Growing Curious Minds: Improving Inquiry Practices and Content Knowledge by Comparing Computational Models to Hands-on Science Experiments

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להצמיח תלמידים סקרנים: שיפור מיומנויות חקר וידע תוכן על ידי השוואה בין מודלים ממוחשבים לניסוי מעבדה

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Abstract

The Next Generation Science Standards (NGSS) defines "developing and using models" and "asking questions" as two essential science and engineering practices. In a week-long science unit, students perform hands-on experiments, design models and finally interact and compare real data with computational agent-based models. In this paper, we describe the unit of heat conduction that took place in a low socio-economic background in 5th-grade class. We present an inquiry-constructionist complex technology-based instructional sequence and demonstrate a significant increase in students' content knowledge as well as improved science practices. By the end of the unit, students are improving their inquiry skills and specifically asking questions and developing models practices. We illustrate how this framework improves students' curiosity about science and specifically heat-transfer.

Keywords: constructionist learning, technology-based environment, students' questions, scientific inquiry, modeling.

Objective

Our main objective was to explore whether our designed learning approach could promote scientific practices such as asking questions and developing models in a science classroom.

Theoretical framework

Science practices and inquiry are placed at the center of many international level curriculums (National Research Council, 2007, 2012; NGSS 2013, British Columbia Ministry of Education, 2011; OECD 2016). One of the main concepts embedded in the new reform in science education is that students should not only learn about topics in science but they should be "doing" science.

The Next Generation Science Standards (NGSS) defines "developing and using models" and "asking questions" as two essential science and engineering practices.

The notion of students asking questions plays an important role in meaningful learning and scientific inquiry. Questions are important in the process of eliciting explanations, evaluating evidence, justifying reasoning, and clarifying doubts (Chin & Osborne, 2008). Questioning also encourages learners to engage in critical reasoning (Zoller et al., 1997; Cuccio-Schirripa and Steiner, 2000). Students who asked high-level questions received better scores on the conceptual performance test than those who asked only simple questions (Chin et al. 2002; Chin, 2004). These studies have suggested that there is a relationship between the quality of students' questions and achievement as well as their conceptual understanding. However, as grade level increases, the number of student questions decreases: students ask fewer "on-task attention" questions that relate to the immediate task (Good, et al. 1987) and even fewer questions in search of knowledge (Dillon, 1988; Graesser & Person, 1994). Very few students spontaneously ask high-quality thinking or cognitive questions (Carr, 2002; White & Gunstone, 1992), with most questions being factual, procedural, or closed in nature. Scardamalia and Bereiter (1992) argued that wonderment questions, which reflect curiosity, puzzlement, skepticism, or knowledge-based speculation, have greater potential for an advance in conceptual understanding relative to basic information questions, which seek for basic orienting information. The nature of the classroom instructional sequence influences the type of questions students ask; for example, inquiry-type experiments have been shown to improve students' ability to ask scientific questions (Hofstein et al, 2004). To investigate the relationship between student-generated questions and teaching approaches, Chin and Brown (2002) found that students' basic information questions, which focused on facts and procedures, were typical of a surface-learning approach and generated little productive discussion. In contrast, questions, which included comprehension, prediction, detection, application, and planning questions, led students to wonder more deeply about their ideas. These questions were indicative of a deep learning approach and stimulated students to generate explanations, formulate hypotheses, predict outcomes, create thought-experiments, and plan the next steps. Hands-on laboratory activities which included open-ended, problem-solving activities elicited wonderment questions more than teacher-directed activities where students asked mostly procedural questions when following step-by-step instructions. Although the students did not always ask wonderment questions spontaneously, they were able to generate such questions when prompted to do so.

The use of scientific 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 (National Research Council, 2007; NGSS 2013). 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).

In this study, we employed a particular approach to inquiry science that challenged students to design, compare, and examine the relationships between physical experiments and computer models (Anonymous, 2006, 2012; Anonymous, et al. 2012; Anonymous, 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. In this paper, we illustrate the employment of this approach to teach 5th-grade students about heat conduction. We present the instructional sequence and delineate how this framework promotes learning while improving inquiry skills and specifically asking questions and developing models.

