

Enhancing sub-micro level understanding: The impact of a science course on teacher students' explanations of phase changes

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Abstract: This study explores how prospective primary school teachers explain the boiling of water at the sub-micro level during and after participating in a compulsory science education course (chemistry and physics) in Finland. Data were collected from 50 prospective primary school teachers and consists of worksheets, written exam answers and illustrations. The analysis focuses on the development of the use of key scientific concepts—related to the phase changes of water—and the ability to distinguish between macro and sub-micro levels when explaining phase changes of water. The results revealed limited use of scientifically accurate terminology, with fewer than one-third of prospective primary school teachers using the correct concepts. Many responses included vague or ambiguous descriptions of particle behaviour. By the end of the course, a significant improvement was observed in how they used the key concepts related to the phase change(s) of water. Despite gains in use of correct terminology, still many prospective primary school teachers continued to confuse observable phenomena with molecular-level processes. A more fine-grained analysis shows that although they use key concepts that refer to the sub-micro level both in worksheets and exam answers only half of them can explain more precisely what occurs at the sub-micro level. Illustrations of the sub-micro level also varied in accuracy, only a few (10%) included correct intermolecular forces (hydrogen bonds) between the molecules in their illustrations.

Keywords: teacher students, sub-micro level, chemistry key concepts, teacher education

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1 Introduction

To understand chemistry requires us to engage with the three interconnected levels: the macroscopic level, which includes what can be perceived by the human senses; the sub-micro level, involving particles such as atoms, molecules, and ions; and the symbolic level, which includes chemical symbols, equations, and formulae (Gilbert & Treagust, 2009; Johnstone, 1982, 1991). These levels, and the ability to transition between them, are essential for making sense of chemical phenomena (de Jong & Taber, 2014; Taber, 2013).



To develop a deep understanding in science involves not only to acquire factual knowledge but also to grasp the underlying principles—*knowing how* and *why* things happen (Treagust et al., 2003). The depth of understanding depends on integrating knowledge across all three representational levels (Chittleborough, 2014; Rees et al., 2018; Treagust et al., 2003). When experts explain chemical phenomena and concepts they use all three levels. The ability to navigate between the three levels has proved to be a challenge for learners at different educational stages (Duangpummet et al., 2022; Gkitzia et al., 2020; Renvall & Kurtén, 2024).

A solid grasp of the particulate nature of matter—particularly the sub-micro level—is foundational for understanding the core principles of chemistry (Merritt & Krajcik, 2013). This is especially important for prospective primary school teachers (hereafter referred to as teacher students), since the foundation of scientific and chemistry key concepts is established during primary education. Teacher students are responsible for introducing scientific ideas and phenomena, such as the hydrological cycle, when teaching. Since much of the chemistry involves phenomena that cannot be directly perceived by our senses, it is crucial that teachers use scientific concepts accurately and confidently and have knowledge about the sub-micro level (Ryu et al., 2018).

However, research shows that many teacher students struggle with fragmented or superficial understanding of key scientific ideas in chemistry (Aydeniz et al., 2017; Härmälä-Braskén et al., 2020; Kind, 2004; Suparman et al., 2024). To address this, teacher education must support the teacher student's development of coherent explanations and the ability to shift between the three different levels in chemistry. This is not only vital for their own learning but also for their future teaching practice (Cabello & Topping, 2020). Students need to work on their own understanding to develop a coherent knowledge structure (Phillips et al., 2017).

In line with this we have in our teacher training courses attempted to create supportive environments where students feel comfortable using the scientific language and concepts that are important in science and chemistry. Through collaborative activities such as laboratory work and group discussions, students are encouraged to articulate, evaluate, and refine their understanding. These experiences help them build the skills they need to explain scientific phenomena clearly and accurately—both as learners and as future teachers.

1.1 Aim and research questions

The aim of this study is to explore the development of teacher students use of key chemistry concepts when explaining phenomena at the sub-micro level in chemistry. Specifically, the study focuses on how teacher students articulate their understanding of the hydrological cycle, with an emphasis on phase changes of water at the sub-micro level, during a science education course. We hope that our study helps us to improve effective teaching strategies that bridge the gap between conceptual knowledge and understanding of the sub-micro level of phenomena in chemistry education. The study is guided by the

following research questions:

RQ1. How do teacher students explain the phase changes of water at the sub-micro level?

RQ2. Is teacher students' ability to explain and understand the sub-micro level improved after participating in a science course?

2 Relevant research

In this section we first elaborate on the three representational levels in chemistry and the difficulties students may face when explaining phenomena at the sub-micro level. We specifically focus on the chemistry content that is the object of this study.

