. 019. T: Ok. They added another dimension that is the villi in the small intestine. 019a. T: You don't erase these pictures.

Group 5's drawing	**Student's Description in large group**

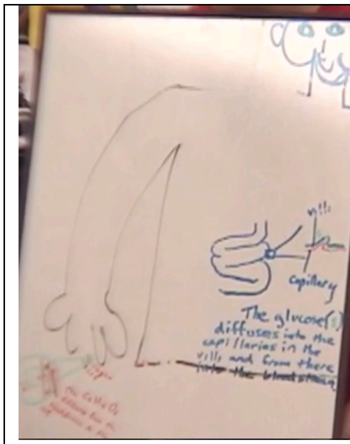
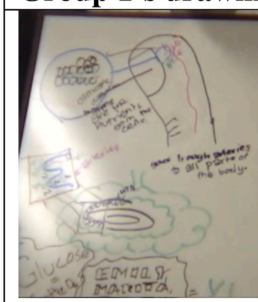
	020. T: table 5. 021. S: Once the glucose gets to the small intestine is [somebody talks in the back] it is absorbed by the villi [S points the villi label with her right index finger to a drawing that contains two curvy blue and red lines] passing through the um the villi [S points to the red line of the previously described drawing] into the capillaries. And the bloodstream [hand circular motion over the drawing] carries it to the cells of the fingers [points to the fingers drawn on the board] and um and once there the glucose leaves the capillaries in the finger [hand movement not on the drawing but pointing to the drawing] and goes into the cells um back to the cell by semipermeable membrane, oh it diffuses into the cell and into the villi.
Group 1's drawing	**Student's Description in large group**
	022. T: table 1. 023. S: We said that when the food gets to the small intestine by the villi and then it went out to the arteries and it was carried to the fingers and the capillaries and there are sources for diffusion happen into the cell where cellular respiration could be possible and we knew that the arteries because um it could have glucose in it and there is a vein [inaudible].

Table 8. Students' Initial Models Group 6, 3, 2, 4, 5, and 1

We interpret this episode by saying that the teacher conducted the Generation of Initial Models Mode (see Table 6) and the Model Generation phase of a Model Construction Process (see Figure 1, Level 3; also see Table 7). In doing this, the teacher skillfully combined individual, small group, and large group work to support the students in generating their initial explanatory models for the pattern to be explained question. Moreover, the teacher asked the students to draw their ideas either in their workbook or in their whiteboards. The creative individual and small group work described so far is represented by only a small space at the very left side of Figure 3, although the class spent a full 35 minutes on it. During this time the teacher encouraged the students to think creatively and come up with their own ideas, and she exerted very little influence on what those ideas were (see Figure 3, lower part, left side of the Classroom Dialogue Diagram). Although, the Generation of Initial Model(s) Mode was not included in the Expert Modeling Practices Framework (see Figure 1, Level 4) we consider that it plays an important role in the classroom modeling processes and we incorporated this mode in the Classroom Modeling Practices Framework (see Figure 6). In addition, we suggest that this mode is the result of the Generation phase of the Model Construction Process (See Figure 1, Level 3).

On the other hand, this study mostly focuses on examining large group discussions. We have found that current literature (Chin, 2006a, 2006b; McNeill & Diane, 2010) often does not interpret teacher-student dialogue in terms of the learner's construction and revision of mental models. As a consequence, we still lack: (1) a clear set of mechanisms to explain how students build mental models about a target; (2) a clear understanding about how a teacher deals with multiple alternative conceptions that arise in large group discussions, and (3) knowledge of how to connect teacher-students interactions with the construction of model mental models.

Summary of the Generation of Initial Model(s) Mode

In summary, in the Generation of Initial Model(s) Mode (Figure 3, lower part, left side of the Classroom Dialogue Diagram and Table 6) the teacher supported the students in giving their first models for the pattern to be explained question. The teacher asked the students to share and compare their individual's ideas and drawings to generate a group explanatory model. We interpret this process by saying that the teacher fostered the Model Generation phase of a Model Construction Process (see Figure 1, Level 3; and Table 7). Although this mode is not shown in Figure 1, Level 4 we think that it is an important step in the modeling processes observed in the classroom and so we will add it to our final Framework on Figure 6.

MODEL EVOLUTION MODE, First Episode

After each group of students generated their initial drawings the teacher and the students might have realized that none of the groups had an explanatory model of the pattern to be explained question. So the teacher supported the students in repairing four students' ideas by conducting the first episode of the Model Evolution Mode (see Figure 1, Level 4). The Evolution Mode refers to the process in which the teacher supports the students in going through one or more rounds of modifications of the initial idea. The modification processes may include additions, replacements, repairs, and refinements of one or more elements of the model. We label each section included in the Model Evolution Mode by using the questions asked by teacher to originate each of the repairs of the students' models (see Table 6).

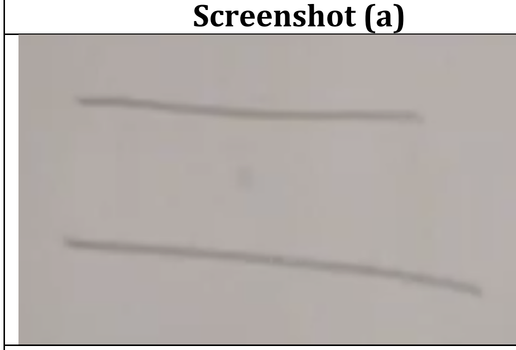
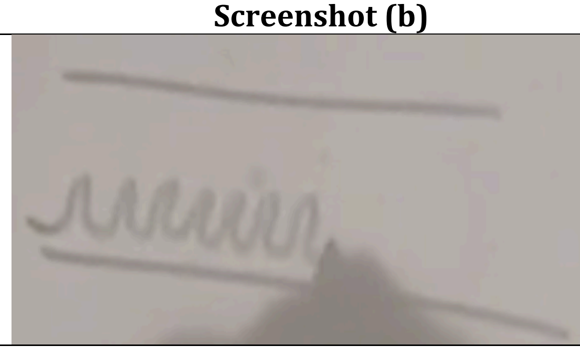
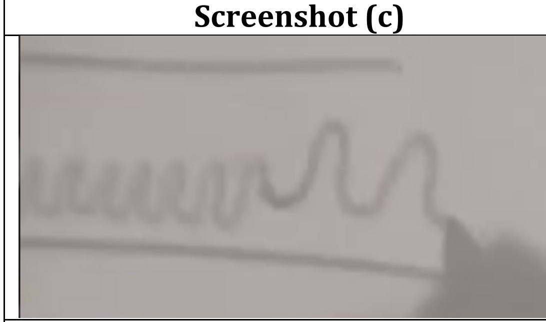
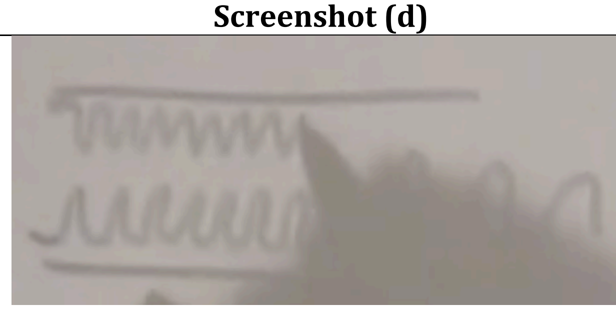
Villi are what?

After the students displayed their drawings, the teacher said that each of the groups had added a new dimension and they are going to think about this model by focusing on a very small segment of the small intestine. In addition, the teacher placed an overhead on top of the overhead projector (Line 024). She said:

> 024. T: … each one of these models has added a new dimension. So let's just take a moment and think about … this model... you only need to give me a small, small segment of the small intestine and that is what I am gonna do right here (teacher puts an overhead on top of the projector)…

The teacher asked the students "what is the small intestine?" (Line 025) and asked "what the small intestine has?" (Line 027) and the students said that the small intestine is a tube (Line 026) and that it has villi (Line 028). The teacher then asked the students "Villi are what?" (Line 029) and a student said, "They are like hands that grab nutrients" (Line 030). The teacher questioned the word "hand" used by the students to describe villi (Line 031) and she said it was a good analogy but that they going to make their ideas a little bit more scientific (Line 033). A student contributed with the idea that villi look like fingers (Line 034). While conducting these interactions, the teacher drew on the overhead two lines (Line 027; Screenshot "a") representing the walls of the intestine and then added finger like structures inside and some of them were enlarged to provide space the students to draw their ideas (Line 035 and Line 037; Screenshots "b;" "c;" "d;" and "e"). They said:

025. T: … I am going to think that the small intestine is really just a what?
026. Ss: Tube
027. T: A tube. And within this tube (teacher draws two horizontal lines separated by one inch. See Table 9, Screenshot (a)) have a what?
028. S: Villi
029. T: Villi and villi are what?
030. S: Hands that grab this stuff at the small intestine.
031. T: Oh, well, it is like a hand?
032. S: Not really.
033. T: Let's see if we can, that is a good analogy but let's see if we can be a little more scientific.
034. S: Fingers [Inaudible]
035. T: Ok, these are like this little fingers like projections (T draws finger like projections on the internal part of the tube on the lower line. See Table 9, Screenshot (b)) and are they big?
036. Ss: No.
037. T: No, in fact they are very, very tinny… (Teacher draws fingers like structures inside of the two lines. See Table 9, Screenshots (c), (d), and (e)) …

Screenshot (a)	**Screenshot (b)**
	
Screenshot (c)	**Screenshot (d)**
	
Screenshot (e)	**Screenshot (f)**

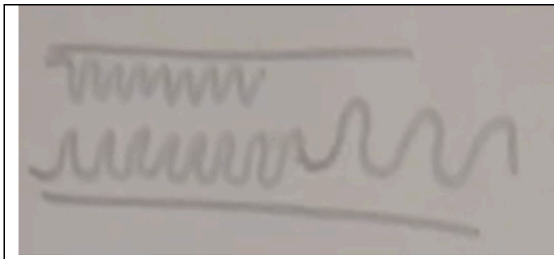
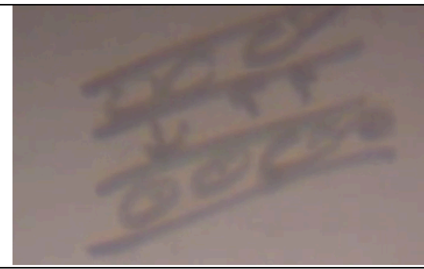



Table 9. Screenshots a, b, c, d, e, and f

We explain this episode by saying that the teacher asked a question (villi are what?) that led a student to generate a small explanatory model (villi are "Hands that grab stuff in the intestine"), that led the teacher to evaluate it (It is like a hand?...is a good analogy), that led to a student and the teacher modifying ("Ok, these are like this little fingers like projections") the initial idea. Table 9 shows the sequence of screenshots taken from the actual video that depicts the teacher's drawing on the overhead projector.

