Right but Wrong: The Independence of Mechanistic Reasoning and Canonical Understanding in Studying Diffusion

Tamar Fuhrmann[1], Leah Rosenbaum[1], Adelmo Eloy[1], Aditi Wagh[2], Jacob Wolf[1], Paulo Blikstein[1], Michelle Wilkerson[3]
Teachers College, Columbia University, NYC, NY, USA[1]. MIT, Cambridge, Massachusetts, USA[2]. University of California Berkeley, Berkeley, California, USA[3]

Abstract: This study explores how the interplay between data analysis and model design shifts 6th-grade students' understanding of diffusion from simple to sophisticated mechanistic reasoning and from non-canonical to canonical ideas about diffusion. Using mixed-methods qualitative analysis, we determine students' mechanistic reasoning and ideas about diffusion at five different points in a curricular sequence using a new tool for computational modeling called MoDa. With this data, we present a framework for the relationship between students' developing mechanistic reasoning and their canonical understanding, suggesting that they develop independently. Further, we illustrate how the computational modeling environment, MoDa, used in this study pushed students' mechanistic reasoning toward sophistication. Moreover, in allowing them to explore non-canonical mechanisms, MoDa supported their convergence on canonical scientific ideas about diffusion.

Introduction & Background

Mechanistic Reasoning (MR) is a powerful thinking strategy that allows one to explain and make predictions about a scientific phenomenon (Machamer, Darden, & Craver, 2000; Salmon, 1979). Within science education, MR is defined as a particular type of causal systematic reasoning that involves the explanation of (1) the sequential stages, from input to output, of the underlying causal events leading to a scientific phenomenon and (2) the relationship between factors that give rise to a phenomenon (Krist et al., 2019; Louca, Zacharia, & Constantinou, 2011; Machamer et al., 2000; Perkins & Grotzer, 2000; Russ et al., 2008; Springer & Keil, 1991). In the past decade, science education reforms (National Research Council, 2012; NGSS Lead States, 2013) called for integrating mechanistic thinking as a crosscutting concept into science instruction and for constructing and applying mechanistic accounts as part of building disciplinary knowledge (Lehrer & Schauble, 2006; Schauble, 1996). According to Russ et al. (2008) and Krist et al. (2019), the use of MR is related to science content knowledge but can also be distinct from it. MR describes the structure of an account of a scientific phenomenon rather than the particular knowledge elements that the account contains (Russ et al., 2008). Thus, an account can be structurally mechanistic (e.g., explain how and why a phenomenon occurs based on proposed underlying processes) but canonically incorrect.

One way for students to develop their MR skills is to explain phenomena by creating models. Designing computer models is one such promising approach that combines the advantages of traditional modeling with computational literacy, opening new possibilities for inquiry-based learning (Wilkerson, Wagh & Wilensky, 2015; Blikstein & Wilensky, 2009).

In science classes, models are often used to confirm a theory rather than as an inquiry tool. As they typically interact with final, canonical models, students seldom have the opportunity to use models to test and explore their own hypotheses. Additionally, students rarely see the lengthy process of model development (Krajcik et al. 2012) and, as a consequence, may not appreciate the role of scientific inquiry and iterative data-based verification in designing canonical models. Understandably, most teachers only use models to illustrate phenomena due to the time required to design such models. As a result, most students only interact with and manipulate ready-made models without participating in their design. With these challenges in mind, MoDa was designed, a web-based, domain-specific, block-based computer modeling environment (Fuhrmann et al., 2022; Wagh et al., 2022).

The paper investigates the implementation of a MoDa diffusion unit (*How Ink Spreads in Water*) with 6th graders. This unit was designed based on the Bifocal modeling framework (Blikstein et al., 2014; Fuhrmann et al., 2018) and addresses diffusion, which is generally challenging for students (Sanger, Brecheisen, & Hynek, 2001). This study investigates the relationship between students' developing MR skills and the accuracy of their scientific knowledge of diffusion. Our research is guided by the following questions:

1. What is the relationship between the level of sophistication of students' MR and their understanding of a scientific phenomenon?
2. In what ways can modeling activities support students in developing MR and canonical understandings of scientific phenomena?

Designing the MoDa Environment. The MoDa environment was designed under the DRK-12 NSF grant award *(DRL-2010413*) and targeted middle school students and their teachers. MoDa is an integrated environment that combines building computational models using domain-specific code blocks (Wilkerson, Wagh & Wilensky, 2015) and comparing models with real-world data (Blikstein, 2014; Fuhrmann et al., 2018; Gouvea & Wagh, 2018). The use of domain-specific blocks means students don't need to learn text-based programming and can instead focus on the scientific ideas. The comparison of the computer modeling results with video capturing the phenomenon in real life helps students refine and validate their models. In creating models to explain the scientific phenomenon, students evaluate competing explanations and model the mechanisms that underlie scientific observations. The MoDa environment consists of a modeling area and a real-world data area (Figure 1). The modeling area includes: 1) block-based coding where students can program their models using domain-specific blocks built on Google's Blockly library; 2) a simulation of the students' coded models based on the NetLogo engine (Wilensky, 1999); and 3) data visualizations that illustrate the modeling results in graphs. For this diffusion unit, the real-world data is a video of ink diffusing in hot and cold water.