Methods

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 the 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 designed unit on the topic of heat-transfer took a total of 5 hours, split across multiple days, in the following instructional sequence:

1. *Introduction to heat-transfer:* Students were introduced to heat transfer by watching the demonstrations of the following experiments: 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, 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 conduction ready-made NetLogo computer model (designed by the authors of this paper), 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.

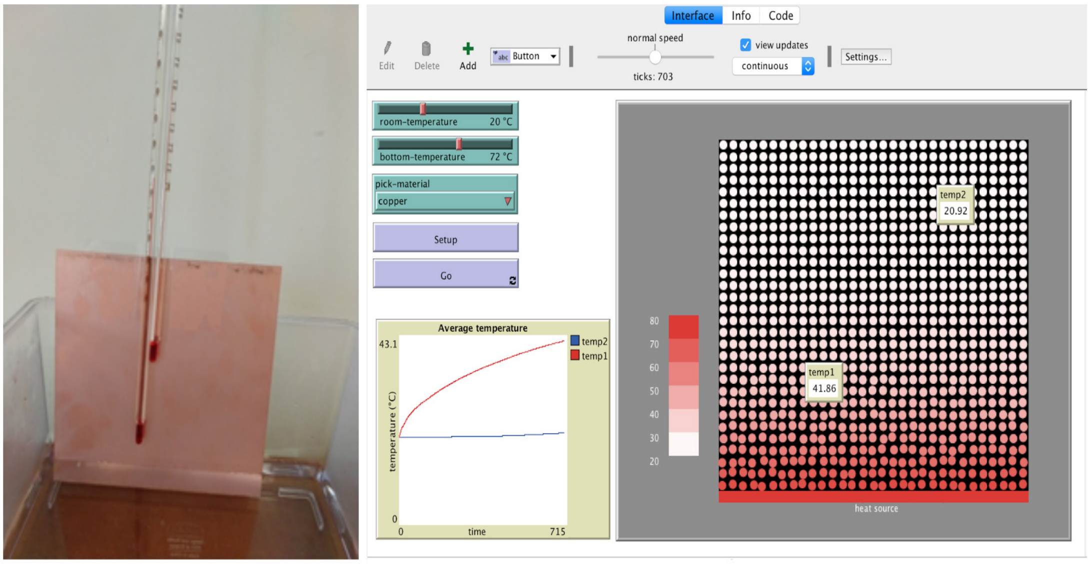


Figure 1. The physical experiment and the computer NetLogo model side-by-side.

Four times during the instructional sequence, students were requested to write their questions regarding the activity (see figure 2). They were provided with empty paper and were requested to ask questions without additional instructions.

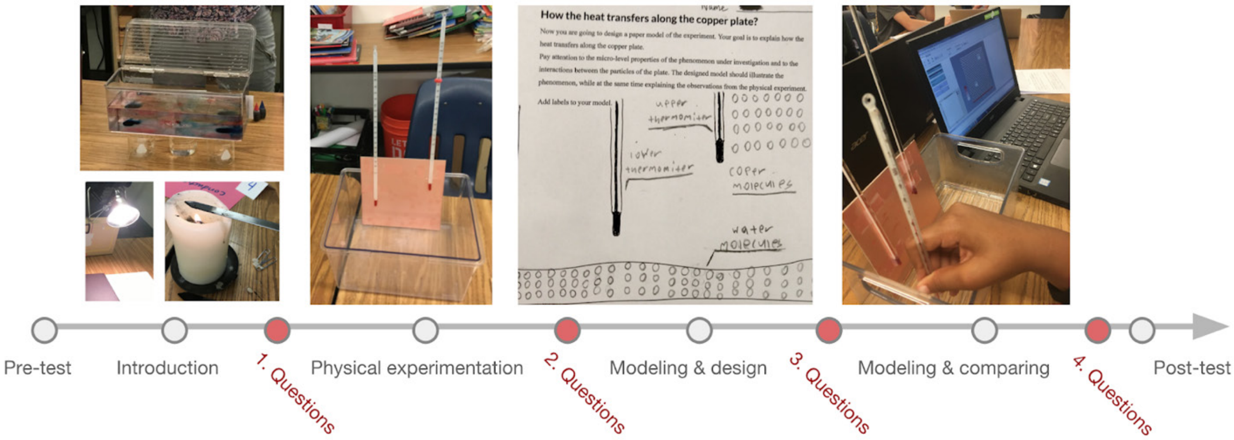


Figure 2. The instructional sequence of the "Conduction" unit.

