Applying the 'Models Of' versus 'Models For' Heuristic to Support Teachers' Learning of Modelling Practices used in Molecular Biology Research

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Abstract

In the United States, the Next Generation Science Standards (NGSS) were published to move science education towards instruction that is rich in content and practice across disciplines. NGSS expects K-12 science teachers to use the practices of scientists to teach disciplinary core ideas [1,2]. One challenge to translating the NGSS to the classroom is the lack of resources and programs that model and feature the science practices [3]. The SHAPE MATTERS program is funded by the National Institute of General Medical Sciences; one of its goals is to increase teachers' knowledge of scientific practices involved in molecular biology research. The program used molecular stories, around diabetes, to engage teachers in "Modelling of" and "Modelling for", because using only "models of" creates a false sense that models are merely representations of the real thing rather than for posing questions and generating and refining knowledge [4].

During the professional development, teachers learned how the structures of proteins are determined using x-ray crystallography, and how scientists make decisions based on data to generate a 3D model of a protein. This model is published in a freely accessible public database, the Protein Data Bank (PDB). Using various PDB insulin files, teachers used JUDE, a molecular visualization program, to examine the active form of insulin, the monomer. Then, teachers looked at the dimer, and finally how insulin was stored as a hexamer. The workshop culminated with a JUDE investigation looking at different designer insulins to answer structure-function questions about how insulin was altered to control blood sugar in diabetes. Teachers were given a modified version of the Students' Understanding of Models in Science instrument [5] as a pre/post test. In cohort 1, multiple participants reported that they agreed or strongly agreed that models were exact replicas. Due to this finding, we altered the workshop in the following years to further highlight uncertainty. Cohorts 2 and 3 had the largest pre-post difference for the Models as Exact Replicas. This difference suggests that the changes made due to the evaluation data had a greater impact on participants' understanding.

Keywords: *Teacher Professional Development, Modelling, Molecular Biology, Science Practices*

1. Introduction

In the United States, the Next Generation Science Standards (NGSS) were published to move science education towards instruction that is rich in content and practices across disciplines. NGSS expects K-12 science teachers to use the practices of scientists to teach disciplinary core ideas [1,2]. This way of teaching emphasizes the importance of not separating the doing from the knowing [6]. Creating learning experiences for students to develop and use both scientific knowledge and scientific practices simultaneously places significant demands on teachers [7,8].

The NGSS names 8 scientific practices: 1) asking questions, 2) developing and using models, 3) planning and carrying out investigations, 4) analyzing and interpreting data, 5) using mathematics and computational thinking, 6) constructing explanations, 6) engaging in argument from evidence, and 8) obtaining, evaluating, and communicating information [2]. Research indicates that relatively few teachers exhibit nuanced understandings of scientific practices that go beyond the rigid, linear scientific method presented in textbooks [9]. This rigid understanding of the scientific practices can be attributed to a number of factors including: most science teachers lacking authentic scientific inquiry experiences [10, 11]; undergraduate science courses tend to include labs that are confirmatory in nature [12]; and most teacher preparation programs do not require their students to participate in experiences that could provide them with more informed views of the process of scientific inquiry [13].

One challenge to translating the NGSS reforms to the classrooms involves the lack of resources and programs to support teachers' development and enactment of a practices-focused curriculum [3]. In addition, designing quality curriculum to meet the three dimensions of the NGSS is a demanding, multiyear, multi-expert process that requires expertise in science, science learning, assessment design, equity and diversity, and science teaching [14]. Successful implementation of high-quality instructional materials requires ongoing and sustained professional learning for teachers [3,15,16].

The **SH**aping **A**uthentic **P**ractices by **E**ngaging in **M**odelling of **A** **T**opic with **T**eachers to **E**xplore **R**esearch in **S**cience (SHAPE MATTERS) program was designed to increase teachers' knowledge of the scientific practices, specifically developing and using models, involved in molecular biology research. SHAPE MATTERS is funded by the National Institute of General Medical Sciences Science Education Partnership Award with a multi-disciplinary team. The team consists of expertise from the Penn State College of Education, College of Medicine, and Eberly College of Science. The team chose to focus on the practice of modelling for multiple reasons including: 1) its presence in molecular biology research at Penn State, 2) teachers' views for how to use models for student learning are highly teacher-centered, mostly describing how they, as teachers, can use models rather than how students can use models for promoting their own learning [9]; 3) and teachers frequently view models as teaching tools for representation and explanation but miss using models for developing questions, generating data, making predictions, and communicating ideas [9].

