Identifying Discrepant Events as a Strategy to Improve Critical Thinking About Scientific Models in a Heat Transfer Unit in Middle-School

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Abstract: The Next Generation Science Standards (NGSS) define "using and developing models" as an essential science and engineering practice. In a week-long science unit using the Bifocal Modeling approach, students perform hands-on experiments, design models and finally interact and compare real data with computational models. In this paper, we describe the Bifocal Modeling unit of heat conduction that took place in a low socio-economic background 5th-grade class. We present the instructional sequence and demonstrate a significant increase in content knowledge as well as improved modeling skills. We illustrate how this technology-based framework promotes learning while improving inquiry and specifically modeling skills and critical thinking regarding models.

Objectives

Our main objective was to explore whether the Bifocal Modeling Framework is a learning approach that could promote students' learning on two levels: content knowledge and modeling practices. More specifically, our goal was to examine the impact of our design on students' abilities to develop scientific models.

Theoretical framework

A scientific model is an abstract, simplified representation focusing on particular aspects of a natural phenomenon, which may be used for generating explanations or predictions of a "mini-theory" (Schwarz, et al. 2009, Schwarz, et al. 2008). Consequently, the use of such models is a core element in professional scientific practice, both for formulating hypotheses and for describing natural phenomena (Pluta, Chinn, and Duncan 2011), modeling activities play a central role in the formation and justification of new knowledge (Halloun 2011; Koponen 2007).

The idea of model-based learning is taking an important place in K-12 science, technology, engineering, and mathematics (STEM) education. Model literacy has claimed "modeling" as a central goal of STEM education and a core component of school curricula (Bryce et al., 2016; Gilbert & Justi, 2016). National policy documents have placed modeling activities at a central place in the curriculum (National Research Council, 2007; NGSS 2013), and modeling is becoming gradually an integral teaching and learning tool woven throughout the Next Generation Science Standards (NGSS).

The involvement of students in developing a scientific model has been shown to enhance their disciplinary knowledge as well as their understanding of the epistemology of scientific models (Lehrer & Schauble, 2006; Schwarz & White, 2005; Stewart, Cartier, & Passmore, 2005). Although NGSS provide a clear statement on performance expectations, they do not specify how instructions should be developed nor do they serve as objectives for individual lessons. NGSS do not include curriculum units and a support system for new teaching practices.

In this study, we challenged students to design, compare, and examine the relationships between physical experiments and computer models (Blikstein, 2006, 2012; Blikstein, et al. 2012; Fuhrmann, et al, 2012, 2014, 2018). Students explore natural phenomena through physical experimentation, the design of a model, and the comparison of the measured and simulated data gathered from the experiment and a computer model. The idea of not only learning about topics in science but "doing" science (experiencing scientific work) is one of the main concepts embedded in the framework, echoing the National Research Council-NRC (NRC 2012) and Next Generation Science Standards-NGSS frameworks (NGSS, 2013). In this paper, we illustrate the employment of this approach to teach 5th-grade students about heat conduction. We present the instructional sequence and illustrate how this framework called "Bifocal Modeling" promotes content learning about heat transfer and conduction while improving inquiry skills like developing scientific models, and critical thinking about models.

Participants and Settings

The study was conducted in a K-12 charter school located in a predominantly Latino urban population. 85% of students are low-income, 90% are expected to be first in their family to go to college, 68% are learning English as a second language. 55 participants were drawn from two 5th grade classes taught by the same science teacher. The main focus of the current study curricula was heat transfer and specifically conduction.

Study design and instructional sequence

The Bifocal Modeling unit on the topic of heat conduction took a total of 5 hours, split across multiple days, in the following instructional sequence (figure 1):

1. Introduction to heat transfer: Students watched demonstrations of three ways of heat transfer: 1. convection, 2. radiation and 3. conduction.
2. Physical experimentation: Following an activity guide, groups of 3 students examined heat transfer from a heat source to thermometers placed on the copper plate. They used a 500ml clear container, a copper plate (15*15 cm.), two thermometers taped to the copper plate, and a timer. The students recorded the room temperature; they added boiling water to the bottom of the container and monitored the temperature change as a function of time. They ran multiple iterations and documented their measurements in a table format. Graph paper was used to summarize the results and plot the data.
3. Modeling and design: Students were asked to design a paper model to explain the physical experiment they conducted.
4. Modeling and comparing: Students were asked to compare a NetLogo computer model (Wilensky, 1999) to their experiment (both of which were displayed adjacent to each other) and to manipulate the model in order to provide the best explanation of their empirical observations (figure 2).