A comprehensive understanding of chemistry requires the capacity to think and reason across multiple levels of representation (Becker et al., 2015; Gkitzia et al., 2020; Kapici, 2023; Treagust et al., 2003). Johnstone (1982, 1991) proposed a conceptual framework that has since become foundational in the field of chemistry education, commonly referred to as the "chemistry triplet." This model delineates three distinct yet interconnected representational levels. The three levels are: the macro level, which includes observable phenomena that are accessible through our senses; the sub-micro level, which refers to what is not directly observable and needs to be conceptualised through theoretical models and/or visual representations; and finally the symbolic level, which includes the use of chemical symbols, formulae and equations to represent chemical processes and structures (de Jong & Taber, 2014; Taber, 2013).

While experts move without problems between these three levels, students often struggle to make meaningful connections among them (de Jong & Taber, 2014; Taber, 2013). Research has shown that students of different ages have difficulties when navigating between the three levels (Duangpummet et al., 2022; Gkitzia et al., 2020; Renvall & Kurtén, 2024). Students may rely heavily on macroscopic observations without fully understanding the underlying sub-micro mechanisms (Rees et al., 2018; Saritaş et al., 2021; Treagust et al., 2003). This disconnect can hinder the development of a coherent and scientifically accurate understanding of chemical phenomena. It is crucial for students to establish connections between the macro and sub-micro levels and to navigate seamlessly between them (Becker et al., 2015; Saritaş et al., 2021).

The sub-microscopic level poses significant challenges for students. Because it involves abstract and invisible entities, students must rely on models and visualizations to conceptualize what occurs at this level. Difficulties in this area are well-documented and include misconceptions about particle behaviour, bonding, and phase changes (Duangpummet et al., 2022; Espinosa et al., 2025; Gkitzia et al., 2020; Suparman et al., 2024). Moreover, students often find it difficult to translate between the sub-micro

representations and symbolic or macroscopic descriptions, a skill that is essential for scientific reasoning and communication (Gkitzia et al., 2020; Renvall & Kurtén, 2024).

Understanding the particulate nature of matter is fundamental to grasping the core principles of chemistry. However, research consistently shows that students across educational levels often possess a fragmented or superficial understanding of this concept (Hadenfeldt et al., 2014, 2016; Shi & Bi, 2023). While terms such as "atoms" and "molecules" are familiar to most students (Lee et al., 1993), they frequently erroneously attribute macroscopic properties—such as colour, and temperature—to individual particles at the sub-micro level (Albanese & Vicentini, 1997; Krnel et al., 1998). This indicates a lack of integration between the observable (macro) and particulate (sub-micro) levels, which is essential for developing a scientifically coherent understanding of chemical phenomena.

Even when students can correctly identify a phenomenon, such as condensation, they often struggle to provide scientifically accurate explanations. For instance, Håland (2010) found that while many teacher students recognized dew formation as condensation, they incorrectly believed that oxygen was transformed into water. These findings suggest that students may associate the correct terminology with a phenomenon without fully understanding the underlying process at the sub-micro level and thereby struggle to provide a scientifically accurate explanation for the phenomenon.

Chemical bonding represents another domain in which students encounter significant conceptual difficulties (Ballester Pérez et al., 2017; Nimmermark et al., 2016; Tsaparlis et al., 2018). Common alternative conceptions include viewing chemical bonds as tangible "glues" that physically hold particles together or that bond breaking releases energy in all cases, contrary to the principles of bond energetics. Such conceptual limitations further hinder students' ability to accurately explain phase transitions and other chemical phenomena at the sub-micro level (Luxford & Bretz, 2014; Othman et al., 2008).

Students also encounter persistent difficulties when explaining the nature of elements, compounds, mixtures, and phase changes at the sub-micro level. Studies have shown that students often fail to distinguish between these categories in terms of particle composition and interactions (Kahveci, 2009; Sheehan et al., 2011; Valanides, 2000). These difficulties are often rooted in an incomplete or incorrect understanding of the particulate nature of matter, which impedes their ability to reason about chemical processes at a deeper level. As Shi and Bi (2023) emphasize in their review, the development of a robust learning progression for the concept of matter is critical for supporting students' understanding of phenomena at sub-micro level.

Students' poor explanations of the sub-micro levels in different phenomena may be the result of a fragmented understanding of the particulate nature of matter. Matter is a key concept in chemistry and its learning progression is important for understanding the sub-micro level in chemistry (Shi & Bi, 2023).