Molecular biology is an ideal discipline to explore the practice of modelling with students. Molecular biology instruction is loaded with visual representations including, but not limited to, cell membranes, organelles, macromolecules like proteins, and biochemical pathways. These structures are also presented in a variety of ways [17]. For example, proteins alone are represented in multiple formats including cartoons, backbone format, space-fill models, ball-and-stick models, ribbons, and "pac-man" cartoons [17]. Yet, students are not taught how to interpret biomolecular representations. The most common use of visualizations in the classroom is merely exposure [17]. Engaging students in modelling as a scientific practice can help students to develop a more sophisticated understanding of natural phenomena and the nature of scientific research [18,19].

To provide teachers with a window into the practice of developing and using models in molecular biology, we used the *modelling of* and *modelling for* framework. *Modelling of* focuses on mapping between the real molecule and its representation while *modelling for* emphasizes the ways in which models are built and used in science as tools that support inquiry and exploration [4]. Using only *modelling of* in the science classroom creates a false sense that models simply map onto the real world in some one-to-one way [4]. During the workshop, we engaged teachers in both *modelling of* and *modelling for*. Using a mixed method formative and summative evaluation, we seek to answer the following question: *To what extent do teachers who participate in the Summer Workshop increase their knowledge and skills in developing and using models in molecular biology?* Findings from this work contribute to understanding of how teacher professional development programs can be designed to build teachers knowledge of specific practices, such as developing and using models.

2. The Professional Development

The SHAPE MATTERS program is a two-week summer professional development program funded by the National Institute of General Medical Sciences Science Education Partnership Award and recruits secondary science teachers, specifically biology and chemistry teachers, in Pennsylvania and other eastern states. Over the course of the program, we have offered three two-week long workshops at the Penn State University Park campus in 2021, 2022, and 2023.

One of the SHAPE MATTERS program goals was to increase teachers' knowledge of the scientific practices, specifically developing and using models, involved in molecular biology research. The program focused on a storyline of diabetes as it is a global health epidemic. The number of people with diabetes rose globally from 108 million in 1980 to 422 million in 2014 [20], and its prevalence continues to rise. Due to its increasing level of incidence, most students will know someone who has diabetes or even may be affected themselves.

During the two-week workshop, we engaged teachers in *modelling of* and *modelling for* using molecular stories around diabetes. Molecular stories explore why a protein is important and how the structure of the protein relates to its function. Multiple molecular stories can be explored using diabetes as a context like insulin structure and function, designer insulins, glucagon, GLP-1 agonist drugs, glucose transporters, and many more. The workshop was intentionally designed to include and alternate between *modelling of* and *modelling for* such that teachers experienced both approaches and gain a deeper understanding of the ways in which scientists develop and use models in authentic research (Tab. 1).

Tab. 1. SHAPE MATTERS Workshop Activities and Modelling Practices

Workshop Activity	Modelling Practice
Water Kit (3-D Molecular Designs)	*Modelling of*
Process of Crystallizing Molecules	*Modelling for*
Amino Acid models and Starter Kit (3-D Molecular Designs)	*Modelling of*
X-ray Crystallography Lab - from crystals to 3-D visualizations	*Modelling for*
Insulin MRNA to Protein Kit (3-D Molecular Designs)	*Modelling of*
Exploring the Protein Data Bank	*Modelling for*
JUDE Tutorials and 3-D Printing - 3-D models	*Modelling of*
Investigation of Designer Insulins	*Modelling for*
Developing Molecular Stories from Research at Penn State	*Modelling for*