Data sources and analysis

To explore student learning during participation in our design activities, we administered two paper-and-pencil pre- and post-assessments. To determine whether the differences in the learning outcomes of these groups were significant, a paired-samples t-test was performed and compared the total final scores on the test as well as the score of the modeling and content sections of the test. An alpha level of 0.05 for this analysis was utilized, and Cohen's d was employed to calculate the effect size for each mean difference.

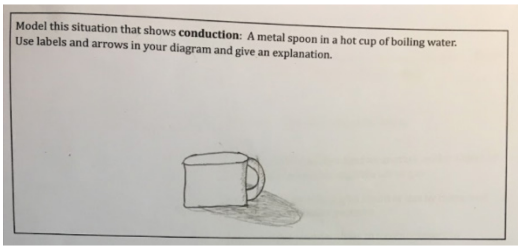
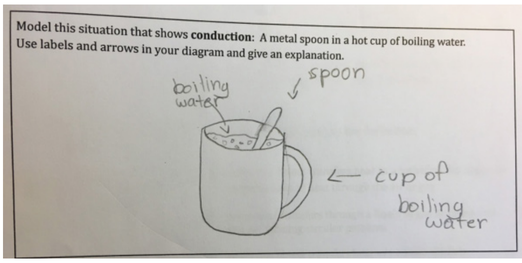
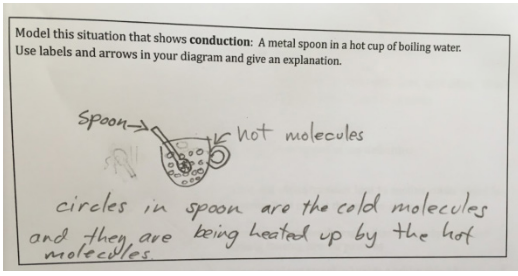
Student-generated questions were collected following each class activity. Their questions were rated by the authors of this paper using a rubric. The developed "Questions' type" rubric evaluates the types of questions that emerge from students' responses throughout the unit's activities (Leydens, Moskal, and Pavelich, 2004). We created four categories of question types in a bottom-up grounded theory procedure. The following are the types of questions: 1. No questions and irrelevant questions, 2. Procedural questions about the experiment, 3. Questions about models, and 4. Wonderment questions (Scardamalia and Bereiter, 1992) (see Table 1).

Table 1. The "Questions' type" rubric, definition and example.

Type of question	**Definition**	**Example quotes**
No questions and irrelevant questions	Students don't know what to ask and they specifically say that they don't have any questions. Students may ask an irrelevant question.	• *I don't know* • *Are we going to learn more about it?*
Procedural questions	Students are asking procedural or technical questions about the experiment conducted in class. Basic questions	• Why does boiling water makes the food color go up? • How does the wax make the paper clip sticking to the metal?
Modeling questions	Students are asking questions regarding the papers and computer models	• How do the tiny particles are smaller in the computer model but bigger in real life? • Why is the computer model different than what we did in real life?
Wonderment questions (Bereiter & Scardamalia (1989))	Students ask scientific questions that show curiosity and are not related directly to lessons conducted in the classroom. Students also ask questions regarding the mechanism/reasoning and process that were not part of the classroom scope.	• Do molecules have molecules inside them? • Does the gas [steam] from the water has anything to do with the temperature? • What if you use ice-cold water not hot water? • Does the heat go through the metal or on the metal?