Taken together, these findings underscore the importance of explicitly addressing the connections between the macroscopic, sub-microscopic, and symbolic levels in chemistry education. Without a coherent understanding of the particulate nature of matter and its

role in chemical processes, students are likely to retain fragmented or incorrect conceptions that hinder their ability to reason scientifically.

3 Methods

This section outlines the context and participants of the study, followed by a description of the study design and data collection procedures. This is followed by describing the coding and analysis of the data and concludes with a discussion of the limitations of the study.

3.1 Context and participants

This study was conducted within the context of Finnish teacher education, where primary teachers pursue a Master's degree in Pedagogy, comprising 300 credits of the European Credit Transfer and Accumulation System (ECTS)¹. Of these, 60 ECTS comprises the various subjects they will teach as teachers in grades 1–6. In the core curriculum for the comprehensive school in Finland (Finnish National Board of Education, 2016), chemistry, physics, biology, geography and health education form an integrated subject, known as Environmental studies for grades 1–6.

The participants in this study were teacher students participating in a mandatory science course (chemistry and physics, 5 ECTS) in their second year of teacher education. The content of the science course consisted of science concepts found in the Core Curriculum for grades 1–6 (FNBE, 2016) and pedagogical strategies on how to teach them. The chemistry part of the science course lasted for 6 weeks and consisted of 12 lectures. The key chemistry concepts covered included states of matter, phase changes, the characteristics of water, mixtures, chemical reactions, and pH. These concepts are both part of the science curriculum in grades 1–6 and key concepts in chemistry. In this study, the focus is on how teacher students explain concepts related to the water cycle. A total of 50 teacher students participated in this study.

3.2 Design of the study and data collection

Data for this study were collected from two key points during the chemistry part of the course: worksheets from an activity conducted during the third lecture (1.) and answers and illustrations from an exam (2.) administered six weeks later. The overall design and timeline of the study are illustrated in Figure 1.

During the first two lectures, students received instruction on states of matter, chemical bonding, and phase changes. The course teacher, who was not part of the

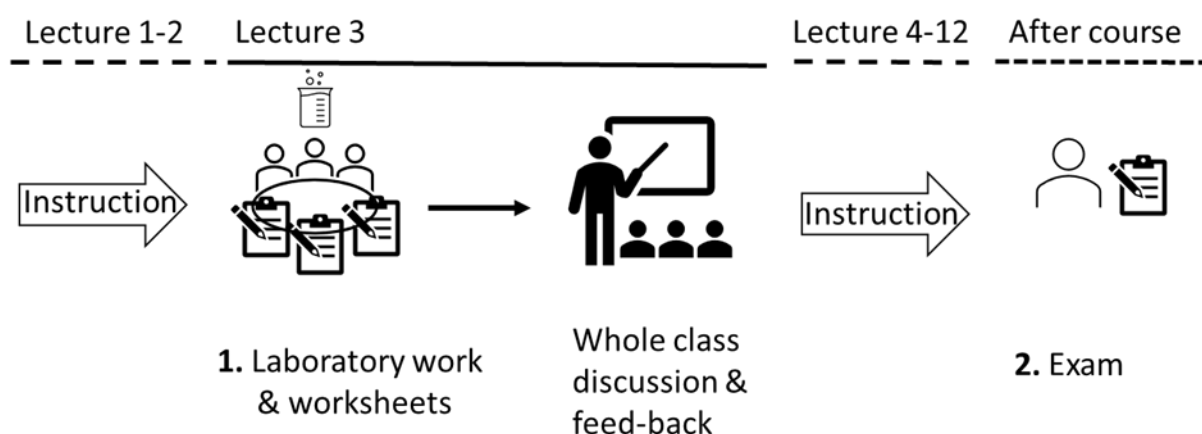
¹ The European Credit Transfer and Accumulation System, [ECTS] is a tool of the European Higher Education Area, it is used across the European Union and other collaborating European countries to help to describe and compare study programs between countries. ECTS credits represent learning based on defined learning outcomes and their associated workload, 60 ECTS credits are the equivalent of a full year of study (see European Commission)

research team, led all instructional lectures. Lecture three focused on the phases of water and associated phase changes. As part of this lecture, students worked in small groups (3–4 students per group, totally 15 groups) where they conducted an experiment with boiling water. Each teacher student was required to individually complete a worksheet (Appendix A) during the activity, they were asked to write down their observations on macro level and provide explanations of the boiling process at the sub-micro level (Figure 1, Timepoint 1). Although the worksheets were completed individually, students were encouraged to engage in group discussions during the laboratory activity. After the experiment, a whole-class discussion was held, during which the teacher provided feedback and addressed students' questions.

