Meta-Modeling Knowledge: Comparing Model Construction and Model Interaction in Bifocal Modeling

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ABSTRACT

In this paper we will examine students' meta-modeling knowledge in the context of their participation in a Bifocal Modeling activity. Bifocal Modeling is an inquiry-based approach for science learning, which incorporates both physical experimentation and virtual modeling. The current study combines three separate case studies of students participating in different implementation modes of the Bifocal Modeling process. Different implementation methods require different modeling practices, and we will examine the consequences of these practices for students' meta-modeling knowledge. The concern of our investigation will be the ways that students critically evaluate scientific models and their understanding of the limitations of those models. Data suggest that model construction (as opposed to simple interaction) lead to deeper meta-modeling knowledge.

Categories and Subject Descriptors

K.3.1 [Computers and Education]: Computers Uses in Education

General Terms

Design, Experimentation.

Keywords

Education, physical computing, computer modeling, inquiry science, meta-modeling knowledge, bifocal modeling

1. INTRODUCTION

A considerable body of literature recognizes metacognitive knowledge as a key component in learning [8]. Metacognitive knowledge enhances students' awareness of the inquiry process by providing them better opportunities to reflect upon their progress, which, in turn, permits them to refine their inquiry process Given the importance of teaching scientific inquiry in schools, curricula should be developed in a way that helps students learn not merely about content knowledge in science, but also acquire and use metacognitive knowledge when participating in inquiry activities.

Modeling is a core element in science and scientific practices. A scientific model is an abstract, simplified representation of a phenomenon that focuses on one of the phenomenon's key elements and may be used in the production of an explanation or a prediction of that phenomenon [7, 8]. For the scope of this paper, we will mainly focus on meta-modeling knowledge, the aspect of metacognitive knowledge most crucial for development of scientific models. This type of knowledge is defined as the learners' understanding of how models are used, why they are used, and what their strengths and limitations are [8].

Involving students in the development of scientific models may enhance their knowledge of the discipline, as well as their epistemological understanding and expertise in building or evaluating scientific models. If students' scientific modeling practice proceeds adequately, they may gain a significant opportunity to learn about the nature of science as well as an enhanced understanding of meta-modeling. In general, however, scientific modeling practices have been limited to illustrating phenomena, which weakens the epistemic value of such modeling [8].

This study is an examination, in the context of the Bifocal Modeling framework and activities, of different modes of implementation in school settings as well as their effects on students' meta-modeling knowledge. We will mainly focus on students' ability to understand the limitation of models. In particular, we will investigate the extent to which the active (versus passive) participation in the design of virtual and physical models influences what students learn from Bifocal Modeling activities. Our initial hypothesis is that involving students in both conceptualizing and programming models will affect their notions about the limitations and usefulness of scientific models and ultimately determine how they engage in scientific inquiry.

2. RESEARCH SETTING

Bifocal Modeling [2, 3] is an approach to inquiry-driven science learning that challenges students to build and compare in real time physical and virtual models. In these activities, students explore a scientific phenomenon such as the properties of gases, bacterial growth, or wave propagation by conducting physical experiment, constructing a virtual model and connecting the experiment and the model in real time. Bifocal Modeling includes various distinctive sub-activities as described in figure 1 [3]

Figure 1: A general structure of Bifocal Modeling activities

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A. Design – Students select questions they would like to answer, generate hypotheses about what they plan to observe, and design physical experiments and virtual models that will potentially confirm their hypotheses. In designing the virtual model, students typically define the possible variables, and conceptualize micro-rules or equations to describe the phenomenon.

B. Construct/program - Students structure both their physical experiment (e.g. a ball and ramp) and virtual model (e.g. a computer model of ball rolling down a ramp) both of which are intended to capture the phenomena under study.

C. Interact - Students gather data from their physical experiments using embedded sensors. Similarly, they collect data from the virtual model by changing parameters, and running it.