We interpret this episode by saying that the teacher conducted the Model Generation phase, the Model Evaluation phase, and the Model Modification phase of a Model Construction Process (see Figure 1**Error! Reference source not found.**, Level 3; see Table 7) to modify the student's initial idea. These three phases are also collectively known as GEM Processes (see**Error! Reference source not found.** Figure 3, lower middle part, of the Classroom Dialogue Diagram).

What is the purpose of villi?

The teacher then asked the students about the "purpose of the villi" (Line 038) and one of them said that they "just grab the little bits of glucose like fingers" (Line 039) and the teacher challenged the word "grab" by comparing it with a "mouth scooping stuff in" (Line 040) and a student said "no" and concluded that villi were a site "to absorb substances" (Line 041). They said:

038. T: What is that sole purpose of villi?
039. S: Just grab the little bits of glucose like fingers?
040. T: Ok, so let's see if we can rephrase that in a different way. First of all we don't want to use the word grab because they are not, are they scooping the stuff in like a mouth?
041. S: No. They are absorbing this (glucose).
042. T: They are absorbing this…

We explain this episode by saying that the teacher first asked a question (what is the purpose of villi) and a student generated an explanatory model (the purpose of villi is to grab the little bits of glucose like fingers?). This led the teacher to evaluate (First of all we don't want to use the word grab… are they scooping the stuff in like a mouth?) and that led to a student and the teacher to modify their explanation (They are absorbing these nutrients).

We interpret this episode by saying that the teacher conducted the Model Generation phase, the Model Evaluation phase, and the Model Modification phase of a

Model Construction GEM Cycle Process (**Error! Reference source not found.**see Figure 1, Level 3; see Table 7) to modify the student's initial idea (**Error! Reference source not found.**see Figure 3 lower middle part, of the Classroom Dialogue Diagram).

What is the advantage of having these villi? Episode 1

Even though the students appear to have reached the idea that the villi's role is absorbing nutrients, the teacher went further and wanted the students to examine the *advantage* of having the small intestine have this design (fingers like structures called villi) (Line 043). She drew on the upper part of the overhead a small portion of the small intestine without villi (See Table 9, Screenshot (f)). She asked the students come up with ideas in small group to compare drawings of small intestine with villi and without villi (See Table 9, Screenshot (e) and (f)). After a couple of minutes the teacher called group 3 to report their ideas (Line 045). A student suggested that "villi may act like filters" (Line 046) but teacher asked the students "what are villi made of?" (Line 047) and the students said "Cells" (Line 048). The teacher told the students that because "villi are made of cells" and "each cell has a cell membrane" so "she was not sure how villi are going to act as filters" (Line 049). They then discussed that the small intestine is made of cell and that cells have semipermeable membrane that might act as sort of a filter (Line 051). They said:

043. T: …What is the advantage of having these [villi]?... (The teacher draws a tube without villi showing cells inside. See Table 9, Screenshot (f)) put your heads together and see if you can came up with an advantage of this (design).
044. S: (Small group discussion for about 30 seconds)
045. T: All right …table 3.
046. S: …maybe there is a kind of filter and it is just the semipermeable membrane for the cell that let out some stuff that they did not want to, the villi get the glucose and the vitamins and other stuff in?
047. T: So you told me that the villi are made of what?
048. Ss: Cells
049. T: …if they [villi] are made of cells and each cell is made of semipermeable membrane then I am not sure how they are going to act like a filter, and that is a good idea, isn't?... It is very creative… villi have cells and... what is the inherent filter in the cells...?
050. S: The membrane.
051. T: The membrane….this semipermeable membrane might act like a filter.

We describe this episode by saying that the teacher asked a question (What is the advantage of having this [villi]?) and a group of students generated an explanatory model (maybe there is a kind of filter and it is just the semipermeable membrane for the cell) that led the teacher to evaluate (I am not sure **how** they are going to act like a filter, and that is a good idea, isn't?-- It is very creative...) that led to a student and the teacher to modify their explanation (Villi cells have semipermeable membrane that might act as a filter).

We interpret this episode by saying that the teacher conducted the Model Generation phase, the Model Evaluation phase, and the Model Modification phase of a Model Construction Process (see Figure 1, Level 3; see Table 7) to modify the student's initial idea (see also Figure 3, lower middle part of the Classroom Dialogue Diagram).

What is the advantage of having these villi? Episode 2

The teacher repeated the question "What is the advantage of having these villi?" (Line 052) and called students from Group 6 to answer the question. The student said that villi maybe give "more space" to absorb glucose (Line 054). Teacher asked the students to remember something that they had discussed earlier in the curriculum: "if the small intestine is stretched out it will reach the size of a tennis court" (Lines 055-Lines 058). They then discussed about the importance of having a large "surface area for nutrient absorption at the small intestine" (Lines 058-062). They said:

052. T: What is the advantage of having this [villi]?... table 6.
053. S: When it is bumpy there is like more spaces that can absorb the glucose?
054. T: Ok, lets talk about this. When we talked about small intestine I gave you a … fact about villi, does anybody remember what that fact was?
055. S: That we can stretch it out…
056. T: If we can stretch this out (teacher extends together her arms in front of the body and opens them out as she is talking about stretching the small intestine out] so that this villi (teacher repeats the movement of opening her extended arms) are all now flat, the surface area that we recover would be the size of a
057. Ss: Tennis court.
058. T: Tennis court [teacher keeps her arms open]... So [name of student] said that by having these villi we are increasing the what?
059. S: The surface area.
060. T: The surface area so that means that these nutrients would be absorbed all along the surface of this little villi. So I am going to put all these little dots here showing that all these nutrients can be possibly absorbed through (Teacher draws little dots on top of villi and compares the surface area for absorption in both drawings. In addition, she moves her finger on top of the villi following each of them to illustrate all the surface area available for absorption. See Table 10, Screenshot (g)) all these indentations. So by increasing the surface area, I am increasing the amount of what?
061. S: The amount that is absorbed here.
062. T: This means that these nutrients (represented like little green dots) can be absorbed all of the surface of these little villi.

We explain this episode by saying that the teacher asked a question (What is the advantage of having this [villi]?) and a group of students generated an explanatory model (more spaces to absorb glucose) that led the teacher and the students to evaluate (if small intestine is stretched it would the size of a tennis court) that led to a student to modify their explanation (villi increase the surface area for absorbing nutrients).

We interpret this episode by saying that the teacher fostered the Model Generation phase, the Model Evaluation phase, and the Model Modification phase of a

Model Construction Process (see Figure 1, Level 3; see Table 7) to modify the student's initial idea (see Figure 3, lower middle part of the Classroom Dialogue Diagram.

Summary of the Model Evolution Mode, First Episode

In summary, within the first episode of the Model Evolution Mode (see Figure 1, Level 4; see Table 6) the teacher supported the students in conducting four episodes of the Model Construction Process (see Figure 1, Level 3; see Table 7). Through each of these episodes the students generated, reviewed, and modified four intermediate small explanatory models: (1) "villi are hands that grab stuff…"; (2) "villi grab glucose like fingers…"; (3) "villi are like filters…"; and (4) "villi provide spaces to absorb glucose…". These four Model Construction Processes are shown on the lower part of Figure 3, under the Model Evolution Mode. It is interesting to note that most of the generation of ideas was done by the students and that most of the evaluation of ideas was done by the teacher. On the other hand, the modification of the students' ideas was conducted by both. Another emerging pattern in this unit is that model generation mostly takes place at the individual or small group level while the evaluation most of the time happens at the large group level (see Figure 3 of the Classroom Dialogue Diagram).

DESCRIBING A PATTERN TO BE EXPLAINED MODE, Second Episode

Where to locate capillaries to make villi an efficient absorbing machine?

The second episode of Describing a Pattern to Be Explained Mode is discussed next. After the teacher supported the idea that villi are finger like structures included in the small intestine and that they have the function of absorbing nutrients, the teacher asked the students "where the capillaries should be placed to absorb nutrients to make villi an efficient machine?" (Line 063). She asked the students to think in their small groups before providing an answer. She said:

063. T: Now to make this thing a mostly efficient machine and you told me that these capillaries that it is going to be absorbed into, where do I want to place those capillaries?…

We interpret this as *Describing a Pattern to be Explained* for this section (see Table 6). The teacher asked the students to come up with an explanatory model in the form of an underlying mechanism to understand glucose absorption at the small intestine.

GENERATION OF INITIAL MODEL(S) MODE, Second Episode

The second episode of the Generation of Initial Model(s) Mode (see Table 6) happens when the students generate an explanatory model to answer the Pattern To Be Explained question. In order to do this, the teacher asked the students to think in their small groups where to put capillaries with respect to villi.

