CONSTRUCTING MODELS AND LEARNING THROUGH THE PROCESS: MODELING-BASED LEARNING IN SCIENCE EDUCATION

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Abstract
Research in Modeling-based Learning (MbL) in science has highlighted its value and significance for science teaching and learning. Despite the abundance of research in the area, there is to date limited research on MbL practices among novice modelers. In particular, there is no information whether young (grades K-6), novice modelers follow the same modeling steps and practices of a MbL enactment. The purpose of this study was to investigate whether the modeling steps and practices, as described in MbL cycles in the literature, apply to K-6 students and if not, to describe the alternative steps that these students follow. Our findings revealed that K-6 novice modelers follow a different route when enacting MbL than the one described in the literature.

Keywords: science education, modeling-based learning, elementary school

1. Introduction

Modeling, which is defined as the process of developing representations of physical phenomena [1], plays a central role in the formation and justification of new scientific knowledge [2; 3] and it is a core activity of scientists' daily work [4]. Models are constructed through the involvement in the modeling process and seek to describe the underlying mechanism(s) that cause(s) the physical phenomena. In this sense, models have an important role in science both for formulating hypotheses to be tested and for describing phenomena [5]. Thus, science can be defined as the process of constructing models of physical phenomena, which includes the development of explicit representations that are analogous to the phenomena they represent, offering better ways to visualize and understand a phenomenon under study). Therefore, it is not surprising that research in science education acknowledges that models and modeling play a crucial role in the development of scientific literacy [6; 7; 8; 9; 10] and can support educators' ongoing efforts to introduce and engage students in authentic scientific inquiry. Viewing teaching science from this perspective provides a powerful approach that unites both the processes and the products of science [7].

Students' involvement in the process of modeling and the reiterative nature of constructing and refining models within a context, can achieve better learning outcomes. Modeling better supports conceptual and operational understanding of the nature of science and develops the ability to employ procedural and reasoning skills, than currently possible through other learning environments or tools [11; 12]. Additionally, it encourages student discourse and engagement by providing opportunities to think and talk scientifically about physical phenomena [13], to share, discuss and critique their ideas [14; 15] and to reflect upon their own understanding [6; 16]. We refer to this as the Modeling-based Learning (MbL) approach in science.

Despite the great emphasis of research on MbL in science, which has highlighted its value and significance for science teaching and learning, there is limited research on how students, especially novice/young modelers engage in MbL. Most of the theoretical structures describing the MbL process have been based primarily on the modeling work of scientists and on the theory and philosophy of science, with no reference to detailed data relating to actual enactments of modeling [e.g., 17]. While these descriptions may have been to some extent successful in describing expert modelers' MbL, it is not clear whether younger students follow these same steps or engage in other modeling stages and practices not currently reflected in the MbL cycle. Such an insight is crucial for understanding how MbL could be incorporated into educational practice, especially in early grades [18]. From our recent work in MbL [19; 20; 21], we have seen evidence that provides a reasonable basis for pursuing this issue further.

2. Theoretical framework

2.1. The Modeling-based Learning Cycle

The MbL process, widely known as the MbL cycle, as described by a number of researchers [1; 17; 22; 23; 24; 25; 26; 27], involves two phases: the model formulation and the model deployment. During the model formulation phase students develop a model about a physical phenomenon/system. They begin with the need to describe, predict and/or explain a physical phenomenon, which then guides them through the *Collection of observations and experiences* step. This involves the collection of experimental evidence and observations from the physical world. Their explicit purpose is to identify the parts constituting the physical phenomenon (physical objects, processes and entities), the processes that guide its operation and the interactions between the various constituents. This step is followed by the *Construction of the model* step involving the construction of a model of the phenomenon by integrating pieces of information about the structure, the behavior, and the (causal) mechanism of the phenomenon.