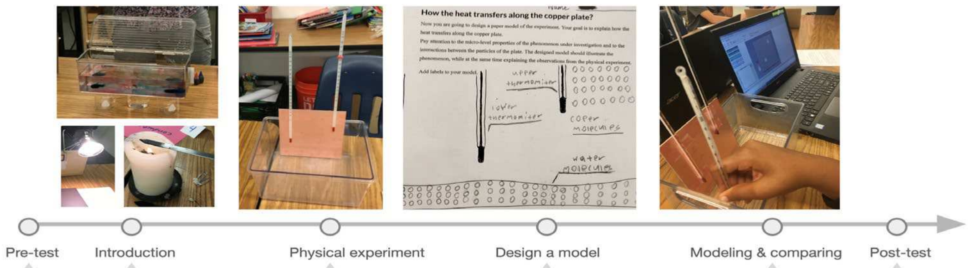


Figure 1. the instructional sequence of the Bifocal Modeling "Conduction" unit.

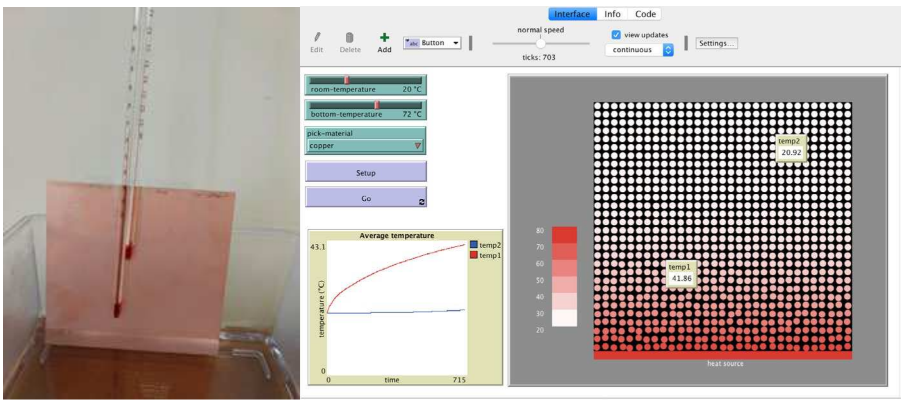


Figure 2. the physical experiment and the computer NetLogo model side-by-side.

Data sources and analysis

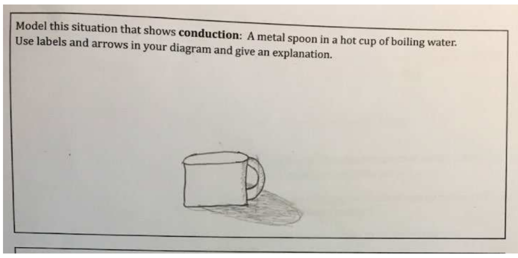
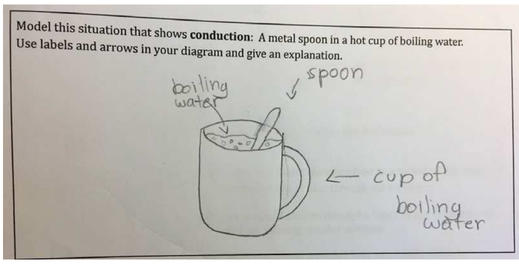
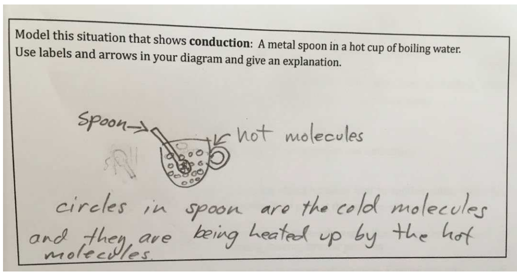
To explore students' learning during participation in our design activities, we utilized different assessment tools and data sources: paper-and-pencil pre-tests and post-tests, worksheets with model-drawings, and a researcher's reflective journal. We analyzed the data in three levels:

1. General learning outcomes: to determine whether the differences in the learning outcomes were significant, we performed a paired-samples t-test and compared the total final scores on the test as well

as the score of the modeling and content sections of the test. We utilized an alpha level of 0.05 for this analysis, and Cohen's d was employed to calculate the effect size for each mean difference.