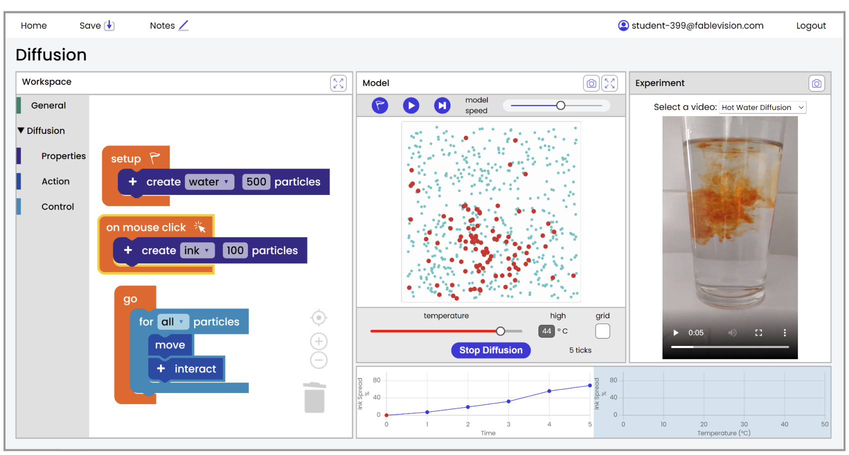

Figure 1: Unit 1, *How Ink Spreads* in MoDa-computational modeling and data environment

Methods

Participants. The study occurred in a private school in California. Students from two 6th grade science classes taught by the same teacher participated in the study. Across the two classes, 16 students consented to participate[1] (8 girls, 6 boys, and 2 non-binary students).

Instructional Sequence & Data Sources. The unit took place over eight class periods and included activities to explore ink diffusing in hot and cold water. Students conducted an experiment with ink in water, drew paper models to explain diffusion, designed computer models using MoDa, and compared their models with videos of the experiment. The science classes did not meet every day of the week, so a few days passed between days of the instructional sequence. We draw on five data sources, indicated by the day of the instructional sequence and bolded in the timeline in Figure 2. These five data sources are of varying modalities: written/typed responses to open-ended questions, models drawn on paper, and verbal descriptions of computational models shared during class presentations.

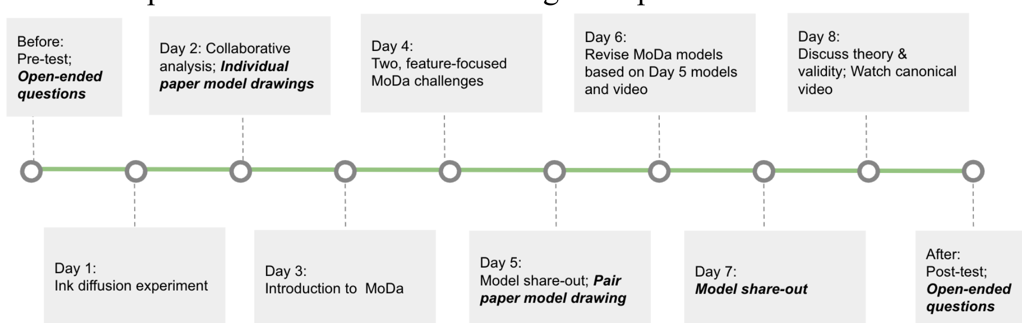

Figure 2: The instructional sequence of the diffusion unit and ***data source*** used in the study

Data Analysis

Each data source was coded separately to assess students' MR skills as well as whether their explanation of diffusion was canonical or not. In coding students' reasoning skills, we used a modified version of Russ et al.'s (2008) framework for MR, omitting the first two codes (rubric omitted due to space restrictions). Two researchers independently coded all 5 data sources, achieving at least 92.5% match rate on a training set of 5 students and at least 85% match rate on the subsequent students' data. Students' statements about diffusion were coded in a grounded fashion (Chong et al., 2015). Two researchers identified keywords from students' responses, drawings, and models (Table 1) and judged each student's understanding to be either canonical or non-canonical.

Table 1. Rubric for canonical understanding of diffusion

Canonical		**Non-canonical**	
Idea	*Example Responses*	*Idea*	*Example Responses*
Particles interact by bouncing.	"when the ink and water particles collide, they bounce off of each other"	Other particle interaction	"Spreading throughout the water molecules and attaching to them as they go." "water particles making a barrier"

[1] On Day 2 of the instructional sequence, two students were absent, leaving a total of 14 for Day 2 only.

Particles move faster with heat	"The hotter the water, the faster the water particles move."	Other effect of temperature	"if the water was cold, it would be more solid in a way. [...] if the water is hot or warm it flows better?" "cold [water] has a density, hot has air bubbles"

Results

Throughout the unit, we document a shift in students' understanding of diffusion. Students initially presented non-existent or non-canonical explanations for diffusion, with more students demonstrating a canonical understanding as the unit progressed. For example, ideas like "ink dissolves in water" disappear after Day 2. The canonical idea that "particles bounce off each other" gained traction throughout the unit (Figure 3).