After a model is constructed to what the students consider a satisfactory level, they initiate the second phase, which consists of the deployment of their model in a new situation. In order to identify new situations in which their models can be applied, they need to decontextualize the constructed model and essentially reformulate it in a new context, in a way that enables them to make testable predictions (*Evaluation of the model* step). In all cases, students need to test one part of their model at a time, and evaluate it based on whether it can better describe or explain a given situation. This process can provide feedback for improvements and additions of new physical objects, processes and/or entities that are part of the physical system being studied (*Revision of the model step*).

2.2. Modeling as a cyclical process

Students usually go through the formulation and deployment phases several times, in a process of a step-by-step construction of the model from a simple to a more advanced level [28]. Complex models in science are developed "through a process of successive elaboration and refinement in which scientific models are created and modified to account for new phenomena that are uncovered in exploring a domain" [27, p.7]. The resulting final models (as well as the comparison between the initial models and the revised ones) may be used for evaluating students' developing understanding about the phenomenon under study, as well as the learning process itself. This evaluation may be based on various criteria concerning the necessary components of models [20; 29], which include representation of physical objects, physical concepts (object characteristics and object states), and their relationships.

2.3. MbL for novice modelers

Constructing models of physical phenomena that include analogical representations of the mechanism underlying the phenomena is a complex task [30]. Consequently, young and novice modelers encounter numerous challenges. Sins et al (2005) [30] provide a comprehensive summary of the literature describing a number of MbL related difficulties concerning the task perception, the content addressed, and the tools used.

Firstly, novice modelers tend to view a modeling task more as an engineering problem to solve, rather than a scientific one. Instead of focusing on the representation of the causal mechanism underlying the phenomenon under study, they focus on whether the model results in an output that is closely related to how the phenomenon looks [19; 31]. This in turn pushes them into a process of making adjustments to their model until the model output resembles the observed empirical data [32; 33]. This leads students to develop, what Grosslight et al (1991) [11] named, a phenomenological model; as Sins et al (2005) [30] state, the model becomes an artifact that has to "work", not something that provides explanatory power in understanding a phenomenon [32; 34].

Secondly, students have difficulties conceptualizing the complex phenomena. Especially so in relation with the representation of physical entities involved in the phenomena that are usually represented as variables and physical processes [30]. In complex physical processes even older, more experienced modelers seem to consider the influences of individual variables separately [e.g., 32; 33; 35], thus failing to represent or understand the connections and interactions between physical entities and physical processes.

Thirdly, novice modelers face difficulties in using modeling means and language as a way of representing their ideas. They find it challenging to express their ideas in a modeling formalism because of their limited experience with the modeling tools and the modeling process and epistemology itself [30]. For instance, students have difficulties in deciding the type of variable they would like to implement into their model and students also frequently struggle to specify the mathematical relationships between variables in the model [e.g., 36; 37; 38].

Research in Modeling-based Learning (MbL) in science has highlighted its value and significance for science teaching and learning. Consequently, considerable evidence has been accumulated about what comprises a model and a successful modeling-based learning enactment, which modeling tools could be used, as well as the difficulties students encounter when engaged in MbL science implementations (see [39] for a review). However, to date there is limited research on MbL practices among novice modelers. In particular, there is no information whether young (grades K-6), novice modelers follow the same modeling steps and practices of a MbL enactment. Such an insight is crucial for understanding how MbL can be incorporated into educational practice, especially in early grades ([40]. Our purpose in this study was to investigate whether the modeling steps and practices, as described in MbL cycles in the literature, apply to K-6 students (novice modelers) and if not, to identify the alternative steps that these students follow.

3. Methods

While maintaining the epistemological foundations of the modeling practices involved in the existing (dominant) MbL cycle, we followed ground research approaches [41] to revise the descriptions of the MbL cycle practices/steps to apply to young, novice modelers. We collected data from 4 classes of students, (two fifth-grade classes, comprising 33 students working in 10 groups; and two pre-K classes, comprising 41 students working in 11 groups). All students had access to a variety of modeling media (computer-based programming environments, paper-and-pencil, 3-dimensional materials) to construct models for the same physical phenomenon, namely dissolving substances in water. Data collection took place over two semesters, during the first semester we examined the fifth-grade groups and in the second semester the pre-K groups. The duration of the study for each group varied between 3-5 weeks.