Teachers engaged in *modelling of* by using classroom molecular modelling kits from 3D Molecular Designs, including: 1) the Water Kit, 2) amino acid building block models, 3) the Amino Acid Starter Kit, and 4) Insulin mRNA to Protein kit. These kits were used to help build teachers' content knowledge, to map between a real molecule (insulin) and the representation being used, and to prepare teachers to engage in *modelling for* later in the workshop. Teachers engaged in *modelling for* through learning how the structures of proteins are determined using x-ray crystallography and how scientists make decisions based on data to generate a 3D model of a protein. Models generated from x-ray crystallography are published in a freely accessible public database, the Protein Data Bank (PDB). Using various PDB insulin files, teachers used JUDE, a molecular visualization program, to examine the active form of insulin, the monomer. Then, teachers looked at the dimer, and finally how insulin was stored as a hexamer. The workshop culminated with an open JUDE investigation looking at different designer insulins. Teachers worked in small groups to answer structure-function questions about how insulin was altered to control blood sugar in diabetes. Teachers were then paired with a research mentor to engage in molecular modelling of current research projects at Penn State.

3. Teacher Participants

The project team recruited a total of 24 teachers over three different cohorts: eight teachers in 2021, four teachers in 2022, and twelve teachers in 2023. More than half of teachers (63%) taught in Pennsylvania schools. Teaching experience varied, with 42% of teachers reporting they had been teaching for 11 to 20 years. Teachers also indicated that they taught a range of subjects, the most common being biology (67%). Most teachers (88%) indicated their highest degree earned was a master's degree. Teachers most often listed teaching credentials in biology (75%), chemistry (34%), and general sciences (34%). Most teachers were high school teachers who indicated that they taught 12th grade (78%), 10th grade (78%), 11th grade (75%), and/or 9th grade (63%). Additionally, of the 24 teachers, 21 provided demographic information. Most of these teachers (75%) were white, two (8%) were Black or African American, and one (4%) was Asian.

4. Evaluation

4.1 Evaluation Methods

Magnolia Consulting, the external evaluator, collaborated with the SHAPE MATTERS project team to implement a mix-methods formative and summative evaluation aligned with the project goals. The formative evaluation supported ongoing project improvements, and summative evaluation provided information about the project's impact on outcomes of interest. Evaluators and the team used multiple data collection methods: 1) teacher surveys (Summer Workshop Survey and Molecular Modelling Survey), 2) project team interviews, 3) teacher interviews and focus groups, and 4) review of documents and existing data.

The Summer Workshop Survey was administered to teachers after each summer workshop to examine: 1) teachers' reactions, 2) teachers' learning, 3) organizational support and changes,

4) teachers' use of new knowledge and skills, and 5) student learning outcomes [21]. Some of the survey items incorporated a retrospective pretest-posttest design to gauge how teachers perceived their knowledge, skills, and confidence before and after the summer workshop. The project team administered the Molecular Modelling Survey to teachers before and after each summer workshop. The survey included modified items from the Students' Understanding of Modelling in Science survey to capture teachers' knowledge of molecular modelling [5].

In the fall of each year, virtual interviews were conducted with project team members to better understand the development and delivery of the SHAPE MATTERS project. Post-workshop interviews and focus groups were conducted with Cohort 1 and Cohort 2 teachers to understand their experience with the project and how they applied what they learned after their participation. Finally, relevant documents shared by the project team were analyzed, including workshop agendas, work products generated by the teachers during the workshop, and student classroom research posters.

Collected data was analyzed using both quantitative and qualitative approaches. Statistical analyses were performed on data collected from closed-ended survey items. Specifically, descriptive statistics (frequencies and averages) were generated. For pre-post data, paired samples t-tests were conducted to determine whether the mean differences between participants' ratings from before to after their participation in the workshop were statistically significant. Data collected from open-ended survey items and interviews were analyzed using open coding and thematic analysis methods. Themes were identified within the evaluation framework using a thematic analysis approach [22]. The findings were triangulated from multiple data sources.

4.2 Evaluation Outcomes

After the three Summer Workshops, teachers rated their knowledge about scientific practices, concepts associated with molecular biology, and cutting-edge research topics before and after their participation in the workshops (Figure 1). Their self-reported knowledge of all topics increased from before to after their participation. The mean differences between their pre-and post-ratings were all statistically significant based on the results of paired sampled t-tests.