2. Modeling practices: to investigate the ability of students to design models, a rubric was developed. Models were ranked on a two-point scale, from a low value of 0 to a high value of 2 (Fuhrmann et al., 2018). Coding was assessed by the researchers of this paper; an agreement was reached after several cycles of refinement. Rubrics' categories are described in the table below.

Table 1: The "Model drawing" rubric with scores and examples

Score	Criteria Definition	Example
0	No drawing or not relevant to the scientific phenomenon. *The example presents an artistic drawing without any scientific relevance to conduction.*	
1	Modeling the scientific phenomena of conduction without using molecules and explanations. *The example illustrates a description of the experiment without reasoning and explanation of conduction.*	
2	Modeling the scientific phenomena of conduction with micro-level explanations (presenting molecules in the drawing or explaining with texts). *The example presents molecules and explanation of conduction.*	

3. Students' critical thinking about models: in a bottom-up grounded theory procedure the researcher's reflective journal, students' free discussions and written assignments were analyzed. All the discrepancies event students had between the experiment and model were revealed and sorted. We found that those events led to some students' discussion about the advantages and limitations of models which could be defined as meta-modeling knowledge.

Results

In this section, we present and interpret the data according to the three levels described above: 1. students' learning outcome regarding content and meta-modeling, 2. students' modeling skills, and 3. students' discrepancies events between experiment and models that led to critical thinking about models:

Students' learning outcomes: To determine whether there was a significant difference between the means of pre- and post-test, a paired t-test was conducted. Figure 3 describes students' pre- and post-test average scores for the total score of both tests: content knowledge, and meta-modeling knowledge.

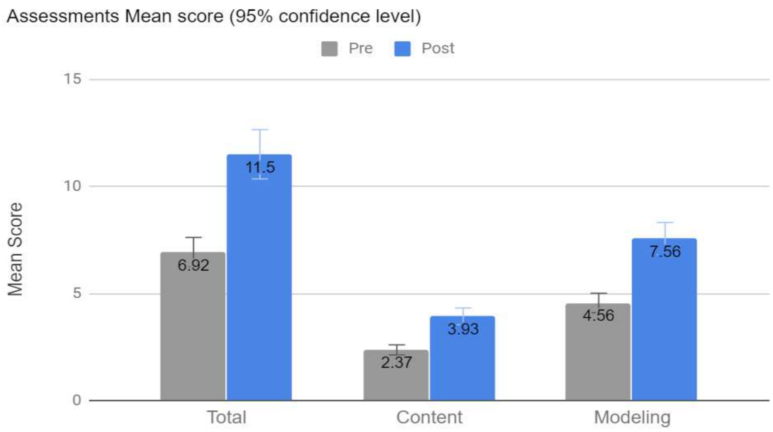


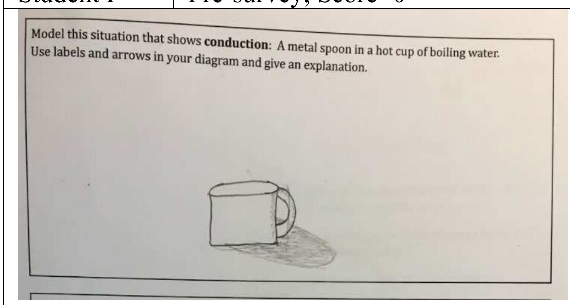
Figure 3. Descriptive statistics of the pre- and post-test. Error bars represent standard errors.