We used transcripts of student conversations and student constructed models as the primary data sources. Student conversations were coded for modeling practices [11] (Table 1) and for activity patterns [31] (Table 2) and each utterance was analyzed separately. All codes used were developed during the Authors' other studies over the past decade, following the same line of research regarding MbL, and these were combined to provide a detailed picture of combined analyses.

Coding Categories	Code Description
Description of the story of a physical object or a physical system	Students talked about the overall story of a physical system or a physical object. This usually involved descriptions about what would happen to the overall physical system, without any reference to the mechanism that was actually causing the overall phenomenon or the behavior of the object.
Description of experiences /data in support of the story of the physical system	Students used experiences from the physical world to support their answers or ideas in the conversation.
Description of physical processes conceptually	Students described a physical process (such as change in position, change in velocity etc.) qualitatively, without any reference to the mechanism that was actually responsible for causing the changes in the physical process.
Quantitatively	Students described a physical process (such as change in position, change in velocity etc.) by using numerical examples. No reference was made about the mechanism that was actually responsible for causing the changes in the physical process.
Operationally defined	Students described a physical process (such as change in position, change in velocity etc.) by describing a series of actions that would result in the physical process.
Description of physical entities conceptually	Students described a physical entity (such as velocity, acceleration etc.) qualitatively, without any reference to the mechanism that was actually responsible for causing changes in the physical entity.
Quantitatively	Students described a physical process (such as velocity, acceleration etc) by using numerical examples. No reference was made about the mechanism that was actually responsible for causing changes in the physical entity.
Operationally defined	Students described a physical entity (of changes to a physical entity) (such as velocity, acceleration etc.) by describing a series of actions that would result in the physical entity (or the changes in the physical entity).

Table 1. Codes used for analysis of modeling practices, adopted from [19]

After analyzing all conversations from the 21 student groups, the three discourse analyses for each student group were combined in a timeline graph that displayed students' total work under investigation. Figure 1 is an example of a timeline graph from a particular group of students. By comparing and contrasting these timeline graphs (within and across age groups), we identified similarities in the code-revealing patterns. These subsequently guided the development of emerging themes, which in turn ultimately directed our descriptions of the various steps of the MbL.

Activity patterns
Explore the modeling medium/materials
Construct the model (typing or drawing or gluing)
"Read"/describe the model
Make corrections to the model for depiction
Make corrections to the model for science
Make corrections to the model for fitting to their story
"Create" variables
Try out the model
Identify model flaws

Table 2. Codes used for analyzing student activities during MbL, adopted by [31]

To support the discourse analyses, we also collected the student-constructed models, which were analyzed using a coding scheme developed elsewhere [20] (Table 3). The findings from this analysis were added to the timeline graphs, aligning the analysis and timing of each model construction to the graphs, so that these could support the initial data. Each author coded all data independently and differences were resolved through discussion.

Category	Codes
1. Representation of physical objects	1.1. Physical objects internal to the physical system 1.2. Physical objects external to the physical system
2. Representation of object characteristics (physical entities)	2.1. No representation of physical entities 2.2. Represented with a non-variable numerical value 2.3. Represented with both a variable & a non-variable numerical value 2.4. Represented with a variable
3. Representation of object behaviors (physical processes)	3.1. Non-causal 3.2. Semi-causal 3.3. Causal

Table 3. Codes used for analysis of student-constructed models adopted from [20]

4. Findings

Our findings revealed that K-6 novice modelers follow a different route when enacting MbL than the one described in the MbL cycle in the literature. More specifically, we found that the content and the context of the various modeling practices/steps differ, as well as the sequence in which these modeling practices occur. Our findings also identified a four step MbL "cycle", but this differs from the one described in the literature. Below we provide a summary of our findings for each step separately.

