Investigating Sixth Graders' Mental Models of the Particle Model of Matter via a Modeling Curriculum on the Three States of Water

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Abstract

The particle model of matter (PMM), now included in Taiwan's elementary curriculum, is globally emphasized. However, research on student model development and conceptual difficulties remains limited. This study investigates how students develop and revise their PMM mental models and identifies where conceptual difficulties emerge during a structured curriculum on the three states of water. This design-based research with 36 sixth-graders implemented a curriculum structured into macroscopic, microscopic, and model transfer stages, each with observation and analogy substages. Expert science educators conducted interviews and collected student responses, which were analyzed using an eight-model framework by Chen & Lin [15]. Results showed that students primarily used Continuous, Descriptive, Mixed, and Basic Particle Models. In the macroscopic stage, 89% used Continuous Models, but this proportion dropped to 47% when analogies were introduced. In the microscopic stage, about half of the students demonstrated Mixed Models, with only a few reaching Basic Particle Models. In the transfer stage, 42% reverted to macroscopic reasoning, while 50% maintained Mixed Models and 17% demonstrated more advanced particle reasoning. Some students continued to show difficulties consolidating microscopic concepts, especially when applying models to novel contexts. Overall, analogy-based modeling tasks proved more effective than purely observational tasks. Findings highlight the importance of structured scaffolding and iterative practice in modeling curricula to deepen PMM understanding and to inform chemistry teachers on strategies that support scientifically accurate model development in the classroom.

Keywords: Analogy-based modeling, Particle model of matter, Design-based research, Chemistry education

1. Introduction

The Particle Model of Matter (PMM) is a key concept in chemistry education, as it explains the states of matter, phase changes, and material properties [1]. Learning PMM is not merely about memorizing facts—it also requires students to engage in scientific modeling to develop a deeper understanding of particle theory [2].

In recent years, many countries have introduced PMM into the elementary curriculum at earlier stages, recognizing its importance for science learning [3,4]. However, this shift also creates challenges. Research shows that students often form misconceptions. For example, even if they acquire particle-related terms, they may still perceive matter as a continuous whole rather than adopting a genuine particle perspective [5]. If particle ideas are introduced "too early" without sufficient support, students may become confused, lose confidence, or disengage from science learning [6].

In Taiwan's new curriculum guidelines, the content is explicitly stated: "Matter is composed of tiny particles, and these particles are in constant motion." Yet, many teachers still struggle to connect students' everyday reasoning with the progression toward abstract particle concepts [7]. This underscores the need for instructional scaffolds that align with students' developmental stages and systematically guide them toward more scientific models.

With this in mind, our study investigates how elementary students progress from macroscopic to microscopic particle concepts. We focus on how their mental models evolve during the process of model construction and how modeling-based instruction can support this learning. Our research questions are as follows:

1. What mental model of PMM do elementary school students hold regarding the three states of water?
2. How do elementary students' mental models of PMM change across six stages?
3. How does an analogical modeling curriculum influence students' model development, and what implications does this have for chemistry teaching practice?

2. Literature Review

2.1 Scope of PMM in Elementary School

The Particle Model of Matter (PMM) is central to modern science, and some even call it a "threshold concept" [2]. Many researchers have argued that PMM should be one of the core learning goals in K–12 science, which is why there has been a push to introduce it earlier in the curriculum [3].

Still, students frequently encounter misconceptions and difficulties when learning this concept. For example, Novick and colleagues [8] identified four basic particle properties that became the foundation for later studies. From a science education perspective, de Vos and colleagues [9] expanded this framework into eight key particle properties, directly connecting particle theory to phase changes, chemical reactions, and the structure of matter. In Taiwan's new elementary curriculum guidelines, the concept of atoms is deliberately omitted at this stage. To align with this approach, Lin [10] proposed eight simplified propositions for teaching PMM at the elementary level, providing a practical framework for teachers to design lessons on particle-related ideas.

2.2 How Students Learn PMM

Merritt and Krajcik [2] observed that while teachers often use analogies as tools for teaching PMM, they typically emphasize only the content of the analogy. What tends to be overlooked are the functions of models and the crucial role that modeling plays in helping students understand chemical behavior. For example, when students role-play atoms or molecules in different states, many mistakenly believe that liquid particles are spread out like in a gas rather than packed almost as closely as in a solid.

To address this, teachers need to recognize students' initial models and potential learning pathways. Instruction can then be designed using Learning Progression (LP) variables, so that students gradually move from descriptive models, through hybrid and basic models, toward a more complete particle model. This progression increases both the complexity and accuracy of students' scientific ideas, while also clarifying common points of confusion that teachers must address.