To assess students' modeling practices, students' drawn 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 2. 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.*	

Results

In this section, we present and interpret the data in both quantitative and qualitative terms. First, our quantitative analyses of content learning and modeling knowledge are based on student responses provided on the written pre-and post-tests. Next, our qualitative analyses present thorough examinations of students' abilities and progress of asking questions and designing models. We will focus on the number of questions students ask during the activities, the type of questions and the process through which they asked questions while learning about conduction. We will describe Students' modeling practice as they explain the phenomena of heat transfer while developing a paper model of conduction.

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

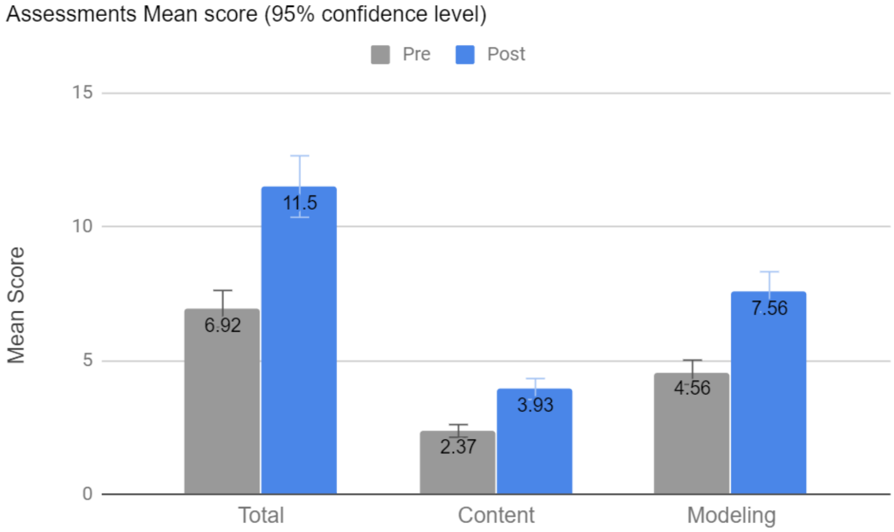


Figure 3. Descriptive statistics of the pre- and post-test. Error bars represent standard errors.

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

Students' number and type of questions: Results demonstrate that the number of questions students were asking increased throughout the unit. The number of questions was doubled from Day 1 to Day 3 (33 questions on Day 1 to 62 questions on Day 3). In addition, the number of questions increased with each day (Day 1-33 questions, Day 2-48 questions, Day 3-62 questions). However, on Day 4, there was a slight decrease in the number of questions to 52 questions. We believe that this was due to students' "end of the unit" syndrome where students were tired and asked fewer questions.

Regarding the type of questions, the transition from students observing a demonstration of an experiment (Day 1) to students performing hands-on experiments (Day 2) resulted not only in an expected increase in the procedural-based questions but also in an increase in the number of wonderment-based questions. This means that the active inquiry enhanced students' curiosity, reasoning, and desire to know more about the subject that is being taught in the classroom. The introduction to modeling (Day 3) produced an increase in modeling-based questions. Data showed that students started to ask questions about models, which increased on Day 4 when students were comparing the computer model to the experiment. Data illustrated that on Day 3, there was a major increase (2.7 times) in the number of wonderment-based questions (Day 2-17 questions, Day 3-45 questions). On Day 3, we introduced students to designing models, students were engaged to think about an explanation for the phenomenon of conduction using models, which is one reason for the increase in wonderment questions on that day. The following graph (figure 4) illustrates the total number of questions that were asked in each day, sorted by the types of questions.