At the end of the six-week course, students completed an exam covering the chemistry content (Figure 1, Timepoint 2). The exam included open-ended questions related to water phenomena. Students were asked to explain the boiling process at both macroscopic and sub-micro levels and to create illustrations representing the sub-micro processes involved (see question in Appendix B).

Student-generated illustrations have been recognized as effective tools for assessing conceptual understanding in chemistry (Ryan & Stieff, 2019). Illustrations of sub-micro phenomena can enrich the analysis of written responses by revealing deeper insights into students' mental models. Moreover, such illustrations have been shown to influence collaborative reasoning and discussion (de Andrade et al., 2022). For these reasons, the inclusion of teacher students' own illustrations were an additional component of the exam design.

Figure 1. Design of the study



3.3 Coding and analysis

Teacher students' written explanations from both the worksheet and the exam were analysed as described below. All worksheets (Time point 1; N=50 teacher students) and exam answers (Time point 2; N=50 teacher students) were read through by the author and after that transferred verbatim into Word documents. All students were anonymised in the

beginning of the coding process. The author conducted the subsequent analysis. Throughout the analytical process, continuous discussions were held with other research colleagues to critically examine emerging concepts and themes, and to ensure consistency in their application. This collaborative approach aligns with established practices in qualitative research to enhance analytical trustworthiness (Bryman, 2016). Different types of collected data were studied to answer the research questions. From the worksheets, sentences explaining the phase changes of water at the sub-micro level, particularly during boiling (see Appendix A), were identified. The frequency of explanations was counted for all students (see Table 1 in the Results section). These were further categorised to three key concepts:

1. **States of Matter** – references to the physical states of water (solid, liquid, gas), particularly the identification of water vapour during boiling.
2. **Phase Change/Transition** – mentions of changes in state, including general terms such as phase change as well as specific processes like evaporation and condensation.
3. **Chemical Bond(s)** – references to intermolecular forces, especially hydrogen bonds, and students' understanding of how these bonds are affected during boiling.

These three key concepts were chosen because they are fundamental for explaining phase changes and understanding the sub-micro level in chemistry. Furthermore, we know from earlier research that students also have challenges with understanding these concepts (Härmälä-Braskén et al., 2020; Kind, 2004; Othman et al., 2008; Suparman et al., 2024).

Similarly, answers to an open-ended question in the exam (wording of the question, see Appendix B) were analysed. Sentences describing the phenomenon of boiling water were identified and the frequency of explanations were counted for all students in the same way as for the worksheets. These explanations were categorised using the same three key concepts (see Table 2 in the Results section). Concepts and words that appeared only in a few students' worksheets and exam answers were included in the analysis. Teacher students' use of key concepts is presented as relative frequency.

In the final exam teacher students were asked to illustrate the sub-micro level when water boils/undergoes a phase change. In the data analysis these illustrations were used as a complement to students' written explanations in the exam. Teacher students' illustrations were examined and grouped into three representational categories:

1. **Particle Diagrams** – simplified models using spheres to represent particles in different states (solid, liquid, gas), often showing changes in arrangement and motion.
2. **Molecular Diagrams with Intermolecular Forces** – more detailed illustrations depicting water molecules and hydrogen bonds between them.

3. Other Representations – scientifically inaccurate models or responses where no sub-micro illustration was provided.

Each of these categories was further refined through detailed sub-categorisation based on the accuracy, completeness, and clarity of the scientific content (see Table 3 in the Results section).

The analysis of the data in this study was done originally in Swedish and then translated into English.

3.4 Limitations of the study

A limitation of this study is its relatively short duration. It was conducted over a six-week period, and the study captures only immediate learning outcomes and does not account for long-term retention or delayed conceptual development. As such, the findings may not fully reflect the sustained impact of the instructional interventions on students' understanding.

Categorization of open-ended responses in qualitative research is challenging. Coding qualitative data is inherently subjective; researchers must ensure transparent documentation of coding decisions. To enhance reliability collaborative coding is needed and this was conducted with colleagues in this study. The nuanced nature of open-ended responses further complicates efforts to achieve consistency, as such data often reflect complex cognitive processes that resist reduction into discrete categories.

By incorporating interviews in the study, we could provide an insight into how students perceive and differentiate between the macro and sub-micro levels in chemistry and thereby enrich the interpretation of their written and visual responses.