Other studies also suggest that instruction should be grounded in conceptual change theory [11] and supported by stronger teacher content knowledge of microscopic particle concepts [12]. In this context, analogy-based modeling provides valuable insight into how students actually learn PMM. Justi and Gilbert [12] and Mozzer and Justi [13] emphasized that analogies are not merely explanatory tools—they can also serve as creative entry points for modeling. Through analogies, students can engage in the full modeling cycle of generating, representing, testing, and revising models. This process helps them move from making surface-level comparisons of macroscopic events to constructing deeper connections that integrate both macroscopic and microscopic levels. They also learn to apply their models in new contexts while recognizing their limitations.

For students to learn PMM effectively, they require scaffolding across representational levels, explicit model-based language, and interactive tools or activities that encourage them to create and reflect on their own analogies. These strategies make abstract ideas more accessible and help students apply models more flexibly to novel problem situations.

However, most existing studies have only described general teaching strategies and outcomes. Few have examined the specific particle ideas that students generate in analogy-based modeling, or how well these align with what teachers and researchers expect. To address this gap, the present study designs a PMM teaching program centered on analogy-based modeling, focusing on how students' mental models and understanding develop across different learning stages, with the aim of providing practical and research-based insights for chemistry teachers.

3. Research Methods

3.1 Research Design and Participants

This study was part of a larger research project that initially examined teachers' instructional analyses [15]. While teacher-level data were collected, the present paper focuses exclusively on students' model development.

The participants were thirty-six sixth graders from an elementary school in Taipei City. The activities were conducted in small groups of six students with one teacher, and a total of six teachers participated. To ensure consistency across instruction, we organized preparatory interviews and demonstration lessons before the study began. Student selection included a mix of high-, medium-, and low-achievers, but ability-level differences were not the focus of this analysis.

3.2 Instruction Design

Before formal instruction, a short warm-up activity (Figure 1) was designed to introduce the idea of analogy. For example, students imagined ink diffusing in water as "fairies running around." Sample analogical mappings included:

- water particles → blindfolded fairies
- ink particles → fairies in ink-colored clothes
- temperature → a joyful atmosphere

This playful task offered students an accessible entry point into analogy, while also laying a foundation for subsequent lessons on the particle model.

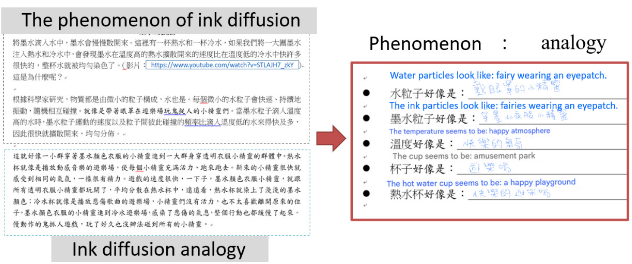

Figure 1. Preliminary activity design

Our formal lesson design followed Lin's analogy-based modeling framework [10], which emphasizes observation and analogy activities for the Particle Model of Matter (PMM). The curriculum focused on phase changes of water and was organized into three levels: macroscopic (Ma), microscopic (Mi), and transfer (Tr). Each level included two parts: phenomenon explanation (P) and analogy construction (A). The specific tasks and example items for each stage are summarized in Table 1.

Table 1. Framework of the analogy-based modeling curriculum on PMM.

Stage (Code)		Description	Example Item
Macroscopic models (Ma)	Phenomenon (P) Explaining	Explaining the Phenomenon of water's three states.	Why does ice gradually melt into water and then gradually evaporate into steam when heated by an alcohol lamp?
	Analogical modeling (A)	Construct analogical models to explain the three-state change of water during macroscopic observations.	Please design an analogy to explain the three-state changes of water.
Microscopic models (Mi)	Phenomenon Explaining (P)	Construct analogical models to explain the three-state change of water during microscopic observations by PhET.	Please use this powerful magnifier to observe and compare the smallest 'components and structures' of ice, water, and water vapor in PhET (https://reurl.cc/7joALN). Use <, >, = to compare the distance between particles: Particles (ice state) □Particles (water state) □ Particles (water vapor state)
	Analogical modeling.	Construct microscopic analogical models of water's three states.	Please design an analogy to explain how the speed of movement, the distance, and the chaotic degree of arrangement among particles (ice), particles (water), and particles (water vapor), as observed by a powerful magnifier, can result in the change of the three states of water.
Transferring models (Tr)	Phenomenon Explaining (P)	Explaining that phenomenon in the video water vapor in a conical bottle becomes water vapor after heating, and that the air in the bottle expands when heated, causing the balloon to grow larger.	After heating to 200 degrees for a while, use the powerful magnifier again to observe inside the balloon. Predict the observed phenomena: Will the size of the balloon change? Will the water level change? Predict and draw on the right diagram. After making your predictions, observe PhET (https://reurl.cc/pZxZvl), does it match your prediction?
	Analogical modeling (A)	Use self-generated analogical model to explain phenomenon of thermal expansion.	Using the analogy you designed for the "three-state change of water" in Question 4, try to explain why the size of the balloon changed.