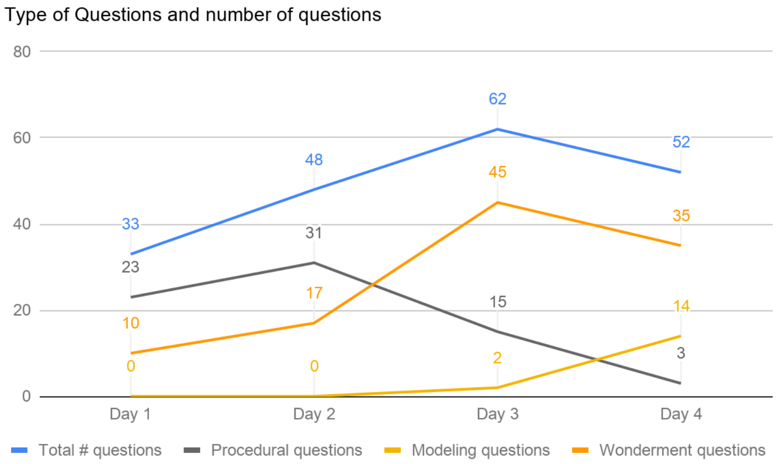


Figure 4. Total number of questions in each day, sorted into types of questions.

Students' questioning practice: The following table is a case-study sample of 4 students' questioning through the 4th day of the unit and the process through which they asked questions while participating in our activities.

Table 3. Evolvement of students' questioning practices.

Student #1			
Day 1	Day 2	Day 3	Day 4
I don't have a question	Why did the thermometer change a lot? When I touch the water at 10 minutes, it still felt the same?	Why did the molecules of hot water move faster than the one in cold water?	Why is the computer model [different] then what we did in real life?
Description: Student #1 questions altered throughout the course of our unit. On the first day, she had nothing to ask. On the second day, she asked a procedural question and drew a comparison between the readings of the thermometer to the heat she felt while touching the water. On the third day, she asked about the reason behind the phenomena discussed in class, and on the last day, she asked about models. Note how closely related her questions are to the timeline of the unit design: the questions are directly related to what was done earlier in the classroom (Day 2: physical experiment, Day 3: design paper model, Day 4: computer models).			

Student #2

Day 1	Day 2	Day 3	Day 4
Why are we doing this?	What are we doing?	How do molecules spread by heat transfer?	Why is wood (which is the softest materials compared to stone and metal) does not heat up as fast?

Description: Student #2 didn't ask questions related to the subject matter in the first two days of the unit. On the third day, however, he asked about the mechanism through which the molecules moved and spread. On the fourth day, he went beyond the data addressed in class in a new way, combining his daily experience, previous knowledge, and the experiment done in class. This integration led to a creative and innovative question.

Student #3

Day 1	Day 2	Day 3	Day 4
I don't have questions	No questions	No questions	What are other ways that molecules can move each other except heat?

Description: Student #3 didn't ask any questions during the first three days of the unit. On the last day, he inquired about new means of movement on the molecular level, which indicated both his understanding of the subject matter as well as curiosity and desire to learn more.

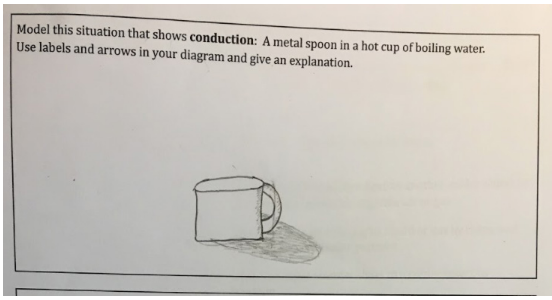
Student #4

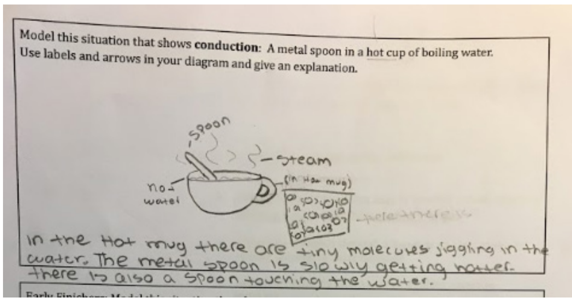
Day 1	Day 2	Day 3	Day 4
I do not have any questions yet	Can heat transfer through any object in the world?	3 questions: Is radiation deadly or harmful? Does heat travel through the air? How many types of radiation molecules are there?	4 questions: How hot can copper get? Are atoms the same as molecules? How many atoms are in a molecule? Can extremely hot water cause fire?