Where did you place capillaries in respect of villi?

The teacher asked the students to report the group ideas to the whole class by drawing on the enlarged villi drawn on the overhead that was on top of the projector. Students drawing are shown through the Screenshots shown in Table 10. Group 3 generated Model A (Lines 066-071). Group 3 generated Model B (Lines 078-082). Group 1 generated Model C (Lines 083-086). They said:

064. T: Put your heads together…
065. S: [Small group discussion]
066. T: Gabe (table 4)
067. S: [Inaudible]
068. T: Tell me what do you mean by that? Come here and show me.
069. S: (The student walks toward the overhead projector)
070. T: Draw in the enlarged part of the drawing. (The teacher turns to the other side the transparency)
071. S: (The student draws three vertical lines close to the enlarged villi on the wall of the small intestine outline. See Table 10, Screenshot (h))
072. T: Does anybody have a different model?
073. S: [No answer]
074. T: table 6, do you have a different model?
075. S: No, we have the same model.
076. T: table 2, do you have a different model?
077. S: [Inaudible]
078. T: table 3.
079. S: … they are on the tip (student waves her hand)
080. T: (T touches her hair) Ok, so yours is going on this side? (Teacher points to the tips of villi drawn on the overhead)
081. S: Yeah.
082. T: (Teacher draws a red line on top of villi. See Table 10, Screenshot (i))
083. T: table 1. Somebody come up if yours is different. (Teacher walks away from the overhead projector)
084. S: Yeap. (A student walks toward the overhead projector and draws capillaries inside of villi. See Table 10, Screenshot (j)).
085. T: Ok, draw me another one.
086. S: (The student drew another capillary inside of villi. See Table 10, Screenshot (j))
087. T: Ok, let's look at this.

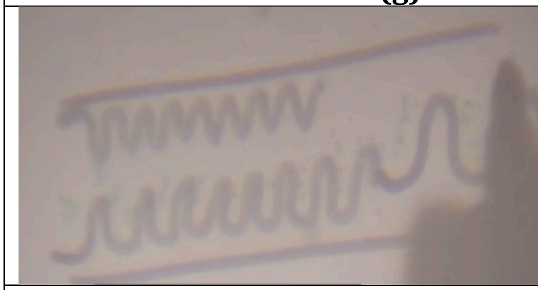
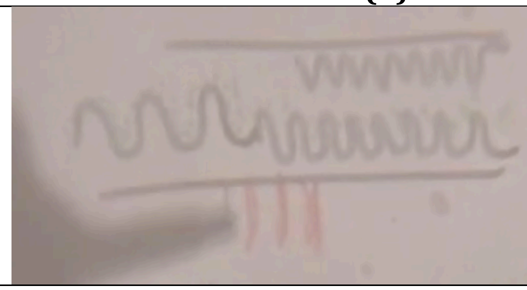
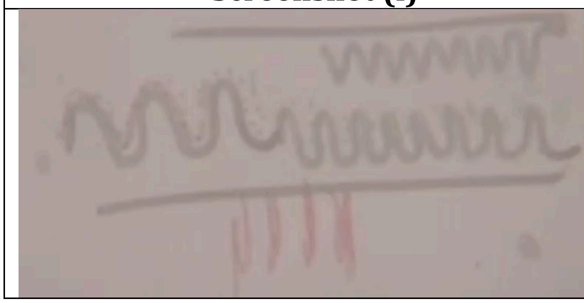
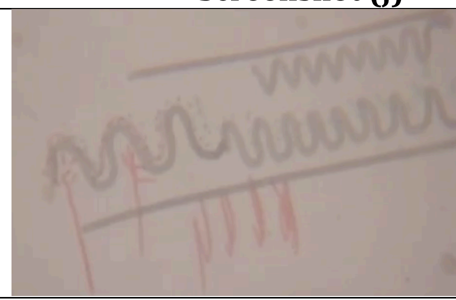
Screenshot (g)	Screenshot (h)
	
Screenshot (i)	**Screenshot (j)**
	

Table 10. Screenshots g, h, i, and j

Note that the three different student models appear on the same drawing. We explain this episode by saying that the students generated three different explanatory models to locate the capillaries with respect to villi: (1) outside of the intestine (Model A, Screenshot (h)); (2) on top of villi (Model B, Screenshot (i)); and (3) within villi (Model C, Screenshot (j)). Two of these places (Model A and Model B) were incorrect and the third one (Model C) was somewhat correct. We interpret this episode by saying that the teacher fostered the Model Generation phase of a Model Construction Process (see Figure 1, Level 3; see Table 7).

Summary of Generation of Initial Model(s) Mode, Second Episode

In summary, in the second episode of the Generation of Initial Model(s) Mode (see Table 6) the teacher supported the students in answering the pattern to be explained question: “Where to place the capillaries to make villi a more efficient absorbing machine?” (Line 055) The teacher asked the students to come up with an idea in their small group and draw them on the overhead. This mode appears to be an important step in the modeling processes observed in the classroom (see Figure 3 and 4, lower left side part of the Classroom Dialogue Diagram). Therefore we have added it to our final framework as shown in Figure 6.

MODEL COMPETITION MODE

In this section, we will examine the process conducted by this teacher to foster in the students the disconfirmation of Models A and B and the confirmation of Model C as the most promising by conducting an episode of the Model Competition Mode (see Figure 1, Level 4; see Table 6). (The teacher did not write down a label to name the students’ drawings as Model A, Model B, and Model C shown in the screenshots. But the teacher used these names and we keep them in the drawings depicted in the middle row of Figure 4 in the coming descriptions.}

As result of the teacher's question (Line 063), the students displayed three competing ideas (Model A, Model B, and Model C) and the teacher utilized a Model Competition Mode. This mode takes place when competing models are under attention and the teacher supports the students in comparing those ideas and evaluating each of them. This may lead to one idea becoming dominant. The spirit of Model Competition Mode focuses on model comparisons, and making choices based on discussions rather than an atmosphere of "competing for a prize." During the Competition Mode, the students may express their evaluation publicly by voting. Thus, in the Competition Mode, the students are participating in the evaluation process shown as a subprocess of Competition in Figure 1 and 4 (see also Tables 6 and 7). We will describe now how the teacher conducted these modes.

What is the least efficient, Model A, Model B or Model C?

The teacher focused on the competing Models A, B and C that show respectively capillaries outside of the villi (Model A), on top of the villi (Model B), and inside the villi (Model C) (See Table 10, Screenshots (h), (i), and (j)). In this episode, the teacher supported the students in examining these three models and to disconfirm Model A from further consideration. The teacher asked the students whether "Model A, Model B or Model C was the least efficient to absorb nutrients" (Line 088 and Line 089) and the students said "Model" A (Line 091) and the teacher then asked "why Model A is the least efficient" (Line (092) and a students said because "it is not even close" (Line 093). The teacher acknowledged the students answer by saying, "probably is not our model" (Line 094). They said:

088. T: … What would be the most efficient one, this model (A) (See Table 10, Screenshot (h)), this model (B) (See Table 10, Screenshot (i)) or this model (C) (See Table 10, Screenshot (j))?
089. S: Well.
090. T: Well, let's do the least efficient A, B, or C? The least efficient, (student's name)?
091. S: A.
092. T: A. Why do you think is the least efficient?
093. S: It is not even close!
094. T: This is the farthest distance that our nutrients would have to travel and we know that our body is pretty efficient so this probably is not our model…

The explain this episode by saying that the teacher's question led the students to evaluate that Model A was the least efficient because "it is not even close." This evaluation led the teacher and the students to disconfirm Model A from further consideration by saying "nutrients would have to travel and probably is not our model" (see Figure 4, lower right side).

We interpret this episode by saying that the teacher fostered the Evaluation of a model as part of the Competition Mode (see Figure 1, Level 3 and Level 4) by asking the students to think in the "least efficient" location of the capillaries to absorb nutrients in the small intestine (See Table 10, Screenshots (h), (i), and (j). See also Figure 4, lower left side of the Classroom Dialogue Diagram).

What is the most efficient, Model B or Model C?

The teacher then focused on the competing models that show capillaries on top of the villi (Model B) and inside the villi (Model C) respectively (See Table 10, Screenshots (i), and (j)). The teacher supported the students in examining these two models and disconfirming Model B from further consideration. The teacher asked the students whether Model B or Model C was the "most efficient" (Lines 095) for absorbing nutrients. Students voted that Model B was the most efficient (Lines 096). But the teacher helped the students to disconfirm Model B by asking to think whether the environment where these capillaries were located is friendly or hostile (Line 097). The students said that the environment is hostile (Line 098). The teacher then asked the students why the environment where these capillaries are located is hostile (Line 099). The students mention the presence of acids that may damage the capillaries (Line 100-102) and the teacher and the students discuss that the small intestine have a mucus coating on its walls. They then discussed that they have not learned that capillaries have coat of mucus to prevent further damage (Lines 103-106). At the end, the teacher concluded that in the long run acids with a lack of mucus might damage the little capillaries on top of villi (Line 107). They said:

095. T: Okay, what about B or C? … What might be the most efficient B or C? How many of you think B? How many people think C?
096. S: (Students raise their hands)
097. T: You chose B because it is the most efficient! But there is one problem with this model ("B"). What may be the problem with this model? … You can't get any closer than this; you'd be right on the outside of the villi…. Think about the environment in which you are finding these capillaries. It is friendly or hostile?
098. Ss: Hostile!
099. T: It may be hostile, why?
100. S: Acids.
101. T: … Even though the acid is in the stomach, you're having a neutralization of acid here. And so what might happen with these little tiny blood vessels?
102. S: They bite like your walls or something.
103. T: They might not react well in that environment because the walls of the blood vessels are a little different than the walls of the intestines… They are made to withstand and they also have another advantage, they also produce what?
104. S: Mucus.
105. T: Mucus! So they have a coating and have we talked about blood vessels having this ability to produce mucus to coat them?
106. Students: No.
107. T: No, in fact that's not efficient, it makes them less efficient. So even though this group has the model that would be the most efficient, in the long run it might damage these tiny, tiny, tiny, hair-like, hair-size blood vessels, and….