4.1. Step 1: Investigating the physical phenomenon

Our data suggest that the MbL "cycle" begins with students studying parts of the physical phenomena. Figure 1 provides a timeline graph representing data analyzed form a group of students. Despite the fact that literature suggests that modelers enter this step with the explicit purpose of constructing a model to describe the physical system's aspects and behavior, our data suggest that this is not the case for novice modelers. In most student groups studied, such a specific purpose transpires over time or after modeling experience. Moreover, prior experiences appear to be a significant repository of data and information for students enacting MbL, with students referring to their experiences to develop a model representing the phenomenon under study. The first step of the MbL cycle ends when students reach consensus about the story describing the function, behavior and/or characteristics of the physical phenomenon under study.

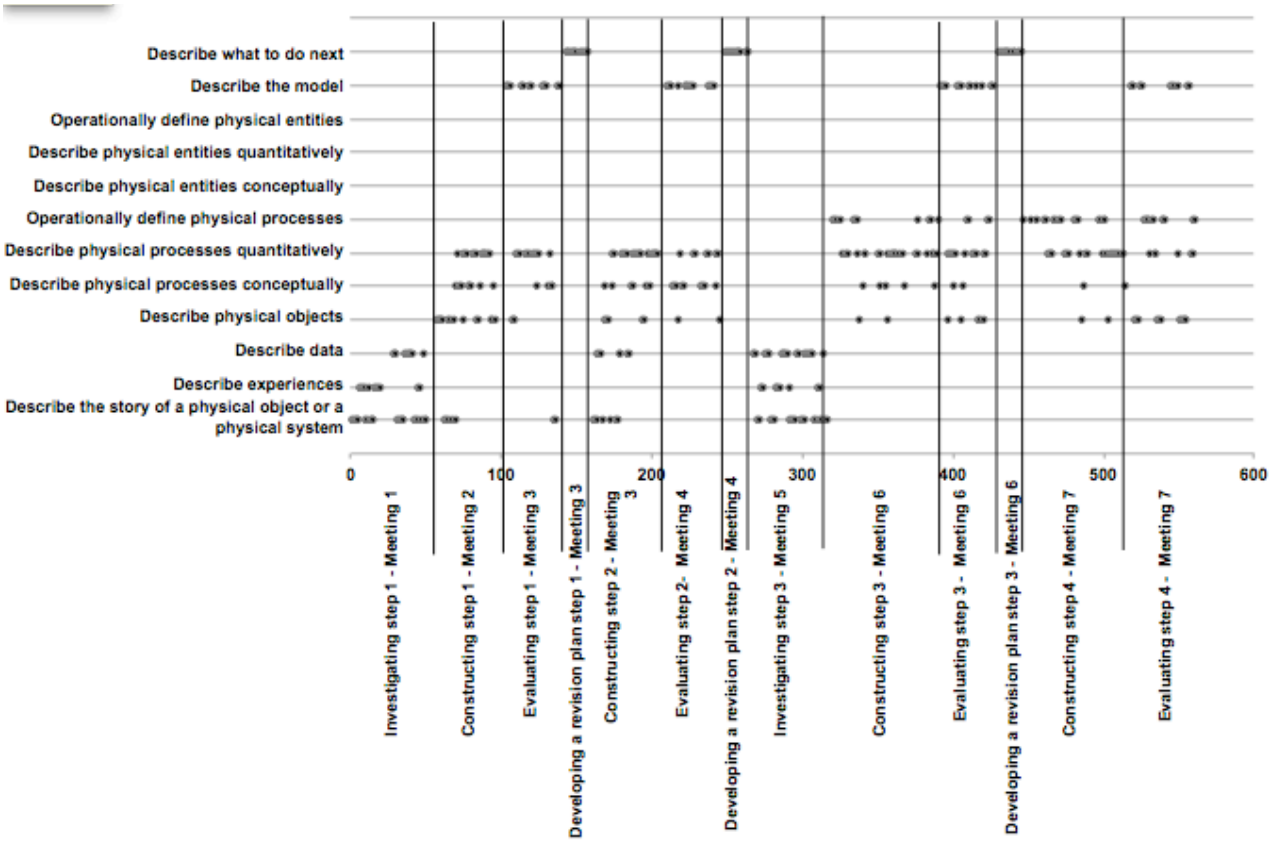

Figure 1. Timeline graph of coded discourse for student group 4.

4.2. Step 2: Constructing a model of the phenomenon

Our data suggest that the construction step of the MbL "cycle" involves two different practices: planning and development. Planning mostly consists of breaking down the studied phenomenon into small pieces that can be incorporated into a model. In this sense, the process of planning is a process of identifying parts of the phenomenon. This is a major difference from the existing MbL cycle descriptions in the literature. In fact, our data suggest that this is probably one of the more crucial aspects of modeling for novice modelers. The data suggest that novice modelers need to start developing a model in order to realize that they need to look for the components, which represent parts of the phenomenon.

The second practice in this step is the development of the model. This process looks like the "writing and debugging" process of formal programming. Learners collect data and experiences, they agree on a story describing the phenomenon under study, they identify the major components of their models, they construct a model, they talk about it, they make small changes based on the agreed story of the phenomenon, they talk about it more, and they make additional small changes until they feel that this representation matches the story of the physical system they agreed on in the previous step. This back-and-forth process is not a formal evaluation of the constructed model, but rather a process of reaching the representation/model they agreed to construct initially. During this step, students actually invent the physical object, the physical processes and the physical entities comprising the phenomenon.

4.3. Step 3: Evaluating the model