The number of students participating in the study was relatively small, allowing only descriptive statistics to be used in addition to the qualitative analyses carried out. The generalisability is also limited due to the context, with only one university involved.

4 Results

This study surveyed teacher students' use of key concepts in chemistry when explaining phase changes of water (e.g. boiling) at the sub-micro level. The first part presents an analysis of teacher students' written explanations on worksheets completed during an activity where teacher students were boiling water. This is followed by the analysis of their written explanations and illustrations from the exam, completed after the course. Finally, we compare the use of key concepts across the two time points and provide a more fine-grained analysis of teacher students' written explanations and illustrations.

4.1 Teacher students' explanations of boiling water at sub-micro level in the beginning of the course

At lecture three when teacher students boiled water in groups, they completed a worksheet individually but were encouraged to engage in discussions with each other. In a considerable number of instances, teacher students within the same group submitted identical or nearly identical explanations. The answers were rather short, a few words or a sentence, and individual teacher students may have used several of the concepts in their answers (See Table 1 for examples of explanations and concepts used at sub-micro level). Less than one-third of the teacher students used scientific correct chemistry concepts to describe the physical change of water e.g. water vapour, breaking of chemical bonds (hydrogen bonds), evaporation and condensation. The concept “water vapour”, categorised as *state of matter* is mentioned by 26%, and 32% of the teacher students mentioned breaking of *chemical bond(s)*. The specific concepts of evaporation and condensation were used by 32% of the teacher students. These two concepts are merged into the key concept *phase change/transition* in this study. Additionally, we found that some students used vague or ambiguous phrases such as: “Atoms and molecules are moving fast” (28%), “Increased distance between atoms and molecules” (38%).

Table 1. Relative frequency of explanations elicited in the worksheets (N=50 teacher students).

Explanations in worksheets	Frequency	%	Key Concepts Total %	Key Concepts
Water vapour	13	26	26	<i>State of matter</i>
Evaporation	7	14	32	<i>Phase change/transition</i>
Water vapour condenses	9	18		
Breaking of chemical bonds	13	26	32	<i>Chemical bond(s)</i>
Explicit mentioning the hydrogen bond between water molecules	3	6		

4.2 Explaining boiling of water after participating in the science course

After a six-week period, teacher students participated in an exam, where they were asked to explain what happens at both macro and sub-micro levels when water boils. As shown in Table 2 teacher students are now more frequently using the concepts water vapour (*State of matter*), breaking of bonds/hydrogen bonds, (*Chemical bonds*), and *Phase*

changes when explaining boiling of water. The concept “water vapour” was now mentioned by 94 % of the teacher students and there is an increase in the use of concepts linked to chemical bonds, especially the concept hydrogen bond, where we can see a significant increased use by the teacher students from 6% in the worksheet to 40% in the final exam. In the exam teacher students use the concept “phase changes” more often instead of the specific concepts evaporation and condensation used within the worksheets. Concepts categorised to *Phase change/transition* are now used by 50% of the students.

Table 2. Relative frequency of explanations elicited in the exam (N=50 teacher students).

Explanations in exam answers	Frequency	%	Key Concepts Total %	Key Concepts
Water vapour	47	94	94	<i>State of matter</i>
Phase change(s)	20	40	50	<i>Phase change/transition</i>
Bubbles are formed (gas)	3	6		
Evaporation	2	4		
Breaking of chemical bonds	28	56	96	<i>Chemical bond(s)</i>
Explicit mentioning the hydrogen bond between water molecules	20	40		

4.3 Teacher students improved use of key concepts related to boiling of water

A summary of teacher students’ use of the key concepts, *State of matter* (e.g., water vapour), *Phase change/transition* (phase change) and *Chemical bond(s)* (e.g., hydrogen bond), as observed in their worksheet responses and exam answers are presented in Figure 2.