We explain this episode by saying that the teacher's question (What's the most efficient, Model B or C?) led the students to evaluate model B as the most efficient place to locate capillaries respect to villi to absorb nutrients. But this idea led the teacher to evaluate whether Model B was the most appropriate place to locate a little tiny capillary by asking the students to think in the environment where these little capillaries are going to be located (She says, "It is friendly or hostile?"). This question led the students to evaluate that the environment is hostile and the teacher conducted a class discussion that led the students to disconfirm Model B from further consideration (see Figure 4, lower right side). We interpret this episode by saying that the teacher conducted the Model Evaluation phase within the Model Competition Mode (see Figure 1, Level 3 and Level 4; see Figure 4, middle part of the Classroom Dialogue Diagram).

Why Model C is the best model?

At the end, the teacher and the students concluded that Model C would be the more efficient and safest place to locate capillaries for efficiently absorb nutrients at the small intestine. She said:

108. T: …probably this (Model C) is the most efficient and safest model

We interpret this episode by saying that they conducted a Model Evaluation and disconfirmation process that led the teacher and the students to confirm Model C as the best place to locate tiny capillaries respect to villi (see Figure 4, lower middle part of the Classroom Dialogue Diagram).

Summary of the Model Competition Mode

In summary, within Model Competition Mode (see Figure 1, Level 4) the teacher supported the students in examining three competing models of the location of the capillaries with respect to villi to make them a very efficient absorbing machine: (1) capillaries are located outside of villi (Model A); (2) capillaries are located on top of villi (Model B); and capillaries are located inside of villi (Model C). The teacher supported the students in evaluating and disconfirming Models A and B. They also evaluated and confirmed Model C. The teacher supported the student in conducting these processes by fostering the Model Evaluation phase, the Model Disconfirmation phase, and the Model Confirmation phase of the Model Competition Mode (see Figure 1, Level 3). It is interesting to note that the teacher and the students collaborate in evaluating, and modifying ideas both in the small group or in large group discussions (see, Figure 3 lower right side and Figure 4, lower right side of the Classroom Dialogue Diagram). As shown in Figure 6 we can summarize steps in the Model Competition Mode as:

1. Evaluate Each Model Individually for Strengths, Weaknesses
2. Disconfirm Non-viable Models
3. Assess Which Remaining Model is Strongest and Has Best Explanation

In this case the last step was not needed because there was only one model remaining. Figure 6 also shows two new modes at Level 4 that go beyond the expert framework we started from in Figure 1: Generation of the Initial Model(s) and Model Consolidation.

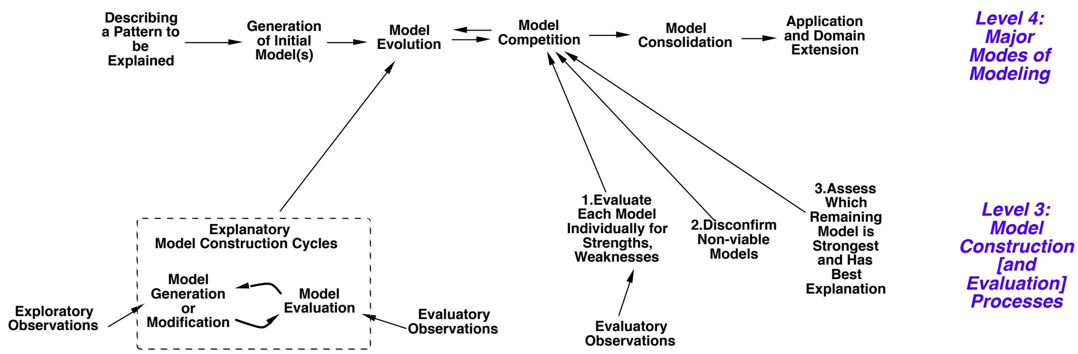


Figure 6. Final Modeling Practices Framework

Figure 6 shows two nested levels of processes. Each process also identifies a corresponding teaching strategy of scaffolding that particular process.

MODEL EVOLUTION MODE, Second Episode

After the teacher and the students confirmed that Model C was the best place to locate capillaries with respect to villi, the teacher supported the students in comparing their current ideas with their initial ideas. To do this, the teacher asked the students to go back to page 204 of the workbook, review it and change if necessary. That episode marked the end of the second lesson of this three-lessons cluster. At the beginning of the third lesson (see Figure 5 of the Classroom Dialogue Diagram), the teacher engaged the students in an extended discussion about nutrients and how they get absorbed in the villi of the small intestine. The teacher then asked the students to draw a team model about nutrient absorption that they had learned during the second lesson. While inspecting the whiteboards, the teacher realized that all the students had placed the capillaries at the right place —within villi— but the capillaries had a wrong shape and that the students did not draw the capillaries by using conventional red and blue colors. So the teacher supported the students in repairing two students' ideas: (1) initial students' ideas drawn on page 204; (2) shape and color of the capillaries by conducting the second episode of the Model Evolution Mode (see Figure 1, Level 4; see Table 6).

Could you show me the best model for absorbing nutrients?

After the teacher and the students concluded that model C would be the best place to locate capillaries at the villi of the small intestine, the teacher asked the students whether this idea makes sense and asked them to review individually their initial ideas drawn on page 204 (Lines 111-112) of the student workbook. They said:

109. T: Now, does this make sense?
110. S: Uh huh.
111. T: Ok, I want you look at your … own personal models in page 204 if you feel that you need to change it and … you don't have to draw the all system … please show me a better model for the absorption for the small intestine and additionally show me just me the delivery of the cells of your body
112. S: (Students look page 204 and draw and write on page 205 of the workbook)

We interpret this episode by saying that the teacher conducted the Model Evaluation phase and the Model Modification phase of a Model Construction Process (see Figure 1, Level 3). The teacher asked the students to evaluate their initial ideas drawn and written on page 204 and modify them if necessary. Notice that the teacher did not rely on simply having confirmed the correct model herself in front of the class--she asked them to repair their own models as a form of active, visual learning. This episode took place at the end of the second day of this three-lessons cluster and the teacher did not have time to review the students' drawings (see Figure 4 right side of the Classroom Dialogue Diagram).

Is there a single red pine-tree shape capillary within a villi?

At the beginning of the third lesson, the teacher conducted in large group discussion a review of what they had been studying. She then asked the students to come up with a team drawing to illustrate the capillaries within villi at the small intestine (Line 113-114)). The teacher then asked the students to raise their drawings to show them to each other group. The teacher examined and described aloud Table 1's drawing (see Figure 7). As it can be seen in the figure, the capillaries where correctly located within each villi but they look like a single red pine-tree. The teacher asked how many students have drawn something similar and it is observed in the video students raising their hands (Line 115-116). They said:

113. T: …so what I want you to do now is start here, this is a review draw in your whiteboards the capillary system…able to absorb… glucose, ok?
114. S: (Small group work. Sound goes to table 6)
115. T: Ok…I will ask you to hold your --- your models, quick, quick, quick (Teacher gives instructions)… I am gonna do this quick. So (Teacher describes Group 1's drawing. See Figure 7) they have capillaries coming up and they have a blood system here and they have capillaries coming up, how many people look like that? How many people look like that? How many people look like that?
116: S: (Many Students raise their hands to indicate that their drawings are similar to table 1)

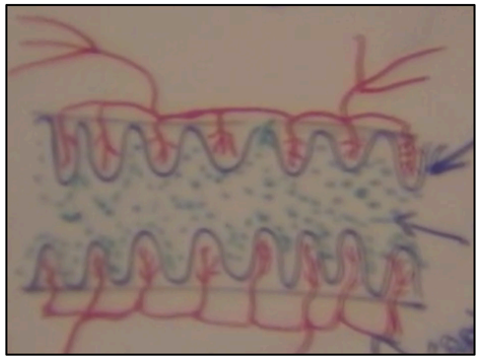


Figure 7. Single Red Pine-tree Shape Capillary Within Villi

We interpret this episode by saying that the teacher conducted the Evaluation phase of a Model Construction Process (see Figure 1, Level 3) that allowed her to realize that the students had placed capillaries in the correct place but they had the wrong shape (capillaries looked like single red pine-trees). In addition, they were not represented with the conventional colors (red and blue). The teacher supported the students in modifying these ideas in the students' models by fostering the second episode of the Model Evolution Mode (see Figure 4, lower right side of the Classroom Dialogue Diagram).

Where is the loop of the capillary?