When students feel that they have constructed a satisfactory model, they move towards a process of formal evaluation. For novice modelers this process does not start automatically; rather the teacher needs to initiate it. Our data show that learners compare their model to the actual phenomenon, examining whether their model accurately represents the phenomenon under study and if their model's use explains how the phenomenon takes place. We have found limited data where novice modelers deploy or decontextualize their model into a new situation or phenomenon in an effort to evaluate its explanatory power, as suggested by the literature. Rather, we have found that the process of model evaluation can take two major forms. First, learners use their model to see whether it can explain the data they collected, or the experiences they recalled or used as a starting point for the model's construction. Second, they evaluate their model in terms of logic; that is whether the model represents a plausible mechanism that can account for what is observed.

4.4. Step 4: Developing a revision plan

A major change from previous MbL cycles is that any revisions of the constructed model, resulting during a particular modeling "cycle", occur within the investigation and construction steps of the following "cycle" of the modeling enactment. As a result, this eliminates the revising step as an independent step in the MbL cycle. In our revised MbL cycle, revision becomes an epistemological or a meta-modeling process, in which students decide which route is more appropriate to follow for revising their model. Either they collect more data or discuss new experiences with the phenomenon they have not previously talked about, prior to moving into the process of model construction or they move directly to the construction step of the MbL cycle, as they have the required data, observations or experiences to re-construct or alter their model. This is another difference from the literature, as the students move from one cycle to the next, the development of a revision plan step can lead them either to the investigating a physical phenomenon/system step or directly to the constructing a model step.

5. Discussion

This study has been motivated by research's acknowledgment that models and modeling play a crucial role in the development of scientific literacy [5; 6; 7; 8; 9]. Even though research has placed great emphasis on MbL in science [1; 17; 22; 23; 24; 27] there is limited research on how students, especially novice/young modelers engage in MbL [19]. Starting primarily from theoretical structures from the philosophy and theory of science, existing literature suggests that the modeling process usually followed by expert modelers (e.g., scientists and engineers) involves a stimulus and four discrete steps, namely *Collection of observations and experiences*, *Construction of the model*, *Evaluation of the model* and *Revision of the model*, and that these follow a cyclical pattern [e.g., 1; 17].