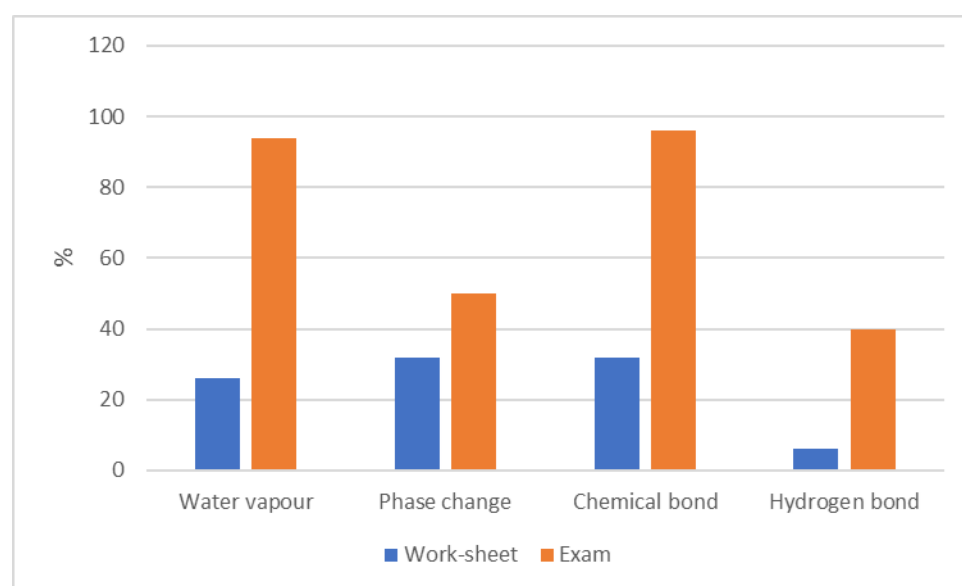
The use of the concept “water vapour” increased significantly in the exam compared to the worksheet responses collected during the third lecture. Specifically, 94% of teacher students mentioned water vapour in their exam explanations of what is inside the bubbles during boiling, an increase of 68%.

Yet, teacher students continued to face challenges with the other two concepts. While the use of “phase change” and “hydrogen bond” also increased over the course, the gains were more modest. In the final exam, only 50% of teacher students used the concept of phase change in their explanations of boiling water (see Figure 2). This suggests that many

still struggle to distinguish between a physical change and a chemical reaction, as some incorrectly stated that both occur when water boils.

Furthermore, although 96% of teacher students referred to chemical bonds or the breaking of bonds, only 40% correctly identified the type of bond as hydrogen bonds or used related terms such as intermolecular forces. This indicates a partial understanding of the molecular interactions involved in phase changes.

Figure 2. Teacher students' use of key concepts (in %) linked to boiling of water during and after the course (N=50 teacher students).



4.4 Ambiguities in Teacher Students' Explanations of Boiling Water

Despite the use of terminology that can be categorised under the three key concepts *States of matter*, *Chemical bond(s)* and *Phase change*, there are ambiguities in teacher students' explanations of the phenomenon of boiling water. A recurring challenge is their difficulty to clearly distinguish between the macro and the sub-micro levels when they describe phase changes of water. Although students were explicitly asked to explain boiling at both the macro and sub-micro levels, only 31 out of 50 students (62%) addressed both levels in their final exam responses. Students give descriptions that include both what can be observed with our senses and what is taking place at the molecular or sub-micro level.

They might think that molecules themselves are visible or that molecules behave in ways that are directly observable. This can be seen from the examples of teacher students' explanations in their exam answers. Our analysis shows that teacher students are mixing what occurs at the observable level with what occurs at the molecular level, sub-micro level. Several students use words like "look like" and "we can see the molecules" in their explanations.

“I will first explain what water molecules look like in liquid form...”
“...You would see the water molecules start to move more and more...”
“At sub-micro level we can see how molecules start to move...”

These examples illustrate a tendency to mix visual observations with molecular behaviour and indicate a lack of clarity about the nature of sub-micro representations. In addition, teacher students also describe how heat causes molecules to move and leads to breaking of chemical bonds.

“As the water heats up, the bonds start to shake and eventually break...”
“When heat is added, ... the water boils, and the molecules move so much that the bonds break”
“When heat is added, the water molecules start to get restless and start to flout around each other...”

While many students correctly mentioned phase changes, hydrogen bond breaking, and water vapour, their use of scientific language was often informal. Phrases such as “molecules dance” or “new substances are formed” suggest misuse of terminology or poor understanding.

“Bonds are broken, and water molecules are free to dance”
“The behaviour of water molecules changes when water boils...”
” Bonds are broken, and new substances are formed in the water”.