Different ways of resource allocation among these sub-activities could yield to various modes of implementation. In this study we have tested three different implementation modes of Bifocal Modeling (Design-Based Research, [5])

3. METHOD

The Biology Study: The first study was about bacterial growth. It lasted a total of about 13 hours, split across three sessions. The students' first task was to grow real bacteria using a set of supplied tools. They were also shown a short video about bacteria growth in a petri dish. Next, pairs of students conducted an online inquiry on bacterial growth curves and factors influential in bacterial growth. Then, the authors conducted a variation of "paper modeling" [3, 4]. In paper modeling, students draw the user interface and a frame-by-frame representation of a hypothesized computer model. In this particular session, students collectively designed an agent-based model of bacterial growth on a whiteboard. Finally, with intense scaffolding, students developed a virtual agent-based model of bacteria growth, ran it, and compared its result with reference patterns gathered from the physical experiment.

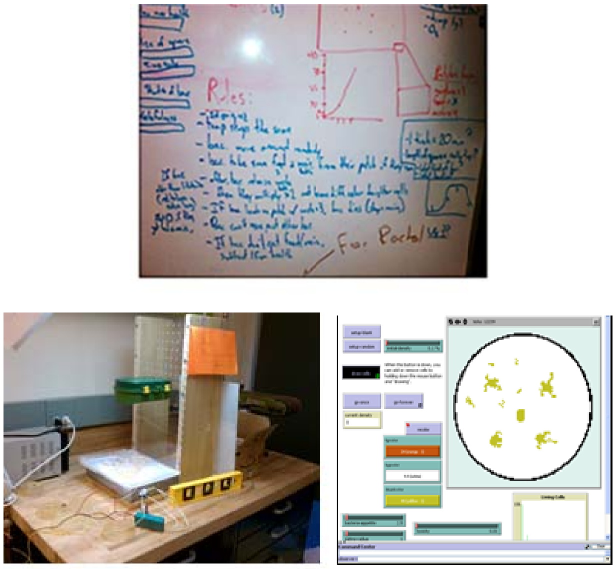

Figure 2: "Paper modeling," bacterial growth physical experiment, and virtual model

The Physics Study: The second study was about Newton's laws. During this study, which took a total of about three hours to complete, students were asked to study the laws governing a ball rolling down a ramp. We started with a short introduction and a movie about the phenomenon, which were followed by the students' first task: to design their own physical experiment. The supplies provided for the experiment included the ramp, a microcontroller-based sensing interface (GoGo Board), infrared sensors, and balls of different masses. When they finished experimenting, students were prompted to consider different factors that may have influenced the time it took the balls to reach the end of the ramp. At this point, they returned to the experimental apparatus, ran experiments again, and documented the effect of mass on the travel time of the various balls. The next task was to design a virtual model of the same phenomenon in a physics-engine platform called Algodoo [1]. This platform offers students a complete virtual world with all the laws of physics, together with many construction blocks that enable build a variety of systems. Using Algodoo, students tried to recreate the same conditions under which they had conducted their physical experiment and measure time for balls of different masses. Finally, they were asked to interact with a second computer model: a previously constructed agent based model of the same phenomenon. In this model, students once again measured the rolling time of the same set of masses. Finally, they compared the three sets of data collected from the physical experiment and the two different virtual models and were encouraged to explain the discrepancies in the results.

Figure 3: The physical ramp setup

The Chemistry Study: The final study was about the gas laws, particularly the relationship between volume and pressure in a closed system. This study lasted six hours and was conducted with a group of high school students. In this study, students did not design their own physical or virtual experiments. Instead, they undertook a number of experiments on laboratory apparatus that had been set up beforehand. Over the course of their experiments they were able investigate and collect data on various natural phenomena relevant to the project. For these activities, students were given two physical apparatuses and one virtual model. For their first assignment, students worked with a previously assembled syringe system, which contained pressure sensors to collect data regarding the relationship between pressure and volume. Next, students were provided with a NetLogo computer model of gas laws [6] which simulates the behavior of gas particles in a syringe. Students compared the data collected from the first physical system and the output of the virtual model. Finally, we gave them a second physical apparatus; a wooden box with a movable divider and multiple micro toy robots known as "hex-bugs," which represented the random movement of gas molecules within the box. We asked students to compare the behavior of the hex-bugs in the box with the gas molecules in the syringe. Additionally, the students could again interact with both physical systems and the virtual model and were asked to compare the behavior of the physical experiments with the data they gathered from the virtual model.