After the teacher realized that the students had drawn capillaries that looked like single red-pine trees, the teacher told the students that she has problem with that drawing (Line 117) and questioned the shape and color of the capillary inside of the villi. They also discussed the role of capillaries in delivering oxygen and picking up sugar at the small intestine (Lines 118-125) and that there is a single capillary within the villi and it has to complete the cycle (Lines 125-130). They said:

117. T: I have a problem with everybody model…I want you to think …in the capillary system and when we were doing the circulation we said capillaries main function was to provide what?
118. S: Just dropping off and picking up things.
119. T: Yeah, how do we call that?
120. S: Um, exchange?
121. T: Exchange, it is a site of exchange… If they (capillaries) are exchanging something your models look to me as if they are dead ends. And that is not how we have drawn capillaries before as I remember. Because if they are exchanging something, they are dropping off what?
122. S: Oxygen.
123. T: They maybe dropping off oxygen and they actually may be dropping off sugar and in this case, they're also going to be doing what?
124. Ss: Taking up sugar.
125. T: Taking up sugar, so they need … to complete the what?
126. Ss: Cycle.
127. T: The cycle…. if … these …villi…are microscopic HOOOOOOW many capillaries do

you think that you are going to fit in there?
128. S: One.
129. T: So, you need to complete the loop, right? And you may have little branches off of this capillary, but I want to see that loop and I want you to see if you can find a colorful way to distinguish the difference in this capillary loop, okay? 30 seconds.
130. S: (Students work at their small group in improving their drawings)

We explain this episode by saying that the teacher supported the students in evaluating the shape of the capillaries drawn within the villi and realized that they had missed in drawing the loop. This realization led the students to modify the shape of the capillaries in their drawings drawn at the whiteboards. The teacher also asked them to find a colorful way to distinguish the blood that is getting into the capillaries and the blood that is getting out of the capillaries. We interpret this episode by saying that the teacher conducted the Model Evaluation phase and the Model Modification phase of a Model Construction Cycle (see Figure 1, Level 3; see also Figure 4, lower right side of the Classroom Dialogue Diagram).

With what color did we represent capillaries before?

While the teacher was walking around the groups and observing their drawing she noticed that some groups had drawn capillaries within villi with the right shape and colors but other groups had not been able to improve the color (Line 31). This originated a large group conversation through which the teacher supported the students in reviewing and modifying the color of the capillary loop to get it closer to the target concept (Lines 131-137). They said:

131. T: Excuse me; I see like half of you having trouble with the color, I think half of you have come up with a solution. How did we draw capillaries before? … With what color?
132. Ss: Red.
133. T: Red and?
134. Ss: Blue.
135. T: And we made the exchange of color at what point?
136. S: When they were sending it, and when they were putting it back through…
137. T: Okay, all right. When … we were either calling them veins or arteries.

We interpret this episode saying the teacher question regarding the color the students had used to represent the capillaries led the students to evaluate and modify their drawings. We explain this episode by saying that the teacher again conducted the Model Evaluation phase and the Model Modification phase of a Model Construction Cycle (see Figure 1, Level 3) to support the students in depicting the capillary loops by using conventional red and blue colors (see Figure 4, lower right side of the Classroom Dialogue Diagram).

Summary of the Model Evolution Mode, Second Episode

In summary, within the second episode of the Model Evolution Mode the teacher supported the students in evolving three students' ideas: (1) initial ideas about glucose absorption at the small intestine depicted on page 204 of their workbook; (2) capillaries within villi that looked like a single red pine-tree; and (3) capillaries within villi that looked like red loops. It is interesting to note that most of the generation and modification of ideas is in charge of the students and that most of the evaluation of ideas is in charge of the teacher. The students modified their ideas either at the whiteboard or in the student's workbook. These ideas are shown in Figure 4, lower middle part of the Classroom Dialogue Diagram.

MODEL CONSOLIDATION MODE

In the Consolidation Mode the teacher supported the students in reaching the target model and to compare their new ideas with their original ones (see Figure 6 and Table 6). In the next paragraphs we will describe how this teacher helped the students to conduct these two processes.

Could you compare your villi model with the scientific model?

After the students generated new understandings about villi, their capillaries, their shape, and the conventional color to represent them, the teacher showed the students several transparencies that depicted the scientific model (Line 138-139).

138. T: (Teacher shows transparency of villi with capillaries inside). So look at this model, if your model looks something like this then you've got it down. You got your blood system, you have a capillary coming up into these villi and you see this change (Teacher uses a pen to trace the shape of the capillaries). If your model looks something like this, you've got it close. I am going to show you another one…. This is without the nutrients. (Teacher shows another transparency. While showing the new transparency there were new teacher students exchanges).
139. S: (Students observe transparencies and react to teacher's comments about the shown information)

We explain this episode by saying that when the teacher showed the students the transparencies led them to evaluate and modify their ideas to reach the scientific model. We interpret this episode by saying that the teacher fostered the Model Evaluation phase and the Model Modification phase of a Model Construction Process (see Figure 1, Level 3) that allowed the students to reach the target model (see Figure 5 of the Classroom Dialogue Diagram).

Could you improve your villi model?

The teacher then asked the students to go to page 204 and to modify their original drawing by creating a new drawing on page 205 (Line 140) of the glucose absorption that occurs at the small intestine. She gave 2 minutes to the students to work on the task.

140. T: Go back to page 205… Erase your boards… I am giving you each individually 2 minutes… to draw the exchange that occur in the intestines, so modify your original model that is on page 204, I am giving you 2 minutes to modify it on page 205.
141. S: (Students improve on page 205) their drawings individually)

We explain this episode by saying that the teacher asked the students to repair their initial ideas, if necessary, by comparing them with their newer ideas (capillaries have loop shape and are represented by conventional red and blue colors). We interpret this episode by saying that the teacher conducted the Model Evaluation phase and the Model Modification phase of a Model Construction Process (See Figure 1, Level 3; see Table 7; see Figure 5 of the Classroom Dialogue Diagram).

Summary of the Model Consolidation Mode

In the Model Consolidation Mode the teacher supports the students in reaching the target concept (see Figure 5, lower left side of the Classroom Dialogue Diagram). The process is done into two steps. In the first step, the teacher discloses to the students the scientific model by using a transparency, a movie, or a talk. The condition to do this is that the students should have previously worked on their ideas and they are very close to the scientific model. Disclosing the target concept may bring closure to the students by confirming their ideas. In the second step, the teacher supports the students in repairing their original ideas by comparing their newer ones. The Model Consolidation Mode did not appear in the expert Modeling Practices Framework (Figure 1, Level 4) because it has not been observed yet in expert protocols. (However, we believe it may map well to cases in the history of science.) We also hypothesize that this mode may be also engendering the Model Evaluation phase and the Model Modification phase of a Model Construction Process ('fine tuning'--see Figure 1, Level 3). This mode may be an important step in the modeling process for students to achieve closure (see Figure 6).

MODEL APPLICATION AND/OR DOMAIN EXTENSION MODE

In the “Model Application and/or Extension Mode” the teacher supports the students in applying the newly learned model to a different case for explanation or prediction (see Figure 1, Table 4; see Table 6). In other words, the teacher asks students to transfer the learned idea to a new situation. In the next paragraphs we will describe how this teacher attempted to help students to transfer their understanding about the structure and function of villi at the small intestine to alveoli at the lungs, even though she had very little time to do so.

Alveoli are sort of villi?

This teaching episode took place at the end of the third lesson. The teacher reminded the students that they had talked the day before about how the glucose molecules go to the cell and that now they are going to talk about how oxygen molecules go to the cells (Lines 142-145). Then she asked the students to go to page 240 of the students' workbook and draw the exchange mechanism in the lungs. While the students were drawing, the teacher walked around the groups and looked their drawings. The teacher found that most of the students did pretty well in drawing the pulmonary system (Lines 144 and 146). So the teacher showed the students a transparency of the respiratory system that displayed its general structure. She said:

142. T: Ok… please turn to page 240. Now we talked about the glucose gets there (cells), now we have to talk about what else gets there?
143. Ss: Oxygen
144. T: So on page 240 I want you to draw for me [what] the pulmonary system is gonna look like, we have like 10 minutes to do this…show me how the air gets into the blood and how is the exchange gonna happen?
145. S: (Students draw their ideas individually on their workbook)
146. T: Ok, actually these are pretty good, um people seem to be pretty familiar with what … I am looking for.

The teacher then moved to a smaller part but very important part of the pulmonary system that was not depicted by the students in their drawings. The teacher asked the students to remember the way that the small intestine increased the surface area to get maximum exchange and asked them, "if lungs is another site of exchange, what they might have?" (Line 147) A student said that they might have a "sort of villi" (Line 148). The teacher accepted the student's answer and gave it a name "alveoli" and introduced a transparency depicting a cluster of grapes wrap with a string (Lines 149-151). The teacher then showed the students a transparency including actual alveoli and called the students attention to the capillaries located around each alveoli (Line 151-152) and asked the students to discuss in their small group the significance of the colors of those blood vessels (Line 153). They said:

147. T: Now I am gonna give you a little information…we have to think about this, remember how in the small intestine increase the surface area to get maximum exchange? If this (lungs) is another exchange site…what do you think you may have in the lungs
148. S: Something sort of villi.
149. T: Something sort of the villi and that something that is sort of the villi it is called alveoli and we describe that (teacher shows a transparency with a bunch of grapes wrapped with a string) as a cluster of grapes and what do you think the string may represent?
150. S: Capillaries
151. T: The capillaries, so that is designed in such a way that (teacher shows a transparency of alveoli surrounded by capillaries) we can maximize the exchange by having these little clusters of grapes (teacher uses a pen to point the capillaries located around alveoli depicted in the transparency)…which are totally embedded with these capillaries…And what do we know about these capillaries…This is going to be tricky, I am going to be very impressed… because we have what colors here?

152. Ss: Blue and red
153. T: Blue and red and what is significant about this blue and red (blood vessels), put your heads together and tell me what the blue represents…the red represents…
154. S: [Students discuss in their groups]
155. T: Ok, this blue represents what type of system?

The teacher asked the students to generate ideas about the respiratory system that led the teacher to evaluate that they were close to the target and support the students to evaluate the correctness of their ideas by showing the target model. The teacher then focused on the O_2 and CO_2 exchange site of the lungs. The teacher asked the students to remember the exchange site at the small intestine that led a students to generate the idea that lungs have an exchange site that may be "something sort of villi" that led the teacher to evaluate this idea by showing the "bunch of grapes wrapped with a string" analogy and called each of the grapes "alveoli". The teacher then showed the students a transparency of alveoli within the lungs that led the students to modify their ideas of alveoli as bunch of grapes wrapped in a string to alveoli surrounded by capillaries. The teacher then continued asking the students about the significance of the red and blue colors of the capillaries that surrounded the alveoli but we lack the space to discuss them here. We interpret this episode by saying that the teacher supported the students in conducting the Model Generation phase, the Model Evaluation phase, and the Modification phase of a Model Construction Process (see Figure 1, Level 3; see Table 7; see Figure 5 of the Classroom Dialogue Diagram).