3.3 Data Collection

We also carried out semi-structured interviews with the participating teachers. During the interviews, teachers used paper worksheets to write down key points or sketch their ideas. Each interview lasted between about 45 minutes and an hour and a half, and we recorded both video and audio. We also took field notes at the same time.

Before analyzing the data, we transcribed all recordings word-for-word. For coding, we used a simple labeling system: each teacher (TS1–TS3, TE1–TE3), student (SL1&2, SM1&2,SH1&2), the context (macroscopic = Ma, microscopic = Mi, transfer = Tr), and the task type (phenomenon explanation = P, analogy modeling = A). For example, "TS1–SL1-MaP" refers to Teacher TS1's student SL1 response when explaining a macroscopic phenomenon.

3.4 Data Analysis

After we transcribed the interviews, we coded the teachers' responses using the categories listed in Table 2. To make sure the coding was reliable, two researchers first coded the data separately. Their results matched almost completely—about 96% agreement. For the few cases where there were differences, we discussed them together with the corresponding author until we reached the same conclusion. The rest of the data was then coded by the first author. To double-check, the same researcher reviewed the coding again one month later and found it fully consistent, with 100% agreement.

3.5 Coding framework

For our analysis, we adapted the coding framework from Merritt and Krajcik [2] and Chen and Lin [15]. We conceptualized students' models along a macroscopic–microscopic continuum. To match the analytical needs of the Results section, we employed an eight-category scheme that explicitly distinguishes the four subtypes— M-ic, M-c, B-d, B-m —in addition to C, D, qS, and S (see Table 2). This granularity preserves instructionally meaningful differences (e.g., inconsistency vs. coherence within mixed reasoning; spacing- vs. motion-dominant basic models) and supports actionable implications for chemistry teaching.

Coders prioritized the dominant explanatory resource (e.g., spacing/density vs. motion/disorder) and judged self-consistency across states within a single explanation or drawing (for M-ic vs. M-c). Ambiguities were resolved by reviewing the full response set for the task and discussing until consensus.

Table 2. Categories of PMM as described by Merritt and Krajcik [2].

Model Type (Code)	Concise Description	Typical indicators / coding cues (student utterances or drawings)
Continuous (C)	Matter as a continuous whole; no particles or empty space.	"Ice melts and becomes steam when heated." *(no mention of particles, spacing, motion, or empty space)*
Descriptive (D)	Mentions parts but stays macroscopic; each part keeps original properties.	"It breaks into pieces but each piece is still the same thing." / "It just gets smaller or disappears."

Model Type (Code)	Concise Description	Typical indicators / coding cues (student utterances or drawings)
Mixed–inconsistent (M-ic)	Combines macroscopic and microscopic ideas, but they contradict or shift across states.	"Water vapor has the smallest particles and ice has the largest." / "With heat, particles get denser but also farther apart."
Mixed–consistent (M-c)	Macroscopic→microscopic mapping is self-consistent but partial.	"Solid is like a team in formation; in steam the team becomes loose and disordered." / "Heating makes particles move faster and spread further." *(forces/energy often missing)*
Basic Particle—distance-focused (B-d)	Recognizes particles & empty space; emphasizes spacing/density.	"After heating, the average distance increases and the density decreases." / "Different states have different particle spacing."
Basic Particle—motion-focused (B-m)	Recognizes particles & empty space; emphasizes motion/disorder.	"With heating, particles move faster and become more chaotic." / "Steam has the most vigorous motion."
Quasi-scientific (qS)	Multiple scientific features present but imprecise (e.g., forces, vacuum).	"There's attraction between particles, but I'm not sure how distance changes it." / "There is vacuum, but I can't explain it clearly."
Scientific (S)	Integrates spacing, motion, energy, inter-particle interactions with macro properties; distinguishes substance-specific behaviors.	"When temperature rises, kinetic energy increases; effective attractive influence decreases relative to motion; average spacing increases—hence volume expands. Different substances differ due to structure/composition."