Description: Student #4 did not ask any questions on the first day, asked a single one on the second day, and from there on we were flooded with questions, as if a barrier was removed: he asked no less than 3 questions in the next few days. His questions changed from very general ("Can heat transfer through any object?") to more focused ("Does heat travel through the air?"). One of his questions revealed a misconception ("How many types of radiation molecules are there?"), a misconception that might not have been revealed otherwise. An especially interesting question arose on the last day: "Can extremely hot water cause fire?" This question showed understanding that temperature is a distinctive parameter that can be addressed in the dissociation of the material that carries it. Dan's understanding of this concept expanded the traditional view of water as a fire-distinguisher and invited further investigation on water and fire.

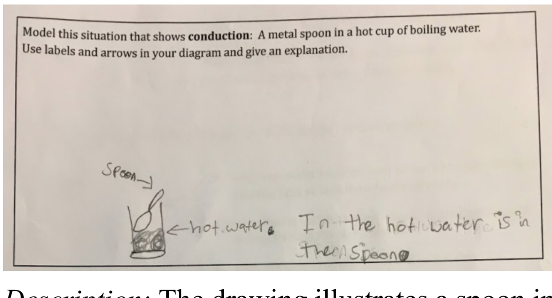
Students' modeling practice: As part of their pre-post surveys, students were asked to explain the phenomena of heat transfer by designing a model of conduction through drawings on paper. Using the developed rubric (above), we ranked the paper-models of conduction made by students. The following table illustrates 3 examples of the ranking system we used and the improvement in students' ability to model heat-conduction in the post-survey.

Table 4. Examples of improvement in students' ability to model using our models ranking rubric.

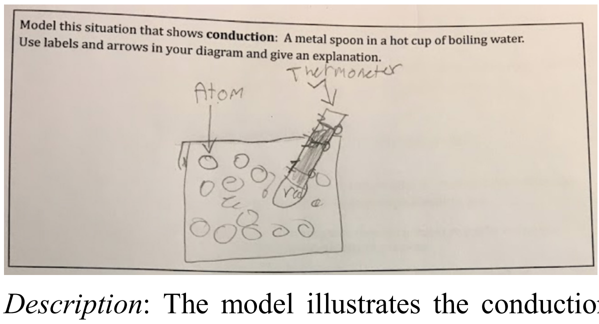
<table>
<tr><td>Student F</td><td>Pre-survey, Score=0</td><td>Post- survey, Score=2</td></tr>
<tr><td colspan="2">

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).

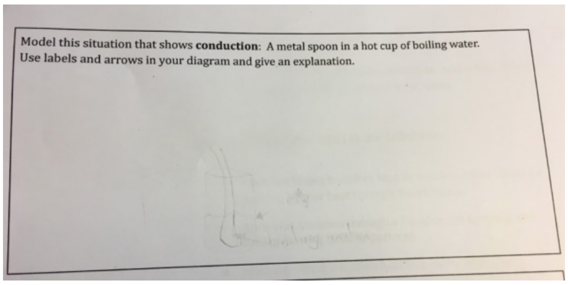
Labels: hot water, spoon, steam, in the mug. "In the hot mug, there are tiny molecules jiggling in the water. The metal spoon is slowly getting hotter. There is also a spoon touching the water."</td></tr>
<tr><td>Student A</td><td>Pre-survey, Score=1</td><td>Post-survey, Score=2</td></tr>
<tr><td colspan="2">

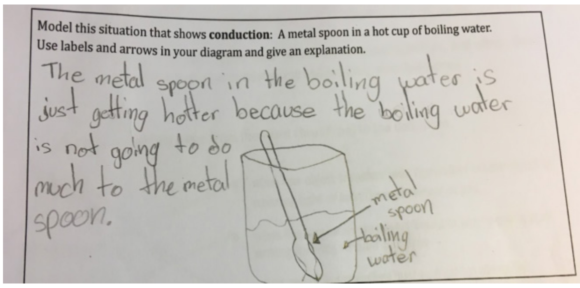
Description: The drawing illustrates a spoon in hot water but does not offer any explanation as to how the heat transfers from the water to the spoon.