While these steps may have been to some extent successful in describing expert modelers' MbL, the findings of this study show that novice/young modelers do not follow the same cyclical path when enacting modeling. Findings that we report in this study suggest several deviations in the content and the context of the various modeling steps from those found in the literature, although they follow the epistemological premises of MbL in science. Deviations are also found in the sequence in which these modeling practices occur. Based on these data, we propose a revised MbL cycle for novice modelers that includes four MbL steps, namely (a) investigating the physical phenomenon/system under study, (b) constructing a model of the phenomenon/system, (c) evaluating the model, and (d) developing a revision plan. These have been presented in detail in the findings section.

The first major difference found from previous MbL steps [1; 17; 22; 23; 24; 27] is that any revisions of the constructed model, arising during a particular modeling cycle, occur within the *investigation and construction steps* of the following cycle of modeling enactment. As a result, the revising step, as an independent step of the MbL cycle, is eliminated. In our revised MbL cycle this revision related step/practice becomes an epistemological knowledge procedure. This is described in the literature, as a process that involves meta-modeling knowledge [20], in which students decide which route is more appropriate to follow for revising their model.

Furthermore, our findings suggest that analyzing happens within the *constructing the model step* of the process, and not during the *investigating step*. Sins et al (2005) [30] describe analyzing as involving decomposing the phenomenon under study into smaller parts, in addition to identifying important model elements to be included in the model. This helps students to decide the type of model to construct as well as to identify the variables and relations that need to be implemented in their model [1; 17]. Our findings imply that most of the learning in MbL, including developing understanding of how the phenomenon works by constructing representations of the phenomenon, takes place during *the constructing the model step*. Of course, this does not undermine the role of the remaining MbL steps.

As our data show, the *constructing a model step* is far more complex than we have thought thus far. It appears that the construction of a model itself also includes processes, such as *synthesizing* which involves inductive reasoning, and requires that students mentally bring the model's content/elements together in order for the model to take shape. This cognitive process takes place during the actual construction of their models and seems to be supported by the context of model construction [30].

A second difference arising from our findings is that MbL is not a cyclical process per se, but a spiral one. Students seem to follow the cycle of investigating, constructing, evaluating and developing a revision plan, but each consecutive modeling cycle deals with a different feature of the physical phenomenon/system studied and modified models usually have more advanced features than the previous models.

A third deviation from MbL cycles described in literature, which relates to the previous point, is that as the students move spirally from one cycle to the next, the *developing of a revision plan step* can lead students either to the *investigating step* or directly to the *constructing a model step*. In many cases throughout the study we saw students bypass the *investigating step*, simply because they felt that they already had information that could help them substantially revise their model.

An additional feature of the modeling discourse, which was somewhat neglected in previous studies, is that we have seen students engage in the cognitive process of *reasoning* more actively during the whole class *evaluating step*. During this step, we have provided data that show students reason on the model elements that are or need to be included in their models, and how these should interact with each other, in order for models to behave in a certain way. This concurs with findings from prior research [e.g., 30]. This process includes detailed elaboration on the relationships between the model structure and the behavior of the phenomenon being modeled.

Our findings also revealed that this latter feature of the modeling discourse relates to the modeling media used. Although, in this study we have seen similar discourse and artifact patterns in both age groups (while using different modeling media), we feel – and we agree with previous literature [13; 21; 27; 31; 33] - that computer-based modeling tools enable students to construct better and more advanced models of physical phenomena, which include causal mechanisms and physical entities, than other non-dynamic modeling tools (e.g., paper and pencil). The fact that the fifth graders felt the need to switch modeling means is further support in favor of this argument. That K students did not include any physical entities in their models (in both motion and plant units) might relate to the modeling means or of course, the absence of physical entities from the K students' models might relate to the students' age (maturity level). Needless to say, this needs to be further investigated in the future.

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