Summary of the Model Application and/or Domain Extension Mode

In the Model Application and/or Domain Extension Mode the teacher supports the students in applying their new understanding to a different topic. In this case, the villi concept from the small intestine was applied to understand the alveoli in the lungs. We hypothesize that this Mode involved also involved a GEM Cycle (see Figure 1, Level 3; see Table 7; see Figure 5 of the Classroom Dialogue Diagram).

Summary of Findings by Research Question

Figures 3, 4, and 5 show the processes that we have identified in the case study. The second row from the bottom shows major modes of modeling, while the lower row unpacks two of the modes into subprocesses that serve them. These modes were constructed by analyzing the transcript, starting from the framework from expert studies. So whereas we did find processes in the classroom that were very similar to those in the expert framework, we did also identify others that were important to support modeling in the classroom, namely Generation of Initial Models and Model Consolidation.

The main results of the case study are shown in Figures 3, 4, 5, and 6. In this section we will first speak to the research questions of this case study.

Research Question 1.

Regarding Research question (1) —Is there a pattern of model construction that occurs on a large time scale of 3-6 lessons?— we have found six large modes included within these lessons, called Level 4: Major Modeling Modes, described in Table 11

Major Modeling Modes	**Description of Mode**
Description of Pattern to be Explained	Students make observations leading to a pattern -- or they generate or receive a question or description of a pattern-- that calls for an explanation using an explanatory model. a. May be an observation pattern—a set of observations that exhibit a regularity b. May be an explanatory model of a system that is accepted and calls for an underlying explanation or mechanism at a different level
Generation of Initial Model(s)	Process of generating an initial exploratory model.
Model Evolution	Process of improving a model, sometimes several times (via model Generation, Evaluation and Modification cycles. Exploratory or Evaluatory Observations may also be involved in these processes.)
Model Competition	Process in which two or more different model structures are focused on as alternative candidates for an explanatory model, motivating their competitive evaluation. Models are (1) Each evaluated for strengths and weaknesses (evaluatory observations may also be involved here); (2) Non-viable models are disconfirmed; and (3) Remaining models are assessed to determine which model is strongest and has the best explanation.
Model Consolidation	Process of summarizing and making any final repairs to the scientific model and encouraging students to review and compare the new model to their original models. Can include articulation of support for the model.
Application and Domain Extension	Once an explanatory model has been formed to explain one or more target cases, process of applying it to a new case for explanation or prediction. If the case is outside the initially perceived domain of application of the model, it may stretch or extend that domain.

Table 11. Major Modeling Modes

The Order of the Modes is Not fixed, but Changes, with Responsive Teaching

Figure 6 shows the Major Modeling Modes in the sequence that they occurred in our case study, but this arrangement is varied in other protocols. Describing a Pattern to be Explained Mode is the starting point for modeling, otherwise there is nothing to model (unless modeling starts by extension from a previous model). The double arrows in particular there indicate that Model Evolution and Model Competition might commonly occur in a different order. (For example, a teacher can introduce two competing models at the beginning of a unit to stimulate discussion.) In addition, it is also possible to find that Model Evolution and Model Competition occur more than one time, as we have seen in this teaching sequence. Model Consolidation would tend to come after Evolution and/or Competition. The Application and/or Domain Extension Mode would tend to come at the end after model development (unless an application occurs to the subject while developing the model). So Figure 6 is intended as a plausible, but loosely ordered sequence, with expected exceptions. We believe that the exact order of the modes might depend on the nature of the models generated by the students' and the order in which they have ideas.

Research Question 2.

Regarding Research question (2) — Is there a pattern of model construction that occurs over a medium sized time scale of 5-20 minutes cycles within lessons?— we have found a set of smaller processes that occur many times within this case study that we call "Model Construction Processes". They include three phases called Model Generation, Model Evaluation, and Model Modification (GEM) Processes shown at Level 3 of Figures 3, 4, and 5. Table 12 explains each of the phases of this pattern. Sometimes these occur in a repeated cycle called a GEM cycle, as shown in Figure 8.

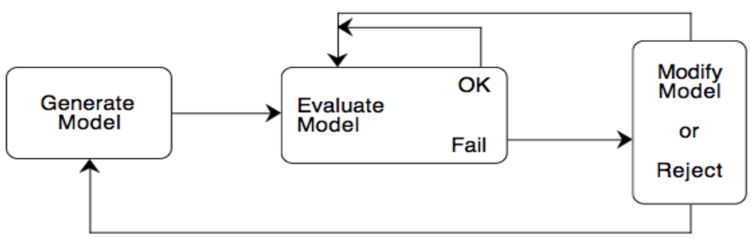


Figure 8. Level 3: Model Construction Cycle (Clement, 2008a)

Model Construction (GEM) Processes	**Description**
Model **G**eneration	In the ***Generation*** **(G)** process the teacher or student statement either asks for or provides a new theory, explanatory model, partial model, or conception. 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.
Model **E**valuation	In the ***Evaluation*** **(E)** process the teacher or student statement refers to a theory, model, conception or explanation that has previously been or is currently under discussion. The statement either asks for or provides an evaluation, judgment, refutation, criticism, support, or endorsement of a particular explanatory model.

Model **M**odification	In the ***Modification*** **(M)** process the teacher or student statement either asks for or provides a suggested change, adjustment, or modification to a theory, or model. This may involve an alteration, subtraction or addition.

Table 12. Model Construction (GEM) Processes (Williams & Clement 2015, p. 88-89)

First, ideas for models are generated; if the students' conceptions included in the explanatory model are somewhat correct, the teacher supports the students in evaluating and modifying those ideas that need further work. The teacher encourages them to add or modify elements of the model. All of this takes place at level 3 as a contribution to the Model Evolution Mode at level 4 (see Levels 3 and 4 in the lower part of Figures 3, 4, and 5 of the Classroom Dialogue Diagram).

Secondly, we found a pattern within the Model Competition Mode where each of several models is assessed for weaknesses (see Figure 6 and Table 10). In the case study, as result of such assessments, two models were disconfirmed, leaving one model to be developed further by returning to the Model Evolution Mode.

Research Question 3.

Regarding Research Question (3) —If present how are these patterns connected? For example, does one pattern describe subprocesses within the other pattern? Based on the result of our analysis depicted in Figures 3, 4, 5, and 6 we propose that the smaller time scale components are "nested" within the larger processes. Another way to explain the nesting concept is to say that the medium sized pattern is a subprocess that contributes to the purpose of the larger process. We show the analysis leading to this finding in Table 13.

In our analysis we have proposed that individual Generation, Evaluation, and Modification processes are nested within two of the major modeling modes. In the Model Evolution mode there are all three GEM processes, while in the Competition Mode there is mostly the model evaluation process applied to different models, leading to some models being disconfirmed. For us the hallmark of the Model Evolution mode is the focus on a single model, the process of model modification and the pattern of GEM cycling on that same model (hence the name Model Evolution mode).

In general, we have also found that in whole class discussion, the Model Generation phase occurs less often than the model Evaluation and the model Modification phases. We explain this finding by saying that once the teacher supports the students in generating an explanatory model that might contain several elements, the teacher guides the students in evaluating and modifying each one of the elements of the explanatory model until it gets closer to the target model. We show the model construction phases (Generation, Evaluation, Modification) at level 3 at the lower part of Figures 3, 4, and 5 of the Classroom Dialogue Diagram. Those phases are subprocesses for implementing the larger modes above them at Level 4. The same is true for the connections between levels in Figure 6.

We also hypothesize that Level 3 Model Construction Processes can also be involved in the Model Consolidation Mode and Model Application and Domain

Extension Mode. However, we need to examine other protocols in order to support this hypothesis.

L4 Major Modeling Modes	**T-S Statements**	**L3 Model Construction Processes or GEM Cycles**
Describing a Pattern To Be Explained Mode, First Episode	T: How does the glucose get out of the intestine and into the blood and then to cells?	
Generation of Initial Model(s), First Episode	(Students build six group drawings)	Model Generation
Model Evolution Mode, First episode	T: Villi are what? S: Villi are hands that grab stuff at the small intestine…	GEM Model Generation, Model Evaluation, and Model Modification
	T: What is the sole purpose of villi? S: Just grab little bits of glucose like fingers…	GEM Model Generation, Model Evaluation, and Model Modification
	T: What is the advantage of having these villi? S: Villi are like filters…	GEM Model Generation, Model Evaluation, and Model Modification
	T: What is the advantage of having these villi? T: When small intestine is bumpy there is more space…	GEM Model Generation, Model Evaluation, and Model Modification
Describing a Pattern To Be Explained Mode, Second Episode	T: Now to make this thing the most efficient machine...where do I want to place those capillaries?	
Generation of Initial Model(s), Second Episode	(Students discuss and generate three ideas indicated below)	Model Generation
Model Competition Mode	Model A	Model Evaluation and Model Disconfirmation
	Model B	Model Evaluation and Model Disconfirmation
	Model C	Model Evaluation and Model Confirmation
Model Evolution Mode, Second Episode	T: Look page 204 and change if necessary	Model Evaluation and Model Modification
	T: (Looking single red-pine tree shape capillaries	Model Evaluation and Model Modification

		within villi) You need to complete the what? S: The loop	
		T: Half of you have problems with the color, with what colors did we represent capillaries before? S: Red, blue	Model Evaluation and Model Modification
Model Consolidation	Consolidating scientific Model	T: (Showing villi transparency) if your model looks like this you've got it down. S: (Observe and comment transparencies)	Model Evaluation and Model Modification
	Comparison to Original Model	T: Ok, erase your boards, 2 minutes to go page 2004 and draw your ideas on page 205. S: (Go to page 204 and 205)	Model Evaluation and Model Modification
Model Application and Domain Extension Mode		T: If lungs is another site of exchange site, what do you think you may have in the lungs? S: Something sort of villi	Model Generation, Model Evaluation, and Model Modification
Describing a Pattern to be Explained Mode = 2 Generation of Initial Model(s) Mode = 2 Model Evolution Mode = 2 Model Competition Mode = 1 Model Consolidation = 1 Model Application and Domain Extension = 1			Model Generation = 7 Model Evaluation = 13 Model Modification = 10 Model Disconfirmation = 2 Model Confirmation = 1

Table 13. Major Modeling Modes and Model Construction Cycles (Appearing in the Protocol)

Research Question 4.