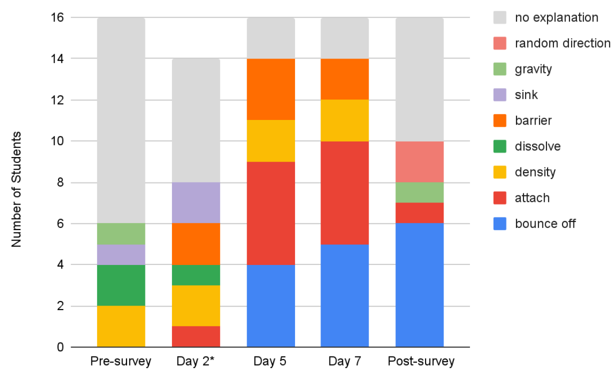

Figure 3: Student explanations for diffusion through particles' interaction

Across the instructional sequence, we also document a shift in students' mechanistic explanations of diffusion (Figure 4). The number of students using MR grew dramatically, though it somewhat decreased in the post-survey. On Day 7, all students exhibited MR skills.

We suggest that students' shift in MR skills and their shift to conceptual understanding of diffusion developed independently. From the pre-survey to Day 2, over four times more students included MR in their explanations for diffusion, but none of the student responses represented a canonical understanding of the phenomenon. By Day 7, all students included mechanisms for diffusion, but only seven students submitted canonical explanations.

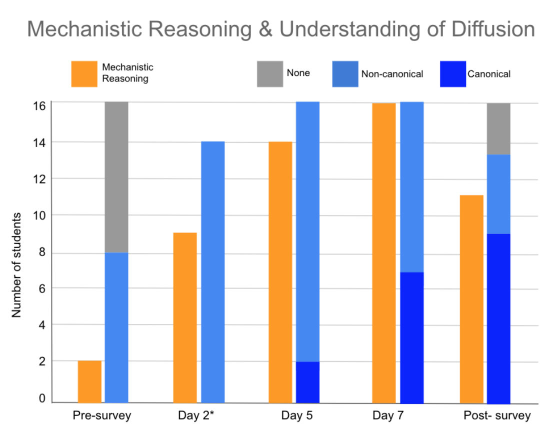

Figure 4: MR and conceptual understanding of diffusion.

Discussion & Conclusions

Based on the data, we propose a new framework to illustrate the independence of students' MR and their canonical understanding of diffusion (Figure 5). It illustrates four types of learners, from students with simple MR and no canonical understanding of diffusion (#1); to students with sophisticated MR and canonical knowledge about diffusion (#4). This framework holds two implications. First, when exploring a new phenomenon, we cannot assume that students already have well-developed theories about its underlying mechanisms. Instead, we must create opportunities for students to explore, develop, and share their theories. Second, to achieve a canonical understanding of a phenomenon, students' explorations of possible theories must be structured to allow them to validate their theories. This validation can occur through formalized trials that compare a theory's outcome to an experimental outcome and through classroom discourse in which students negotiate their ideas with their peers.

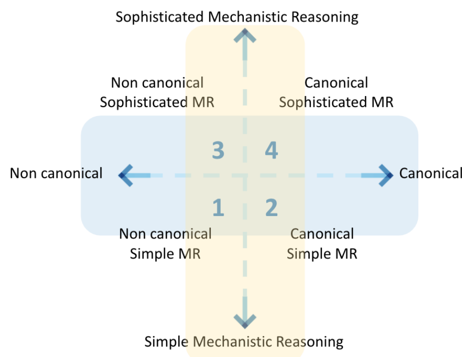

Figure 5: Proposed framework for the independence of students' developing MR and their canonical understanding.

While the scope of this paper does not allow us to show case studies for each quadrant in the framework and cannot illustrate the link between specific features of MoDa and students' development of MR or canonical ideas, the framework implies that, while related, MR and the development of canonical ideas must be attended to as distinct components of students' learning. Because MoDa includes both model building (theory development) and data analysis (theory validation), we hypothesize that these two activities, and more specifically their juxtaposition within the same learning environment, allow students to develop MR in concert with their development of canonical ideas about a phenomenon. Future work could validate this hypothesis by exploring the impact of specific features of MoDa on students' learning.

We acknowledge the limitations of the above analysis, primarily the use of the same coding rubric on data of varying modalities: written responses to open-ended questions, drawn models, and verbal presentations. It could be that certain of these media capture components of students' MR or understanding of diffusion less available in other media. Nonetheless, we maintain that exposing the different ways in which each media may or may not capture student understanding could, with a further systematic investigation, contribute to the research on students' reasoning and understanding.

This study contributes the proposed framework for the independence of students' developing MR and canonical understanding of diffusion. Given the implications of this framework, our future work will show how a modeling environment's juxtaposition against real-world data, such as MoDa, can be especially effective tools to support students' development of both MR and canonical understanding.

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