**Designing Modeling-Based Instruction with a Hypothetical Learning Progression to Track the Evolution of Sixth-Grade Students' Particle Model of Matter**

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**Abstract:**

　　The particle model of matter (PMM) is the foundation for understanding the material world but can be challenging to establish, particularly for younger children. This study aims to develop modeling-based instruction for sixth-grade elementary school students grounded in our hypothetical learning progressions (LPs) of the PMM and to track their construction of the PMM. This study designed scaffolding for modeling-based instruction linking macro-phenomena and micro-simulations (PhET). The visual concept map constructed during the LP design was transformed into structural progression variables to track the mental models of eight groups of students (n = 25). The teacher consciously assisted students in progressively constructing their PMM based on the developed progress variables, adding concepts, and removing, correcting their alternative conceptions. New dynamic factors were integrated into the original structural progression variables to enhance students' understanding of PMM. The progression moves from a Descriptive model at the lower limit of the LP to Mixed, Basic, and ultimately reaching quasi-scientific Model of PMM at the upper limit of the LP. This study provides preliminary support, indicating that our hypothetical LPs can support modeling-based instruction, tracking, and assistance for most elementary school students. Some students even approached the Complete model.

**1. Introduction**

 Global science education faces unprecedented challenges, and the trend of modeling-based inquiry (MBI) is crucial for the scientific literacy of 21st-century citizens. Providing scaffolds for model-based learning can foster meaningful and active authentic learning, enhancing student engagement in scientific practices [1]. One of the significant challenges faced by Taiwan in the field of education is integrating the particulate perspective into elementary curricula, making model-based learning a core practice for fostering scientific literacy. The traditional teaching process does not consider that students may have alternative conceptualizations, and this is exactly what is happening with the current arrangement of textbooks in Taiwan. These textbooks typically use simple diagrams to describe the particle model, expecting students to independently construct a complete particle model and understand its limitations. This highlights the difficulties in establishing the particle model; therefore, a clear and articulated learning progressions (LPs) is necessary to guide students in developing their modeling practices.

 To address this challenge, the first aim of this study is to develop a model-based instruction which grounded on a hypothetical LPs of the PMM to support 6th-grade students' learning. The hypothetical LPs will serve as a framework for organizing the teaching, curriculum, and assessment related to the PMM. The instruction will be designed to introduce the particle theory in an effective manner, motivating students to engage with the material world through the particle perspective. The second aim, this research will explore how the hypothetical LPs can be modified to track and support the evolution of students' mental models of the PMM through the modeling-based instruction. By monitoring the development of students' understanding, the LPs and associated instruction can be adapted to better align with their conceptual progression, addressing any alternative conceptualizations they may hold.

**2. Literature Review**

**2.1 The Importance of LPs and Progress Variables in Understanding the PMM**

Students' ideas are shaped by teachers' instructional methods. LPs depict how students refine their understanding of specific subjects over time. Progress variables have been proposed to monitor students' knowledge, highlighting that LPs are influenced by instructional strategies. Thus, to assist students in comprehending the PMM, teachers should start with real-world examples, acknowledging the various paths students may take [2]. Tracking　 students' long-term grasp of fundamental scientific concepts is crucial, achievable within classroom timeframes[2]. By structuring instructional activities in a detailed sequence, teachers can enhance students' understanding and track their evolving perspectives. Understanding particle concepts involves linking macroscopic phenomena with microscopic explanations, necessitating visual aids and communication opportunities.

**2.2 Modeling Practices in Modeling-Based Instruction**

 This study validates students' theoretical understanding in MBI by focusing on their modeling practice capabilities. It adopts MBI as an instructional scaffold [3], designed according to the phenomena and experiences set for understanding PMM. Starting with students' initial models as a macroscopic continuum, the instructional process progresses through Orientation , Model Construction, Model Evaluation,to Model Revision phases. Students explore, experiment, generate explanations, and revise their models until reaching the target model, approaching the scientific perspective of PMM.