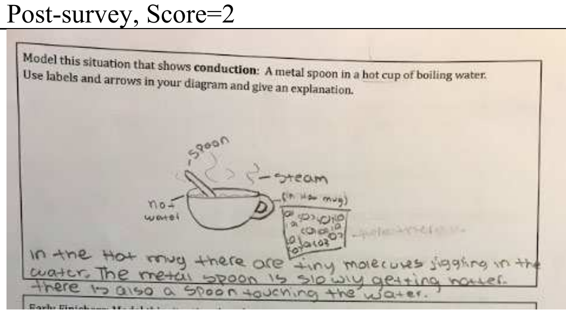
According to data, students improved their content and meta-modeling knowledge significantly (total knowledge: p-value<0.0001***, content knowledge: p-value<0.002**, meta-modeling: p-value<0.0001***).

Students modeling practices: As part of their pre-post surveys, students were asked to explain the phenomena of heat transfer by designing a model of conduction through drawings on paper. Using the developed rubric (above), we ranked the paper-models of conduction made by students.

The following table illustrates 3 examples of the ranking system we used and the improvement in students' ability to model heat-conduction in the post-survey.

Table 2: Examples of improvement in students' ability to model using our models ranking rubric

<table>
<tr><td>Student F</td><td>Pre-survey, Score=0</td><td>Post-survey, Score=2</td></tr>
<tr><td colspan="2">

Description: A detailed artistic drawing of a mug, shade included. It is an artistic representation of a mug, rather than a scientific one.</td><td>

Description: Drawing of a spoon in a steaming mug. The student added a panel titled "in the mug," which emphasized jiggling molecules (the molecules are represented by circles, and the movement is represented by zigzag lines).

Labels: hot water, spoon, steam, in the mug. "In the hot mug, there are tiny molecules jiggling in the water. The metal spoon is slowly getting hotter. There is also a spoon touching the water."</td></tr>
<tr><td>Student A</td><td>Pre-survey, Score=1</td><td>Post-survey, Score=2</td></tr>
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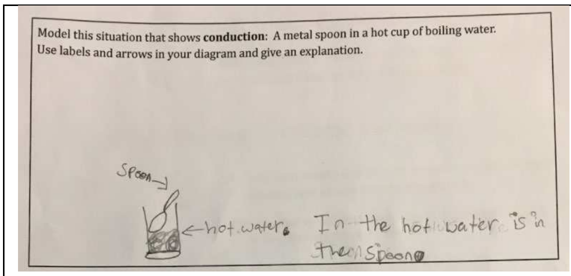
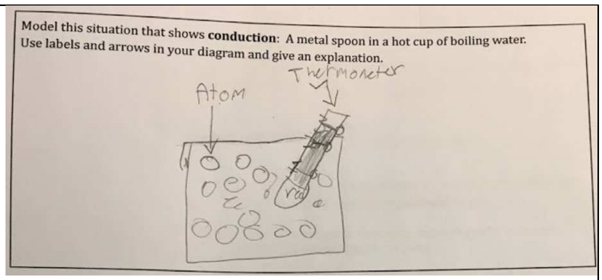
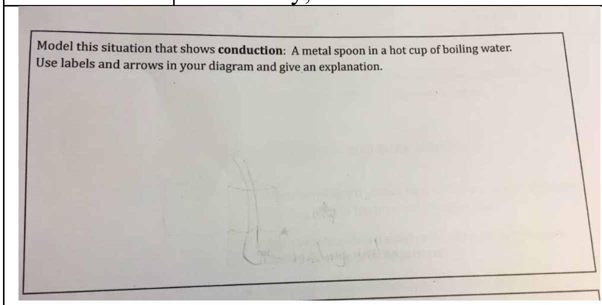
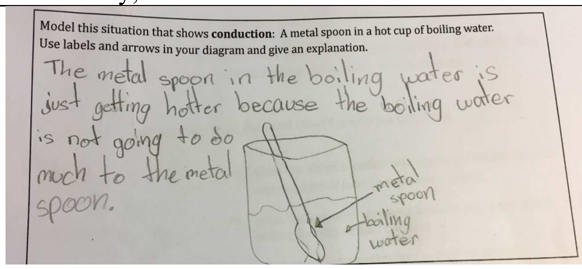
<tr><td colspan="2">

Description: The drawing illustrates a spoon in hot water but does not offer any explanation as to how the heat transfer from the water to the spoon.