Regarding Research Question (4) — Do these patterns suggest a set of model development strategies for teachers?— we hypothesize that a teacher might use the six Major Modeling Modes and their nested Model Construction (GEM) Processes that we have identified in this case study as a framework to scaffold modeling. These Major Modeling Modes could be organized in a "unit modeling sequence pattern" that the teacher might follow to foster modeling processes in their students. This cycle may help to organize instruction at the unit level to develop different explanatory models and mechanisms (see Figure 9).

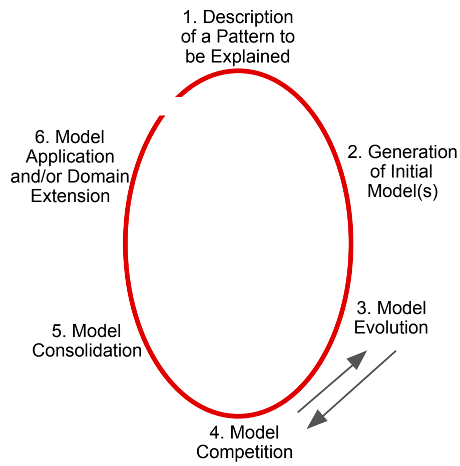


Figure 9. Modeling Sequence Pattern

The double arrow between Model Evolution and Model Competition Modes indicates that there is not a fixed order in which they occur. In the present protocol they appear separately but in others we have seen them alternate rapidly or sometimes occur together. In addition, the drawing shows an incomplete loop to indicate that the modeling sequence pattern may repeat several times tracing not multiple cycles but the coils of a spiral.

While planning the unit, the teacher first should have a clear understanding of the topics and subtopics necessary for that unit. The teacher then might organize instruction of the topics and subtopics of the unit by using the modeling sequence pattern described above for each major subtopic. In other words, the teacher uses the same "modeling practices pattern" to teach different size explanatory models included in the unit. As result, while the students are learning different topics they are also using the same modeling practices over and over but across different contexts.
However, it is hypothesized that this unit modeling pattern should be used adaptively or in a responsive way, since the modes conducted should depend on the topic, the teacher's entry point for the topic, and the student models generated. Teachers may plan their lessons by designing a "planned learning pathway" that will in the classroom be adjusted to become an "implemented learning pathway" that includes the students' ideas regarding the topic, their invented ideas and the paths followed by the teacher to support the students in evolving or disconfirming students' ideas.

Discussion

Features of the Classroom Discussions

Positive features

There were several positive features of the classroom dialog diagram analyzed:

- This was an advanced topic for middle school, but students participated in a Co-Construction process, where they contributed ideas along with the teacher.

They made contributions for generating, evaluating and modifying ideas. What we saw in these three lessons is a non-traditional situation because most of the initial modeling ideas come from the students, most, but not all of the model evaluation comes from the teacher, and both the teacher and the students contributed to modifying ideas (see Williams & Clement, 2017). This close connection between the students and teacher contributions allows us to describe the discussion as a social construction of scientific models in the classroom. The student contributions are key for their experiencing engagement in scientific practices. Instead of learning these practices in a separate course, here students learn them while learning about a scientific subject. This would help to move forward naïve student's ideas into more sophisticated ones before introducing the accepted scientific model.

- There was considerable student engagement via the tapping of student's prior knowledge ideas. Students' ideas such as that "villi were like filters" or that "villi looked like hands that grab things" illustrate how students used their prior knowledge flexibly and creatively to contribute to modeling. In addition, we observed the inventiveness of students in placing the capillaries with respect to villi into three different positions (outside of villi, on top of villi, and inside of villi).
- The teacher skillfully navigated the class through all of the Modes, shown in Figure 9, as scientific practices, by using individual, small group, and whole class work.

Negative features

There were also some negative features in our view:

- In the last class the teacher was running out of time. This meant that she did not allow as many student contributions as she might have done.
- The last section in Model Application and/or Domain Extension Mode was consequently quite short, and although some students made a connection to the new topic of gas transfer in the lungs, we infer that this was far too short a segment to develop any deep conceptual understanding of that area.

Anarchistic teaching?

Although the Modes in Figure 6 are shown in a typical order, we see variations in ordering in other protocols. If the strategies we have discussed are only loosely ordered, do they imply an Anarchistic, unstructured approach to teaching and learning? We would answer "no" because we see this as responsive teaching. The teacher may influence an intelligent ordering of modes depending on the topic, the teacher's entry point for the topic, and the models that happen to be generated by the students spontaneously. In addition, the teacher may have shifted modes adaptively and often by changing the group structure (individual work, small group discussion, or large group discussion) and the task (by either generating, evaluating or modifying a model). We believe that teacher in this study did have some partial control over the modes in this way.

For example, after establishing a Pattern to be Explained Mode, the teacher conducted the Generation of Initial Model(s) Mode where she asked the students to participate in the model generation process by conducting initial individual and small group assignments. Based on the similarity of student models, it was natural for the teacher to pursue Model Evolution for a single model in the segment of the lesson. Later, in shifting to a new subtopic, the teacher restarted the mode sequence with a new Pattern to be Explained and another Generation of Initial Models activity. Since the students generated three different models to locate the capillaries with respect to villi, it was natural for the teacher to have a Model Competition segment by asking the small groups to evaluate the competing models, a mode that was then carried over into the subsequent whole class discussion. Even when the best model (Model B) of those generated had been selected by the class, it still had missing or problematic elements. We believe this is typical for any relatively complex modeling task. (It is certainly typical in real scientific modeling.) This was a natural point for the teacher to then pursue Model Evolution again, by working on one problem in the model at a time. We believe that an increased awareness of these modes and their purposes on the part of teachers may help the teacher with scaffolding by helping to craft assigned questions for small group and whole class discussion, so that teachers can shape the discussion for the needs of further model development.

Time Problem, Picking Fights

A potential enemy of this way of teaching is time. The teacher may get so involved in supporting the students in evolving a model that they lose track of the time invested. Scott, Mortimer, & Aguiar (2006) suggest using this interactive way of teaching when one has detected big differences between students' initial ideas and the scientific model. Teachers under pressure to cover wide content may need to 'pick their fights' in choosing which content areas they think are amenable to student modeling contributions.

Comparison to other descriptions of modeling practices in the classroom

In our view the loosely ordered sequence of 6 large scale modes included in a "modeling sequence pattern" in Figure 9 can serve as a teaching sequence for organizing instruction at the multi-lesson or unit level, which should be of use to teachers and curriculum developers. The processes/strategies in Figure 9 resonate with different aspects of earlier work on large scale strategies by others such as Driver, Scott, Clement, Minstrell, Ramirez, and Schwarz in the sense that the knowledge construction process does not take place in one step but by conducting several steps within which take place distinctive processes. But even though these researchers specified a somewhat similar pattern in developing an explanatory model, we believe we have added a clearer and more complete description of the modeling processes and subprocesses that could take place in each of the steps of the pattern, partly by incorporating insights from expert studies.

In this study we made efforts to identify larger and smaller patterns, and to generate vocabulary for describing them, and to explain their connections. In addition, none of the curricula described above provided a clear explanation about how to teach multi layered explanatory models. While answering research question 4, we hypothesized that a modeling cycle that included the Major Modeling Processes depicted in Figure 6 could be used to teach each of the major subcomponents of a multi layered explanatory model.

Curriculum organization at the unit level

Figure 6 has some similarities to previous discussions of Unit level structure, especially to Driver et al (1996). The greatest contributions of Figure 6 are:

- The central focus on model development that drives the motivation for and gives purpose to the other activities.
- The idea of a number of different major types of modes for modeling, each of which may have its own structure and different needs for teacher support.

The delineation of a different key objective for the two main modes where scaffolding on the part of the teacher is critical, the Model Evolution Mode, where the objective is to improve a single model, and the Model Competition mode, where the objective is to compare the merits of two or more models.

Implications for Managing Different Types of Discussion

The Framework and examples in the case study suggests that classrooms may benefit from different types of discussion leading. The Generating Initial Ideas Mode would appear to benefit from an open style. The teacher used individual, small group, and whole class discussion formats for this (with the teacher mainly restricted to drawing out ideas in the latter). The Competition mode requires a somewhat more active style, with the teacher clarifying the differences between models and prompting students to evaluate the different models. The teacher used both small group and whole class discussion for this. Model Evolution Mode requires perhaps the most activity and the most skill on the part of the teacher because the teacher will often need to creatively figure out how to evolve certain models toward the target model through questioning. This would appear to best be done in whole class discussion. Various strategies for doing this are discussed in Williams and Clement (2017). The GEM processes shown within this mode in Figure 8 could provide teachers with some guidance on how to produce such Model Evolution. It is a blueprint for processes the teacher could involve students in during such discussions.