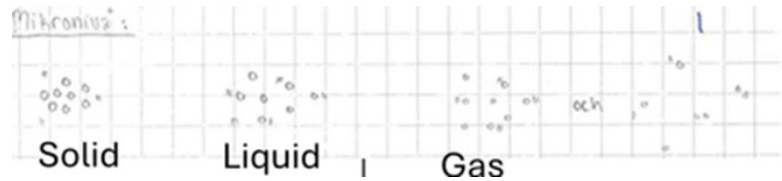
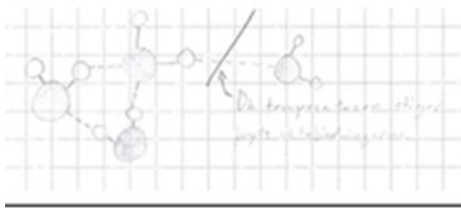
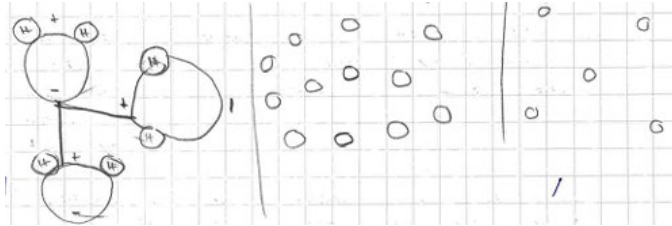
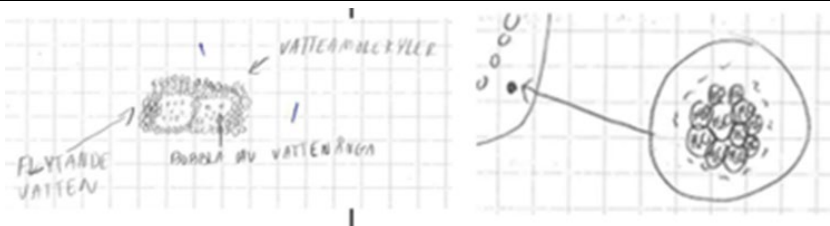
Hence, we can see that students show ambiguities in their explanations of boiling water, and they have difficulties distinguishing between the macro and sub-micro levels.

4.5 Students' illustrations of boiling water at the sub-micro level

In the exam teacher students were asked to illustrate the sub-micro level when water is boiling. A total of 30 out of 50 teacher students used the simple particle model with spheres illustrating the three states of matter. This model illustrates how particle arrangement and movement change during phase changes. In some illustrations, all three states of matter were depicted, while many teacher students focused only on the phase change from liquid to gas or represented only the gas phase.

Nine teacher students drew a model of water molecules with the intermolecular forces (hydrogen bonds) between the molecules. However, in four of these cases, the illustrations contained inaccuracies concerning the intermolecular bonds. In eight cases, teacher students drew illustrations that were scientifically incorrect models. Three of the teacher students did not illustrate the sub-micro level in their exam answers. The categorisation of these representational types is found in Table 3, complemented with examples of students' illustrations.

Table 3. Categorisation of the teacher students’ illustrations of sub-micro level when water is boiling (N=50 teacher students)

Type of representation	Number of Students	Examples of illustration
1. Particle diagrams		
Three phases (solid, liquid, gas)	11	
Two phases (liquid, gas)	12	
One phase (gas)	7	
2. Water molecules and intermolecular forces (bonds)		
Water molecules with intermolecular bonds correct (hydrogen bonds)	5	
Water molecules with inaccuracies concerning intermolecular bonds	4	
3. Other Representations		
Other type of scientifically incorrect illustration	8	
No illustration	3	

5 Discussion

The findings reveal a significant gap between how students use key concepts and the ability to accurately explain the phase changes at the sub-micro level. Despite references to sub-micro level concepts in the worksheets and exam answers, many teacher students struggle to provide precise explanations of the molecular changes occurring during the phase changes of water. Additionally, the teacher students' illustrations often do not align with their written explanations and the key concepts they employ.

The three key concepts state of matter, chemical bond(s) and phase changes are used by teacher students during the course activity (worksheet), and after 6 weeks with an even more frequent use of the concepts in their answers in the course exam. Almost all teacher students (94%) mention in their exam answers that water vapour is formed when water boils. Regarding the concept of phase transition, we cannot see a clear increase from the results during the course activity to the exam. Although half of teacher students mention that boiling is a phase transition, it is only an increase of 18%. Barker et al. (2009) report that teacher students may still believe a chemical reaction is taking place—when it might not be. The same type of results has been shown in other studies (Härmälä-Braskén et al., 2020).

After the course almost all the teacher students mention that chemical bonds are broken when water boils. However, far fewer, only 40% of students, mention that it is the intermolecular forces between water molecules that are broken, i.e. the hydrogen bonds. Student responses suggest that teacher students may not fully understand the difference between the macro and the sub-micro levels. They might think that molecules are broken apart when water boils instead of breaking of the intermolecular forces (Novick & Nussbaum, 1981). This may also be reflected in the results that only half of the students choose to mention concepts that can be classified as the key concept phase change. This also align with the results from a study by Othman et al., (2008) where they show that secondary school students have difficulties to understand chemical bonding due to poor understanding of the concept of matter (sub-micro level).