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>
</table>

<table>
<tr><th>Student S</th><th>Pre-survey, Score=0</th><th>Post-survey, Score=1</th></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 metal spoon, boiling water:
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"</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).

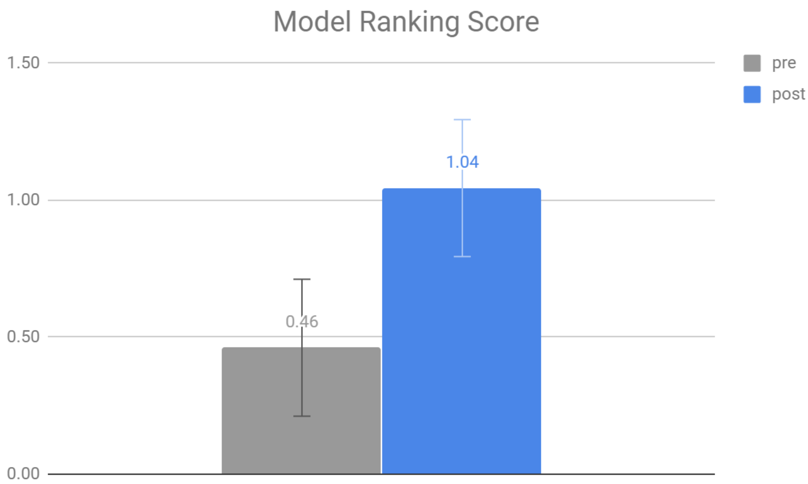


Figure 5. Designing models of conduction: average ranking score.

Summary and conclusion

This paper illustrates a technology-rich heat conduction unit, which increased students' content knowledge, modeling skills and the number and the quality of students' questions. Our design exposed students to both entities; a physical experiment and a computer model. A crucial component was the iterative move from one entity (experiment) to the other entity (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. 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.

The inquiry-driven science learning approach, a constructionist-based framework, encouraged students to reflect and explore. Susskind (1969) observed only about two students generated questions per hour in classroom discourse, a rate that is two orders of magnitude less than that observed in young children at home. Pimentel and McNeill (2013) found that teachers who used more dialogic, student-centered interactions in their teaching encouraged the students to have more reflective thinking, engage in more meaningful discussions, and ask more questions. Our design encouraged students to explore, investigate, change parameters, compare, and revise. This exploration mode created a safe space for students to take risks, dare, and ask questions that otherwise might have been silenced.

Furthermore, it takes considerable domain-specific knowledge to ask good questions (Chin and Brown 2000). Students, therefore, might be in a poor position to ask questions, especially at the beginning of their study of the topic of conduction. However, as students proceeded in the unit, they learned more about conduction and understood better what they didn't know, so they could ask more questions.

And lastly, the result of the cognitive conflict as part of our design may have been another catalyst to question asking. The lack of alignment between students' results from the experiment and the data from the computer model may motivate them to ask questions. Piaget (1985) argued that to foster conceptual change, students must be confronted with "discrepant events" that contradict their conceptions and invoke a "disequilibration or cognitive conflict." The framework we used seems to facilitate cognitive dissonance (Blikstein et al. 2016, Anonymous et al., 2014). Our approach may be one way to provide stimuli for question-asking that would result in a higher level of questions. While comparing the computer's model to an experiment, for example, students noticed that in the real world, the water in the container was getting cold, but in the model, the water stayed hot at a constant temperature. Such discrepancies engaged them to ask more "wonderment" questions, often aimed at explanation or at resolving discrepancies in knowledge. Bereiter & Scardamalia (1989) defined questions that are "knowledge-based questions" as those that spring from a deep interest of someone or an effort to make sense of the world. These types of questions can originate from a gap in students' knowledge or a desire to extend knowledge in some direction. Modeling and asking questions are essential science practices, and we encourage teachers and curriculum designers to incorporate open-ended problem-solving projects and provide scaffolding for students to ask wonderment questions and practice their modeling skills.

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