**3. Methods**

**3.1 Participant**

 This study involved 25 sixth-grade elementary students (divided into 8 Groups) in the north Taiwan. They had not yet experienced the new curriculum MBI and designed PMM curriculum.

**3.2 The Hypothetical LP of PMM**

This study builds upon Lin's (2022) conceptual map of the PMM [4], which uses the three states of water to explicitly link macroscopic properties with phenomena, and how these phenomena connect to the behavior of microscopic particles. Observing the progression of students' understanding of the PMM becoming increasingly complex over time [2], this research deconstructs and maps theories such as fundamental particle theory and kinetic molecular theory [5], along with a framework based on the substance, onto the concept map. A hypothetical PMM LPs is proposed, where numbers indicate a teaching sequence from simple to complex. The first stage of the LPs, illustrated in Table 1 without any marked symbols, defines "structural variables" for unmarked variables. Misconceptions that students must eliminate during the MBI process are marked as "-n\*", and those marked with "+n\*\*" are "dynamic variables" that need to be added. The co-construction large group model building approach by Clement (2008) is used to explain the structural and dynamic variables [6] to generate the second stage of the LPs (Figure 1).

**3.3 Curriculum development**

This study adopted Tyler’s (1949) curriculum development model to design the curriculum [7]. The components include: Objectives, educational experience, organization, and evaluation. Our aim 1 focused on the former three components, our aim 2 provided the further evaluation to revise our hypothetical LP of PMM.

**3.4 Data Collection and Analysis**

 For aim 2, the first author, who also served as the teaching instructor with 28 years of experience and was trained in other PMM related project. All qualitative data were coded as three codes: Data Sources-Subjects-Lessons. Four data sources regarding to learning outcomes were Experiments record (E1-E9); Classroom videos (V1-V12); Student science notes (N1-N25); Teacher reflections (F1-F12). Two research subjects include 25 students (S1-S25) and 8 groups (G1-G8). Twelve lessons were note as L1-L12. Triangulation was employed to track the LP variables throughout the learning process, ensuring students achieved the intended curriculum objectives. Based on classroom video feedback, experimental observations, teacher’s instructional observations and records, as well as the representations or misconceptions presented in students' science notes, qualitative data were used to identify implementation issues and shortcomings. Necessary revisions and enhancements were made to the initial hypothetical LPs, and dynamic variables from the literature were incorporated to further support the complexification of students' PMM learning.

**4. Findings and Discussion**

**4.1 Design of the Modeling-Based Instruction Grounded on the Hypothetical LP of the PMM**

This study designed a 12-lesson MBI for teaching PMM, based on Lin and Li's MBI principles (Top of Table, MBI). In MBI, through instructional activities, students went through stages from Orientation, Model Construction, and Model Evaluation to Model Revision. In the Orientation phase, teachers introduced a particulate perspective and PhET simulations for students to explain phenomena on a particulate basis. In the Model Evaluation phase, teachers presented experiments/phenomena for students to explain using particulate and descriptive concepts. In the Model Revision stage, with the basic PMM established, students used particles to explain phenomena. Teaching objectives followed Taiwan's 2018 curriculum indicators INa-Ⅲ-1, INa-Ⅲ-2, INa-Ⅲ-8, and PMM's LPs (Second column of Table, Curriculum Indicators) [8]. Instructional experiences were aligned with LP and student levels, utilizing textbooks and prior experiences. Lin and Li's MBI approach organized the teaching method and sequence (Third column of Table, Teaching Unit). Set the sequence of hypothetical LPs according to the teaching unit and carry out the actual teaching (Fourth column of Table 1, Hypothetical LPs of PMM).

**4.2 Modification of the hypothetical LPs of PMM through the modeling-based instruction**

  This study arranges the sequence of structural variables of the hypothetical LPs based on literature, and adjusts the dynamic variables based on the actual curriculum and relevant experiments related to phenomena-based teaching situations. It is hoped that the MBI curriculum, designed based on a structured theoretical learning process, will enable students to develop complex PMM in a sequential manner (Figure 1). Throughout the MBI process, teachers provide continuous support and guidance to students through various learning activities, such as prompts, observation of phenomena, and experiments.