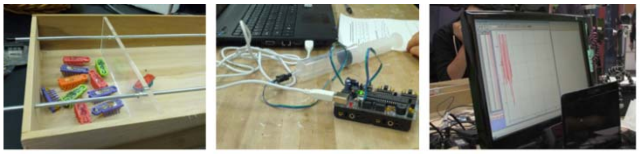

Figure 4: Gas laws: Hex-bugs box, physical experiment and virtual model

The first and third studies were conducted with 13 students (4 females and 9 males), ranging from 9th to 11th grades. The second study took place in an afterschool workshop session with two female high school students (9th grade). All students were given three questionnaires before and after the completion of the activity as well as a mid-test. Students were also videotaped during all activities, their computer usage was documented with screen-capture software, and researchers asked questions and kept field notes.

4. DATA AND DISCUSSION

Data presented here demonstrates the evolution of the students' meta-modeling knowledge in the three case-studies. The main focus is on students' understanding of the role of scientific models and their limitations.

I. Biology Study (bacterial growth): designing and developing a physical experiment and a virtual model

To examine student's meta-modeling knowledge, we included questions to gauge students understanding of the benefits and limitations of scientific virtual models in mid- and post-tests. In both mid- and post-tests, students were asked several questions about the difference between virtual models and real experiments[1]. The data shows that on the mid-test, 10 out of 13 students answered that a virtual model of a phenomenon is not the same as the phenomenon itself. However, their explanations of the differences between a virtual model and a real phenomenon were mostly generic and unspecific. Following are two quotes from students' mid-test:

Student D: "A computer model can make a good estimation but for real data, one needs to study the actual bacteria."

Student G: "…in the physical experiment we get to see the actual thing."

In both statements it is clear that the students evaluated the models but did not add specific explanations about their limitations. Data from the post-test, on the other hand, demonstrates that students had acquired more specific knowledge about the similarities and differences between a virtual model and the real phenomenon. At this point, the students' explanations were much more specific in discussions of the models' limitations. For example a few students described the "step" pattern in the model's graph and explained it by the lack of randomness in the virtual model. One of the students wrote on his post-test: "...I don't think the virtual model is similar to what is happening in real life, since ours [the virtual model] did not incorporate all of the actions of real bacteria, such as colonies…I believe that one reason for these differences is that the bacteria in our simulation were not very random."

Data show that students in the mid-test regarded the virtual model as differing very little from the real phenomena, while during the post-test 80% of students had more precise explanations about the limitations of the virtual model.

II. Physics Study (ball and ramp): designing a physical experiment, interacting with the virtual model

In this study, immediately after accomplishing the design and construction of the physical experiment, students started interacting with a pre-built model in the Algoodo physics platform. The Physics project differed from the Biology study in that the students did not design their virtual model*;* nor did they list the effective variables and the underlying rules of the phenomena observed. After running both the physical experiment and the virtual simulation of the phenomena, they realized that there are considerable discrepancies between the results of the physical experiment and those of the virtual model. However, despite their awareness of the discrepancies, it was difficult for students to determine their cause. Students had an inclination to attribute errors and discrepancies mostly to themselves or to other sources of human error rather than to limitations of the virtual model as is apparent in student R's conjecture: "Maybe it's more accurate [the computer model]! […] We had some problems positioning the sensor, but here, in Algodoo [the computer model], we do not have these problems!"

III. The Chemistry Study (Gas Laws): interacting with both the physical experiment and the virtual model

In the third case study, students interacted with one pre-made experiment and two pre-designed models, rather than designing them by themselves. The students' physical interactions included a syringe with a pressure sensor and a physical model of a box with tens of "hex bugs," or micro toy robots whose unpredictable and erratic movements and collisions were intended to emulate the random motion of gas molecules . The students also interacted with a pre-made virtual model of an isothermal piston in a gas chamber [6].

During the first two parts of the activity, students were supposed to gather data from the syringe using a pressure sensor and compare it with the results of the Netlogo model. During this phase of the experiment, students asked no questions, nor did they notice the discrepancies between these two data sets. When asked explicitly to compare the graphs (the data set gathered from the physical experiment against the data from the virtual Netlogo model), the students tended to place greater trust in the virtual model. In every case during this phase of the project, the students attributed the errors and limitations exclusively to the physical experiment—none of them questioned the computer model. They would state either, "our sensor is not accurate," or "we did not press the syringe correctly."