We believe that getting an understanding of these modes is important because once the teacher opens up the classroom to student modeling, many types of models can be generated, with various differences from the teacher's target model. Understanding modes in which these models can be evaluated and disconfirmed or improved may give teachers more effective tools for dealing with the variety of student models, which can be a challenge.

Another aspect shared with previous efforts is the need for both divergent and convergent discussions (Scott et al, 2006; Windschitl, Thompson, Braaten, & Stroupe, (2012)). The balancing of divergent and convergent thinking is a hallmark of model construction work in science. The modes provide opportunities for divergent thinking (Generation of Initial Model(s)) and convergent thinking (Model Competition) and some involve both (Model Evolution) until reaching the target concept including checking whether the students had modified their initial views (Model Consolidation). Both divergent and convergent thinking are needed for full participation in modeling.

Movement between authoritative discourse and dialogic discourse

While analyzing this teaching episode we observed that there is some overlap between our findings and those reported by Scott, Mortimer, & Aguiar (2006) and the literature discussed by these authors.

Scott et al (2006) provide evidence of the movement between authoritative and dialogic discourse during teaching and learning science in the classroom and that any sequence of science lessons must include both authoritative and dialogic passages of interaction. They say that this tension or shift is an inevitable part of supporting meaningful learning of scientific knowledge. These authors say that for a teacher is **not enough to engage students' in dialogue** about their everyday views of phenomena, rather, the teacher also has to introduce scientific knowledge as an authority. In addition, Scott et al (2006) argue that learning science meaningfully involves making **connections between everyday and scientific** views. In other words, at the end of the dialogic exploration of students' everyday views the teacher needs to introduce the scientific views and connect or contrast them with student ideas. Scott et al (2006) consider "these dimensions as tensioned and dialectic, rather than as being an exclusive dichotomy" (p. 623). Other researchers (Windschitl et al 2012) also describe the introduction of the scientific view during instruction.

We also saw certain issues described by Scott et al (2006) in the sense that within the teaching episode that we analyzed **dialogic and authoritative passages** are rather complementary than independent. In other words, there are moments where the students discuss their ideas about glucose absorption at the small intestine but there is also a moment where the teacher shares the scientific view by showing them the scientific model through a transparency. Although it was not so well observed in the present case study because of time issues, we believe that Consolidating the new model by presenting the students with the scientific model is important. For us this means that the teacher detects the students' ideas, the teacher then supports the students in evolving their ideas until getting close enough to the target concept. Finally, the teacher next introduces the scientific concept in order to reach closure. We have the impression that this approach may involve a longer delay of closure than in Scott's case however.

Scott et al (2006) analyzed their findings in terms of "**productive disciplinary engagement**" as a concept that examines students' intellectual progress, inferred from the increase in quality and sophistication of their arguments, development of new ideas, and disciplinary understandings (Engle & Conant, 2002). The latter authors provided a lists of features of students' discourse that can be considered as evidence of greater disciplinary engagement: (i) more students make substantive contributions to the topic under discussion; (ii) these contributions are in coordination with each other; (iii) few students are involved in “off-task” activities; and (iv) students express passionate involvement and they re-engage and continue to be engaged in the topic over a long period of time. In addition, Engle & Conant (2002) advanced four principles for fostering productive disciplinary engagement: (a) Problematizing content; (b) Giving students authority; (c) Holding students accountable to others and to disciplinary norms; and (d) Providing relevant resources. These are explained as follows: Problematizing: students are expected to **answer questions** rather than assimilating facts and procedures. Giving students authority, students are encouraged to produce knowledge rather than consume it. Holding students accountable to others and to disciplinary norms: the students are asked to consider others points of view and to be responsive to them. Providing relevant resources: includes aspects such as having sufficient time or sources of information relevant that are key to successfully produce science learning.

We find many of the strategies observed in our case study compatible with the “productivity disciplinary engagement” concept. Through the analysis of this teaching episode we have provided evidence that: The teacher problematized the material by asking key questions; Students were given authority to generate ideas; they **discussed** within their small group, considered each other's points of view, and **generated their team models** that **take into account each other ideas**. Accountability was also visible in the many types of model evaluation fostered in the Model Evolution and Model Competition Modes. Evidence for student engagement in general is provided by the large number of on topic contributions through this teaching episode that lasted three full lessons, shown in Figures 3, 4 and 5. We think that the teacher supported the students in conducting large reasoning processes (Describing a Pattern to be Explained Mode, Generation of Initial Model(s) Mode, Model Evolution Mode, Model Competition Mode, Model Consolidation Mode, and Model Application and/or Domain Extension Mode) that utilized medium size subprocesses (Model Construction Process or GEM Cycles). This nested pattern of practices is shown in the two-level framework in Figure 6. A further challenge for our group is to use the framework to explain other protocols and to evaluate and modify this framework as we analyzed the grounded data.

Scott, Mortimer, & Aguiar (2006) also see some overlap of their study with van Zee & **Minstrell's (1997) notion of “reflective discourse**”. In their study an innovative classroom was compared with traditional classrooms in which the teacher’s authority guides classroom discussions. Within a classroom where there is reflective discourse there are frequently three characteristics: (i) Students express their own thoughts; (ii) Teacher and students engage in extended series of questioning exchanges; and (iii) There are student/student exchanges where they try to understand to each other.

We also think that our findings overlap with van Zee & Minstrell (1997) concept of “reflective discourse”. As it was observed in the video and in the transcripts, the students expressed their own thoughts, engaged in extended questioning exchanges, and there were student/student exchanges as they work in their small groups.

Our study also connects with Minstrell et al.'s (2011) in the sense that we unpack processes depicted in their BOLT framework. In particular we unpacked the processes that take place between their phases of *drawing out* the students’ ideas and *agreeing on the class consensus model*. We describe these processes in terms of the

Generation of Initial Model(s), Model Evolution, and Model Competition Modes. In addition we include the Model Consolidation Mode where the teacher explicitly shows the students the scientists' ideas and asks the students to compare their new ideas with their original ideas.

As result of the efforts of the many researchers indicated above and in the theoretical framework section of this study, as well as our own efforts, we believe we are getting closer to having an adequate picture of the modeling practices involved in teaching and learning science.

Theoretical Implications

A Multi-level Framework for explaining modeling processes appears to be useful for describing the complexity of the teaching and learning process. We think that this framework provides three advantages:

(1) It provides an integrated framework for several different size and types of cognitive processes that are spread in the literature regarding the modeling process;
(2) It provides a theoretical framework for analyzing protocols; and
(3) It provides some guidance for teachers and curriculum development about the processes that they may need to include while planning instruction to foster modeling.

On the other hand, the main drawback of this framework is its complexity. But we are confident that as we examine other protocols and provide thorough descriptions of the modeling processes included, it will be easier to understand the teaching strategies used at different levels. We believe it will then be possible to create simplified guidelines for teachers and curriculum developers, one level at a time.

Finally, this framework provides a theoretical perspective on learning as the result of multiple levels of cognitive processes. Further research is needed to evaluate and improve this framework

Expert parallels and how classroom research could affect research on experts

In this study we were able to apply a framework of medium sized expert Model Construction processes to the classroom, including the idea of GEM cycles (lower part of Figures 3, 4, and 5 of the Classroom Dialogue Diagram). These Model Construction Cycles have been described in expert reasoning (Clement 1989 and Nersessian 1995).

In addition, we were able to apply the framework of large sized expert scientific processing modes shown at level 4 in Figure 1 (Clement, 2008a) to classroom interactions and gain a new perspective on large scale teaching strategies being used (upper part of Figure 6). The Model Evolution Mode at Level 4, is reminiscent of Toulmin's discussions of theory evolution in science. On the other hand, the Competition Mode is reminiscent of Kuhn's discussion of competing paradigms in science, even though we are not dealing with fully established paradigms here. Applying these ideas from history of science metaphorically, we can say that both kinds of processes were important in the present classroom sequence. It is somewhat surprising that modes derived from studies of experts solving physics problems could be applied to learning modes in a 7th grade life sciences classroom. We were also inspired by the classroom analysis to adapt and add two major modeling modes to the framework: Generation of Initial Model(s) and Model Consolidation. The last one that includes two subprocesses called Consolidating the Scientific Model and Comparison to Original Model. Through these two major modeling modes we think that the teacher made a concerted effort to depart from the students' ideas and to reach the target concept by disclosing the scientific concept. Even during Model Consolidation, the teacher takes the time to check out whether students' initial views had change as result of the instruction.

Our resulting expanded framework at these levels has the potential to affect further work on expert processes to see if the new modes make sense in an expert context. Certainly the Generation of Initial Model(s) mode may have happened so quickly for the experts that it was missed as a major mode. It does appear akin to a brainstorming mode used in organizational design meetings, and also in some scientific meetings (Dunbar, 1997). It could be that extended forms of this mode are more common in group work than in individual cognition like that studied by Clement (2008a) in developing the initial framework. The Consolidation Mode may have a parallel in expert work in summarizing, articulating, and giving formal justifications for recent progress in developing a model.

Conclusion

In this study we were able to apply a framework of large sized expert scientific thinking practices to a case study of learning processes in the classroom. Our intent has been to describe modeling practices at a greater level of detail than is provided currently in the NGSS, and to provide a different lens for viewing the complex task that a teacher faces in trying to foster real student participation in model construction.

Encouraging students to participate in these processes actively, starting from a Generation of Initial Models Mode, means that a variety of models will be put forward, and these must be compared, evaluated, and improved. Two key modes identified here —Model Evolution and Model Competition— appear to provide different options to the teacher for orchestrating these processes. When combined with different social activities such as individual work, small group discussion, and whole class discussion, there is the potential for students to make significant contributions to model construction. For teachers, the above two modes might be also called 'Model Improvement' and 'Model Comparison' respectively. We see this study as part of our continuing effort to understand what effective scaffolding in the classroom means in terms of various options and strategies for different phases in the learning science process.

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