 In the Orientation stage, students are often confused about state changes, frequently considering "solid," "liquid," and "gas" as three distinct types of substances. Some students even do not regard "gas" as a substance. Students often use curves to represent water vapor. Teachers pose questions like, "What are the differences between the model you drew and the particle model of matter simulated by PhET?" to help students connect visible solid and liquid phenomena with their corresponding PhET virtual models and move into the Model Construction stage. Students understand that ice and water are composed of the same particles. This helps students build a basic understanding of substances before teaching about particles, thereby facilitating their comprehension of the transitions between liquid and gaseous states.

 During the Model Evaluation stage, after the teacher asked, "Are there any differences or missing elements? For example: distances between particles, the quantity of particles, and the modes of motion among the three states of matter, etc." student mentioned "*the distance between particles increases in different substances when heated, just like water particles*(V3-S17-L3)." The teacher continued to ask if there were any differences or missing elements, such as the distance between particles, the number of particles, and the motion modes among the three states, encouraging students to continuously compare their models with the scientist's particle model. After practicing comparisons, student noted, "*When it gets hotter (temperature rises), the particles move more*(V6-S23-L6)." Based on the observations from the copper ball and ring experiment, student recorded that "*the distance between chocolate particles increases when heated, similar to water particles* (E3-G8-L3)." The educator introduced dynamic variables "+ 4\*\*. Other different objects are also composed of particles," to help students approach the particle perspective from a material world viewpoint.

 Students continually encountering misconceptions such as "−3\*. The number of particles varies with different types." and "− 9\*. Particles change in size." during the teaching process could be significantly helpful in establishing a scientist's particle view if confirmed to be removed.

 Finally, during the Model Revision stage, the teacher asked, "Do these models correspond to the phenomena you've observed, similar to those in the PhET simulations?" A student replied, *"Particles vibrate because they have energy* (V9-S14-L9)." Consequently, the teacher added a statement like "+ 10\*\*. After the temperature increases, the motion of particles becomes larger, and the distance between them also increases" to the thermal expansion and contraction experiment. This can help a very few students who are close to a quasi-scientific PMM to have the opportunity to further revise their models.

**5. Conclusion and Implication**

 This study developed a 12-lesson MBI grounded on our hypothetical LPs of PMM and modified this hypothetical PMM’s LPs through the instructional process. Despite limitations due to constraints from the existing curriculum guidelines in Taiwan and a small sample size, it still elucidates the significance and feasibility of initiating a microscopic particle perspective through modeling-based hypothetical LPs instructional activities in the upper grades of elementary school.

**References**

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**Table 1.** The modeling-based Instruction grounded on the hypothetical LP of the PMM

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| --- | --- | --- | --- |
| **lower anchor****Contin-uum Model** | MBI | Orientation - Model Construction - Model Evaluation - Model Revision | **upper anchor****Complete Model****(Scientific model)** |
| Curriculum Indicators | INa-Ⅲ-1 |  INa-Ⅲ-8 | INa-Ⅲ-1 | INa-Ⅲ-2 |
| Teaching Units | Unit 1-3What is matter?Changes in matter due to heatingSolid-liquid phase changes. | Unit 4-7Heat transfer ~ conduction, convection, radiation**.** | Unit 8-10Expansion due to heating, contraction due to cooling | Unit 11-12Practical applications of heat |
| Hypotheti-cal LPs of PMM | + 1. Matter is composed of particles.+ 2. These particles are so small that they cannot be seen even under a microscope. | + 5. Represent particles with the same circle or dot.+ 6. All particles in different phases are the same particles. | + 7. There is a vacuum distance between particles.+ 8. Particles constantly vibrate. |  |

**Figure 1.** Illustrates the relationship between the PMM Modeling-Based Instructional process and the process variables in this study [6].