Bucat & Mocerino, (2009) have discussed the importance of knowing the difference between sub-micro level and macro level and the meaning of these forms of molecular representations to understand chemistry. When students were asked to describe water boiling at both the macro and sub-micro level in our study, 38% of the students did not describe the sub-micro level at all. It remains unclear whether they did not know the difference between the two levels, macro and sub-micro, or whether they did not know at all what is meant by sub-micro level and therefore left it out from their answers. The teacher students who chose to describe both levels were vague in their descriptions of the sub-micro level. Students associated properties to molecules that can only be experienced with our senses. The concept of energy was mentioned by students and could partly be attributed to their thinking about the increase in the temperature of water. Students also described how the water molecules moved quickly, and these explanations were often linked to an increase in water temperature. The same type of challenges has been reported in studies by (Espinosa et al., 2025; Sarıtaş et al., 2021) where students had problems with understanding phase transitions, molecular behaviour, intermolecular forces and had difficulties with understanding the relationship between macro and sub-micro levels.

Combining illustrations with writing explanations how molecules interact are suggested to give a fuller picture of students' understanding in chemistry (Espinosa et al., 2025). Therefore, this was also used in the exam in the study. In, addition to explanations, teacher students were asked to illustrate the sub-micro level when water boils. Only 10% of the teacher students used the intermolecular forces, the hydrogen bonds, between water

molecules in their illustrations. We see that the most common way to illustrate sub-micro level is by using the particle model that shows the three different states of matter, 60% of the teacher students were using this. This model illustrates how particle arrangement and movement change during phase transitions and is widely used in chemistry education across various age groups, which likely explains its familiarity of this model among the students. Hence, we see that most teacher students use models that are common in learning materials to illustrate the sub-micro level of different states of matter, still about 20% of the students were unable to provide any illustration of the sub-micro level.

Nevertheless, the findings of this study indicate that student teachers made progress in their understanding of the sub-micro level in chemistry over the duration of the course. Specifically in terms of the three key concepts state of matter, chemical bond(s) and phase changes examined in the study. However, the results also highlight a continued need to enhance the teaching of chemistry within teacher education programs to better support the development of deep conceptual understanding. To support teacher students' understanding of chemical phenomena, teacher education should include explicit instruction on the chemistry triplet (Taber, 2013). Embedding key concepts into discussions, writing tasks, and feedback promote clarity and precision. Guided use of models and diagrams enhances sub-micro level representations (Treagust et al., 2003), while diagnostic tools and structured feedback help identify and address preconceptions. Integrating sub-micro reasoning into pedagogical content knowledge (Dragnić-Cindrić & Anderson, 2025) equips future teachers to explain molecular-level processes in age-appropriate ways and fosters science literacy.

6 Conclusion

In this study, we investigated how teacher students explain everyday phenomena at the sub-micro level and whether their understanding improves after participating in a science course. Our findings revealed that although teacher students use chemistry key concepts when explaining phenomena at sub-micro level, teacher students' explanations still reveal gaps in their understanding of the phenomenon. Some improvements can be observed after the course and these results highlight the critical role of science education in enhancing conceptual understanding among students in the teacher education. Our research underscores the importance of incorporating teaching of the sub-micro level in teacher training programs for primary teachers. By addressing these educational needs, we can better prepare future teachers to explain complex phenomena, thereby improving science literacy overall. Future research could include a more long-term retention study among students, or a follow-up study when students are working as in-service teachers.

Research ethics

Artificial intelligence

M365Copilot has been used for clarity and improvement of the English language.

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Informed consent statement

Informed consent was obtained from all research participants.

Data availability statement

Data used in the study cannot be shared due to confidentiality.

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Conflicts of interest

The author(s) declare no conflicts of interest.

Appendices

A. Worksheet at lecture three.

Name:



Boiling water:

- Pour a couple of centimeters of water into a decanter.
- Put a watch glass as a lid.
- Heat the water until it starts to boil. Observe and describe at the macro level what you see.
- Explain on sub-micro level what happens.

Before heating

Macro level

Sub-micro level

In the beginning of heating

Macro level

Sub-micro level

While water is boiling

Macro level

Sub-micro level

B. Open-ended question in the final exam: Translated from Swedish to English.

“Your students examine the pot where you are boiling water, they see bubbles and wonder what is inside the bubbles. What explanation do you give to your students? Draw and describe what is happening at the macro- and at the sub-micro levels in the pot with boiling water.”

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