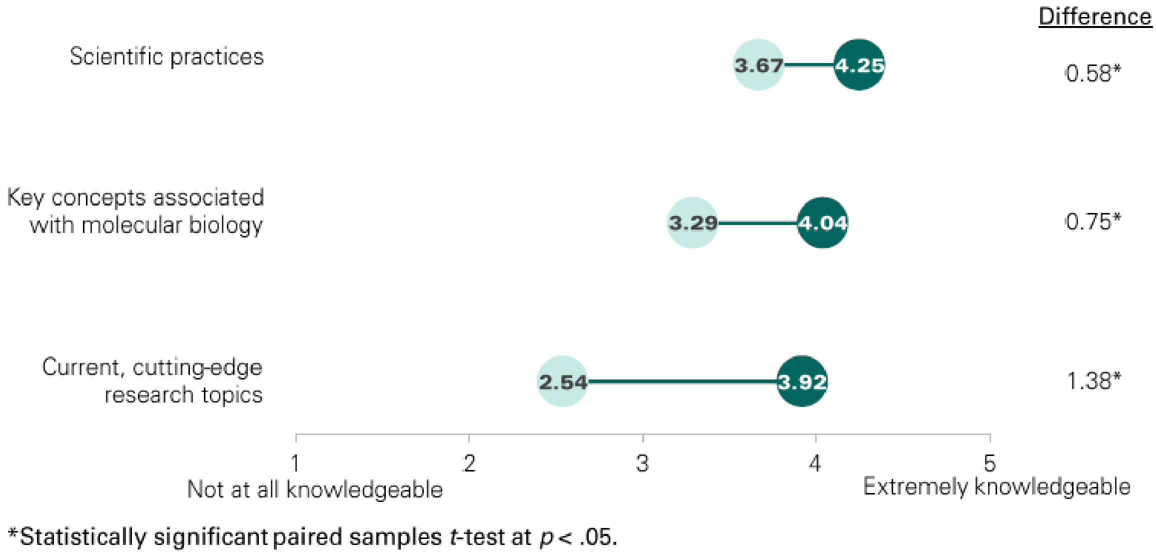

Fig. 1. Teachers' self-rated knowledge before (light green) and after (dark green) the SHAPE MATTERS workshops in Years 1,2, and 3 (n=24).

Teachers who participated in the Summer Workshops had statistically significantly higher self-rated knowledge, skills, and confidence in molecular modelling, research, and science practices after participation relative to before. For example, as shown in Figure 2, teachers' responses suggest that their molecular modelling skills increased from before to after participating in the Summer Workshop.

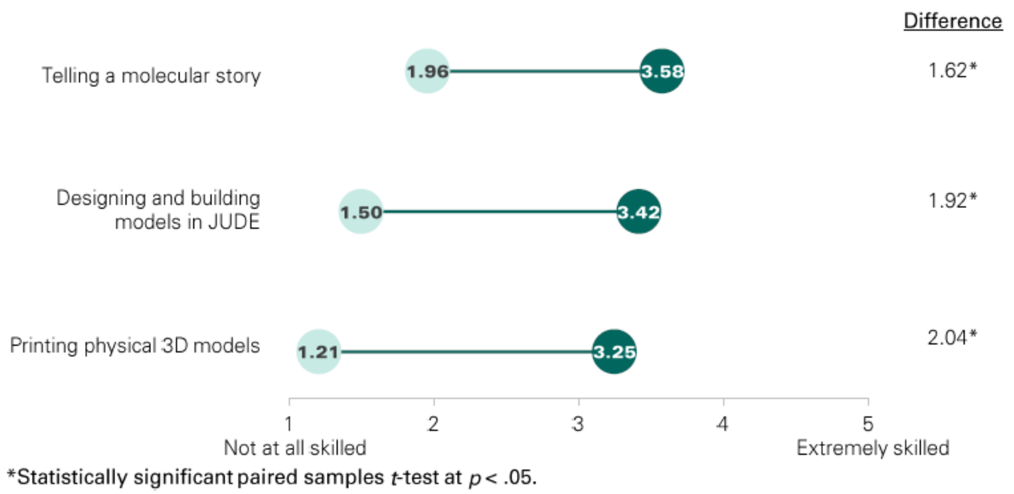

Fig. 2. Teachers' self-rated skills before (light green) and after (dark green) the SHAPE MATTERS Workshops in Years 1,2, and 3 (n=24).