In the next step, students were introduced to a physical model of the "hex-bugs" box. The idea was to explain the relation between volume and pressure in a simple micro-level

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[1] "Do you think the virtual model is similar to what is happening to bacteria in real life?" and "A computer model of a cellular mitosis can simulate the aspect of cellular division quite well. However, microscopic observation of actual cellular mitosis can improve our understanding. Explain why."

experience, using the micro robots as gas molecules, and the box as a container that can change its volume. Note that the hex-bugs model was designed to look exactly like the corresponding Netlogo model: a box with randomly moving particles, which collide with one another. Interacting with "bugs" appeared to be a much more appealing task for them. Compared to their interactions with on-screen models, when students worked with a physical model we noticed more self-initiated discussions between students about similarities and differences between those models. This activity led students' to engage in discussions regarding three main themes:

1. *The constructional limitations of the "hex-bugs" box model and suggesting approaches to improving the model*. For example: "The number of hex-bugs is limited, we need to add more bugs", or "The bugs get on top of each other, let's change their shape into a square or program them to bounce off each other", or "they get stuck at the corners, let's change the shape of the container and make rounded corners".
2. *The conceptual limitations of the hex-bugs box model.* Students compared the behavior of the hex-bugs to the reality of molecular collisions. They also discussed the discrepancies between the bugs and gas molecules. For instance, one student talked about the way molecules move in space: "Gas molecules work in three dimensions, whereas hex-bugs work in two."
3. *Similarities between the model and real phenomenon.* Students also came up with some ideas about similarities between hex bugs and gas molecules, For example: "They both (bugs and molecules) move randomly, move fast until they bump into each other, hex-bugs push on their surroundings in a similar way to how gas provides force against their container."

5. CONCLUSION

Throughout this paper, we have suggested that students can develop a refined understanding of scientific models and their limitations through participation in Bifocal Modeling activities, yet this benefit requires specific design elements to be in place. In the course of bringing the Bifocal Modeling methodology into the classroom, we examined different implementation modes of conducting activities, documented in this paper in three separate case studies. All three cases utilized a virtual scientific model; however, only in the first study, which involved bacterial growth, did students both design (i.e., conceptualize) and develop (i.e., program) their virtual model. In that study, students directly addressed the limitations of their virtual models, which did not occur in the other two studies (the studies of the laws of motion and the gas laws). Involving students in both conceptualizing (designing) and programming (developing) a virtual model appears to support students' meta-modeling process to a greater extent. Active participation in the design and construction of the model helps students become aware of the underlying assumptions in their virtual models. Hence, students were able to understand the limitations of their own models, and even explain how to address some of them. We should note that, in the second study (the use of the ramp and balls to study Newtonian physics), students did not design the virtual model conceptually, so they did not have the opportunity to focus on the underlying assumptions and rules of the model. This may be the reason that they were unable to acknowledge the limitations of the virtual model. In cases of discrepancies between the physical phenomenon and the virtual model, students mostly tended to attribute those discrepancies to human error and the shortcomings of the physical experiments.

In the third case study (the investigation of the gas laws), neither the virtual model nor the physical experiment were designed by the students. During their interaction with the on-screen models, none of the students criticized any of those models or suggested possible improvements—their stance as "expert-made models" led students to believe that they were infallible. It was not until we presented students with the hex-bugs model, which was a physical "rendering" of an on-screen model, that students began to critically evaluate the virtual model. We suggest that this critical insight into the limitations of the virtual model may arise from students' perception of the limitations of its mechanical analogue. Even though it was no more or less adequate than the computer model and followed a very similar mechanism, the hex-bug box was not perceived by the students as "perfect"; consequently, as in the first study, they had sufficient confidence to evaluate its accuracy and to criticize it. Note that most of students' critiques of the hex-bug model would also apply to the on-screen version of it, which again points to the essential similarity of the two models. .

The preliminary results of these three case studies suggest that having students involved in designing and developing scientific models (rather than just interacting with pre-built ones) enhances their understanding of scientific models and their limitations. On the other hand, when students are provided with pre-made models, the affordances of the models as well as the context of the activity may affect students' critical evaluation of them. When students perceive a model as imperfect, they tend to more carefully evaluate the model and better address its limitations, leading to deeper learning about the phenomenon itself.

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