Labels: spoon, hot water. “In the hot water is in the spoon.”</td>
<td>

Description: The model illustrates the conduction experiment performed in class, in which a copper plate was placed in hot water. The circles on the plate are atoms.

Labels: atom, thermometer, red (the tip of the thermometer).</td></tr>
<tr><td>Student S</td><td>Pre-survey, Score=0</td><td>Post-survey, Score=1</td></tr>
<tr><td colspan="2">

Description: The student did not draw a model (started drawing but erased her work).</td>
<td>

Description: The drawing shows a metal spoon in boiling water. The text above the drawing elaborates that the boiling water will heat up the spoon but will not alter its shape or other properties of the spoon. Both drawing and text refer only to the macro level of the phenomena and not to the micro level (molecules).

Labels: Text: “the metal spoon in the boiling water is just getting hotter because the boiling water is not going to do much to the metal spoon”
Labels: metal spoon, boiling water</td></tr>
</table>

Ranking data illustrated that students’ average score for post-test models doubled compared to the average score for pre-test models (pre-test=0.46, standard deviation=0.50, post-test=1.04, standard deviation=0.52).

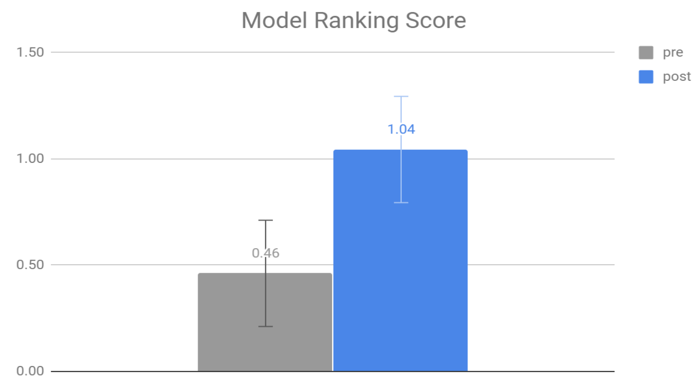


Figure 4. Designing models of conduction: average ranking score.

The table below (table 3) illustrates the number of students and the score they received for their models' designs using the rubric. In the pre-test, the model drawings were general and simple, without micro-level explanations: 28 students out of 52 scored a 0, and 24 students out of 52 scored a 1. None of the students' models scored a 2, as students did not include molecules in their conduction models in the pre-test. However, in the post-test 7 out of 45 students' models were ranked a 2, which meant that they designed a model of conduction presenting molecules or explaining the phenomenon in micro-level. 33 students out of 45 scored a 1 and only 5 out of 45 students scored a 0.

Table 3: Number of students and their models' scores, pre- and post-test

Score	0	1	2	Total # of students:
Pre	28	24	0	52
Post	5	33	7	45

Students' discrepant events: As part of our unit's design, students were asked to compare between the experiment and the computer model in real time. Throughout the comparison, students revealed some discrepancies between the experiment and the model. Revealing the mismatch led students to critically assess the computer model and discuss the advantages and limitations of models. In this section, we provide some typical examples of the discrepancies that students acknowledged, students' quotes and their perceptions about the limitations and advantages of models:

The perception of models' limitation:

1. Wind: during the experiment cool air entered the classroom through an open door and cooled down the copper plate in the physical experiment. Student's quote: "The computer won't stimulate air passage". "The air affects the copper plate (in the experiment) but not the computer [model]." Students noticed that air is a variable that exists only in the experiment and is missing from the model.
2. Heat loss: In the experiment, after a few minutes the heat source (hot water) cooled down. Student's quote: "In the computer model, the temperature [of the plate constantly] increased. In the experiment, the temperature of the copper plate decreased [after the heat source cooled down]"."The heat source in the computer model needs to cool down," "In the real world the water gets cold and in the computer model it stays hot," "The heat source never stops boiling [in the model], it should have a limit." Students understood that in the experiment "heat loss" is something to take into consideration when collecting data. The model did not take into account heat loss into the environment.
3. Steam: In the experiment, students thought that the copper plate was getting hot not only by the hot boiling water but also by the steam that came out from the boiling water. Student's quote: "In the lab experiment you can see the steam and, in the model, the steam is missing." Students wondered if the steam rising in the air impacted the temperature of the copper plate. This is another variable that was noted as missing from the computer model.
4. Materials: In the experiment various materials can be used by a researcher, however the model has only five different materials that can be tested for conductivity of heat. Student's quote: "You can only choose 5 different materials [in the computer model] when there are so many more in real life [experiment]." Another student noticed that the model was limited by its design: we could use any materials for the experiment in reality [physical experiment], but we could not use more than what was designed in the computer model by the developer and on the drop-box for materials.