4. Results

4.1 Common Mental Models of PMM among Students

In students' responses, we identified several recurring models (see Table 2 for definitions). Typical examples include:

- **C (Continuum):** “When something hot touches ice, it melts; when water is heated, it turns into steam.” TE1-SL1-MaP
- **D (Descriptive):** “It’s one whole thing, but it gradually gets smaller and disappears—like something old that turns moldy.” TE1-SL1-MaA
- **M-ic (Mixed–inconsistent):** “Water vapor has the smallest particles, ice has the largest.” TS2-SH1-MiP
- **M-c (Mixed–consistent):** “Ice is like an organized team that stays in place. When it becomes steam, the team becomes messy, so shape and volume can’t stay fixed.” TS3-SM2-MiA
- **B-d (Basic–distance):** “After heating, the particles are farther apart, so density decreases.” TS2-SH2-TrP
- **B-m (Basic–motion):** “Particles move faster, spread further apart, and become more disordered.” TS1-SM2-TrP

Overall, most students’ explanations stayed at the macroscopic level, while only a few managed to consistently use microscopic particle ideas. Notably, no student responses reached the **quasi-scientific (qS)** or **scientific (S)** levels, indicating that their conceptual understanding had not yet progressed to higher-level mental models. This highlights the challenge of helping elementary students construct more advanced and coherent particle-based explanations.

4.2 Changes in PMM Mental Models across Six Stages

The results are summarized in Figure 2, which combines the classification of mental models from Merritt and Krajcik [2] with our six-stage teaching sequence. The models are arranged hierarchically: darker shading indicates closer alignment with the scientific particle model, while lighter shading shows more basic reasoning.

Across the sequence, several clear patterns emerged. In the macroscopic observation stage (Ma-P), most students relied on the Continuum Model (C). With analogy tasks (Ma-A), some began shifting toward Mixed models, showing the first attempts to bring in microscopic ideas. In the microscopic stages (Mi-P and Mi-A), the Mixed-consistent Model (M-c) became dominant, and a few students advanced to Basic models, beginning to describe particle motion and spacing. In the transfer stages (Tr-P and Tr-A), some students regressed to C models, but many maintained M-c, with only a small number extending to Basic models.

Overall, the developmental trend shows a stepwise movement from macroscopic (C) to microscopic reasoning (M-c), with M-c acting as a key transition point. Only a few students moved further toward particle-level explanations of density or motion, and almost none reached more advanced models involving inter-particle forces. This suggests that stronger scaffolding is needed to help students consolidate M-c and extend into higher-level particle models.

	Macroscopic Models (Ma)		Microscopic Models (Mi)		Transferring Models (Tr)	
	P	A	P	A	P	A
TS1-SL1	C	D	C	M-ch	D	M-ch
TS1-SL2	C	M-ich	B-m	M-ch	C	M-ch
TS1-SM1	C	M-ch	M-ch	M-ch	M-ch	M-ch
TS1-SM2	C	M-ich	B-m	M-ich	M-ch	C
TS1-SH1	C	C	M-ch	B-d	B-d	B-d
TS1-SH2	C	M-ich	B-m	C	M-ich	B-m
TS2-SL1	C	D	M-ch	M-ch	M-ch	B-m
TS2-SL2	C	C	M-ich	M-ich	M-ch	M-ch
TS2-SM1	C	C	M-ich	M-ich	M-ich	M-ich
TS2-SM2	C	M-ich	M-ich	M-ich	M-ich	M-ich
TS2-SH1	M-ich	C	M-ich	M-ch	M-ich	M-ch
TS2-SH2	C	C	B-d	B-d	B-d	B-d
TS3-SL1	C	M-ch	M-ch	M-ch	C	M-ch
TS3-SL2	C	X	M-ch	M-ch	M-ch	M-ch
TS3-SM1	C	C	M-ch	M-ch	M-ch	M-ch
TS3-SM2	C	C	M-ch	M-ch	M-ch	M-ch
TS3-SH1	C	C	M-ch	M-ch	M-ch	B-m
TS3-SH2	C	M-ch	M-ch	M-ch	C	M-ch
TE1-SL1	C	D	C	D	C	C
TE1-SL2	C	X	C	X	C	M-ch
TE1-SM1	C	X	X	X	C	X
TE1-SM2	C	C	D	D	C	C
TE1-SH1	C	C	M-ch	M-ch	M-ich	M-ch
TE1-SH2	C	X	C	M-ch	M-ich	M-ch
TE2-SL1	C	C	B-m	M-ch	M-ch	M-ch
TE2-SL2	C	C	X	C	X	X
TE2-SM1	D	C	C	X	D	X
TE2-SM2	C	C	B-m	M-ch	C	X
TE2-SH1	C	C	C	M-ch	C	M-ch
TE2-SH2	C	X	C	X	C	X
TE3-SL1	C	X	D	X	C	X
TE3-SL2	C	X	C	X	C	X
TE3-SM1	C	C	M-ch	M-ch	C	M-ch
TE3-SM2	C	C	D	M-ich	C	M-ich
TE3-SH1	M-ch	B-d	B-m	B-d	M-ch	B-m
TE3-SH2	M-ich	X	M-ch	M-ch	C	M-ch

Figure 2. Changes in students' PMM across six instructional stages.