Interviews and focus groups with project team members and teachers supported these findings. Project team members observed participating teachers gain relevant content knowledge throughout the workshops. Teachers shared that their newly acquired skills supported their confidence and classroom instruction. Project team members shared that the knowledge and skills teachers gained in the workshops were effectively integrated into classroom instruction.

Additionally, before and after the first three summer workshops, teachers answered questions to test their knowledge of molecular modelling on a modified version of the SUMS survey [5] (Fig. 3). Their understanding of molecular modelling across all five domains increased from before and after their participation, particularly their understanding of models as multiple representations. This domain had the only statistically significant mean difference between teachers' pre- and post-ratings based on the results of paired samples t-tests. Gains in other domains, though not statistically significant, may still reflect meaningful improvements in teachers' understanding of molecular modelling. In particular, teachers' understanding of models as exact replicas increased by 0.25 from before and after the workshop.

Fig. 3. Teachers' knowledge of molecular modelling before (light green) and after (dark green) the SHAPE MATTERS Workshops in Years 1,2, and 3 (n=24).

After year 1 implementation of the workshop, evaluation data showed that teachers still thought of models as exact replicas after the workshop. Teachers in cohort 2 and 3 had larger pre-post difference for models as exact replicas compared to cohort 1, which suggests that the changes to the workshop might have supported these teachers' understanding that the molecular models are not exact replicas.

5. Discussion and Conclusions

For teachers to gain a better understanding of specific practices, the design of professional development programs needs to provide teachers with a window into the work of scientists. One way to provide this experience is to use authentic scientific research as the context of the professional development programs in ways that develop both their content knowledge and knowledge of the scientific practices. The SHAPE MATTERS program was intentionally designed to provide teachers with the opportunity to engage in the practice of developing and using models in molecular biology. The program design leveraged the expertise of a multidisciplinary team of scientists and science education faculty on the project team. The science research experts provided the in-depth knowledge of molecular biology research methodologies, specifically in the area of molecular modelling. The science education faculty provided knowledge of how current science research can connect to education standards and best practices in precollege science teaching and learning. When creating materials for the program, science educators and science researchers worked collaboratively to ensure the materials were grade-level appropriate, scientifically accurate, and scaffolded to support learning.

The workshop was intentionally designed to include and alternate between *modelling of* and *modelling for* such that teachers experienced both approaches and gain a deeper understanding of the ways in which scientists develop and use models in authentic research. Research shows that teachers frequently only include *modelling of* in classroom instruction which creates a false sense that there exists a set of models that simply map on the real world in some one-to-one way. This can be seen in the ways in which teachers initially talked about the molecules on the Protein Data Bank (PDB). Teachers believed these models were exact replicas of the molecule. Initially, teachers lacked an understanding of the methodology used to determine these models and were unable to identify areas of uncertainty. Throughout the program, teachers were explicitly taught about the most commonly used technique on the PDB, x-ray crystallography, and how to use the data stored on the PDB to identify areas of uncertainty through scaffolded JUDE tutorials. In addition, teachers were provided insight into a current research lab at Penn State and given the opportunity to work with the lab for three days to tell the molecular story of the current research in the lab.

Ongoing and sustained professional development can help teachers to better understand the scientific practices [23,24]. The SHAPE MATTERS program allowed teachers to acquire both content knowledge and knowledge of the scientific practices as evaluation data shows statistically significant growth in both of these areas. However, the findings of this paper are limited to a small sample size of teachers and the knowledge findings are all self-reported. In the future, evaluation data could include classroom observations as a means of documenting changes in instructional practice.

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