Understanding the advantages of models:

1. Time frame: The exploration process could be faster while conducting it with the computer model to make alterations and quickly see the outcomes. Student said: "You can change time [the rate of heat transfer] on the computer [model] but can't change time in the real world [experiment]." Students noticed that the model has some advances if you like to explore an expedite process in a shorter time frame.
2. Visualize micro-level and molecules: In the experiment, students could see the phenomena, but they cannot see molecules. The computer model environment enabled students to visualize the copper plate on a micro-level scale. Student's quote: "...In the real world [experiment], we can't see what the computer sees like molecules, I can see them [in the computer model]". Students visualized a

microscopic dimension of conduction (the process on a molecular level), which made it easier to understand the scientific phenomenon that was conducted in the experiment.

3. Easy to perform: Students noticed that the computer model could help them study the effect of changes in some of the variables without carrying out changes in the actual physical environment. Student's quote: "A computer model is easy while a 'real lab' is harder. [experiment]". The computer model can be used to study complex systems that would otherwise be difficult to investigate.

Students' acknowledgment of the mismatch between the experiment and the computer model introduce them to the challenges and limitations of models as well as to the advantages of models. Students noticed that the computer model does not include all the variables that impact the physical experiment, and also that a computer model has advantages by providing a way to understand processes that might otherwise be unseen.

Summary and conclusion

This paper illustrates a Bifocal Modeling approach heat conduction unit, where students' total test scores were significantly higher in both content and meta-modeling knowledge. In addition, students' modeling skills and students' awareness towards the limitations and nature of models increased as expressed in their paper model designs and their discussion about models. While it was difficult to determine which part of the activities contributed the most to the change, we offer several points of view for the explanations of our results. Our design exposed students to both entities; a physical experiment and computer model. A crucial component was the iterative move from one entity (experiment) to the other (computer model). Results showed a consistent shift from pre to post in students' model drawings, their design went from being artistic and general to detailed and scientific. Arguably, the transition from an artistic drawing to scientific models could be attributed to the exposure to the Netlogo model which includes molecules and micro-level mechanical reasoning to conduction. We showed that in our design unit, students were requested to compare the computer model to the experiment, and while doing so, they came across discrepancies. Piaget (1985) argued that to foster conceptual change, students must be confronted with "discrepant events" that contradict their conceptions and invoke a "Disequilibrium or cognitive conflict." Disequilibrium of a student's thinking was Piaget's phrase, and Berlyne (1966) called it "epistemic curiosity." The framework we used seems to facilitate cognitive dissonance (Blikstein et al. 2016, Fuhrmann et al., 2014). Our approach included a meaningful comparison component, that encouraged students to compare the experiment's data and the computer model's simulated results. The lack of alignment between students' results from the experiment and the data from the computer model may motivate them to ask meaningful questions (data not shown) and led them to become aware of the advantages and limitations of models while comparing them to a hands-on experiment in real time. This design may be one way to provide stimuli for critical thinking about modeling that would result in an increase in students' meta-modeling knowledge. Schwartz refers to meta-modeling knowledge as a "knowledge about modeling" that enables students to answer questions about how and why models are used, as well as the strengths and limitations of such models (Schwarz & White, 2005; Schwarz, et al. 2008, Schwarz, et al. 2009).

Supporting students' learning of science concepts and training them in being critical about models, understanding limitations and acknowledging advantages is an important issue both in the science education literature and for the NGSS. Our findings indicate that the Bifocal Modeling approach might be of use in this direction.

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