Note: Each row represents one student's responses across the six stages of instruction (Ma-P, Ma-A, Mi-P, Mi-A, Tr-P, Tr-A). Codes indicate model types (C = Continuum, D = Descriptive, M-ic = Mixed-inconsistent, M-c = Mixed-consistent, B-d = Basic–density, B-m = Basic–motion). Shading intensity reflects proximity to the scientific particle model: darker shading indicates more advanced particle reasoning; lighter shading indicates more basic macroscopic reasoning.

4.3 The Impact of Analogy-Based Modeling Instruction on Students' Model Development

Looking at the six-stage teaching sequence (Table 3), students' explanations began primarily in the Continuum Model (C), focusing only on macroscopic descriptions. With the introduction of analogy-based modeling, however, many gradually shifted toward the Mixed-consistent Model (M-c), where particle ideas were more logically integrated. Still, students' reasoning was not yet fully stable, showing that particle concepts remained "under construction." Even so, analogy structures encouraged them to connect visible phenomena with particle-level explanations.

In the transfer stages, some students reverted to macroscopic reasoning, reminding us that without cross-context practice and stronger scaffolding, they may easily return to familiar ways of thinking when facing new problems.

Table 3. Distribution of mental model development.

	Macroscopic models(Ma)		**Microscopic models(Ma)**		**Transferring models**	
	P	**A**	**P**	**A**	**P**	**A**
X	0%	22%	6%	17%	3%	19%
C	89%	47%	22%	6%	42%	8%
D	3%	8%	8%	6%	6%	0%
M-ic	6%	11%	11%	14%	17%	8%
M-c	3%	8%	33%	50%	28%	47%
B-d	0%	0%	17%	0%	0%	11%
B-m	0%	2%	3%	8%	6%	6%

In terms of the eight core propositions (see Table 3), students showed progress in several areas:

- Proposition 1 (matter is composed of particles): Most students recognized that matter is made of invisible, discrete units.
- Propositions 2.1 and 2.2 (random motion and kinetic energy): Many began to describe particles as moving randomly and faster when heated.
- Propositions 3.1 and 3.2 (spacing and vacuum): Some progress was observed, as students noted that particles could be closer or farther apart, though the idea of empty space remained fragile.
- Propositions 4.1–4.3 (interactions and temperature effects): A small number of students connected temperature changes with changes in particle motion and interactions.

However, deeper concepts such as inter-particle forces and emergent properties remained out of reach. This is partly due to their abstract nature, and partly because our curriculum design placed limited emphasis on this aspect. Future teaching should therefore provide stronger scaffolds—helping students not only build particle-level explanations but also understand how particle interactions and structures shape macroscopic properties.

5. Conclusions and Implications

Our findings show that the analogy-based modeling curriculum supported elementary students in moving from the macroscopic Continuum Model (C) toward the Mixed-consistent Model (M-c), where microscopic ideas were more logically integrated. This shift was likely driven by the alternation between observation and analogy, combined with scaffolding from microscopic simulations and teacher guidance. The M-c model became relatively stable across lessons, indicating its role as a key transitional stage.

That said, only a small number of students advanced to more sophisticated particle models—such as explaining inter-particle forces, attraction–distance relationships, or kinetic energy changes with temperature. These abstract concepts remain highly challenging for elementary learners. In addition, during transfer stages some students regressed to macroscopic reasoning (C model), suggesting that microscopic ideas had not yet been fully internalized as flexible knowledge. Their understanding of spatial structures such as vacuum and particle spacing was also fragile.

As Chen and Lin [15] noted, many teachers themselves possess only a basic grasp of particle modeling. Our results confirm that limited teacher knowledge and modeling language constrain how far students' models can develop. This highlights the central role of teachers in advancing students' conceptual growth.

Implications for practice are clear: teacher professional development should include targeted preparation on deeper aspects of the PMM (e.g., inter-particle interactions, spatial structures, emergent properties), along with concrete strategies for scaffolding and analogy use. Integrating such training with analogy-based modeling curricula can help students not only consolidate microscopic reasoning in class but also apply particle models flexibly in new contexts—laying the groundwork for long-term development in scientific thinking.

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