

Gaining insights through thematic analysis about learning dimensions in teaching learning sequences on surface phenomena in liquids

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This study investigates the role of learning dimensions in planning and trialing teaching-learning sequences (TLSs) on surface phenomena in liquids for high school students. Particularly, it aims to identify how different modeling approaches—macroscopic and mesoscopic—impact students’ learning in terms of different dimensions of learning such as conceptual understanding, intellectual growth, and scientific habits of mind. Some results derived from the application of thematic analysis (TA) to qualitative data collected from students’ interviews and feedback, and allowing for the identification of key learning dimensions, are presented. By systematically linking qualitative data to learning dimensions, TA provided a structured framework for evaluating the effectiveness of different instructional strategies. The study highlights the role of both cognitive and affective factors in science learning and underscores the importance of integrating diverse modeling approaches to foster a comprehensive understanding of complex scientific topics.

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I. INTRODUCTION

Science education research aims to address the complexities surrounding science teaching and student learning. Over the years, various theoretical frameworks have been proposed to improve the effectiveness of teaching practices and student learning outcomes [1].

Particularly, the educational reconstruction model introduced by Kattmann and co-workers [2–4] emphasizes the importance of reconstructing scientific knowledge for educational purposes by analyzing both the structure of scientific content and key pedagogical factors. These include the educational context, students’ preconceptions, and core learning processes.

Building on these frameworks, researchers have focused on the development of theme-based educational pathways to support teachers in designing and implementing lessons that promote and improve student learning. Examples of such pathways include teaching-learning sequences (TLSs) [5,6] and learning progressions (LPs) [7,8]. These pathways are structured to facilitate the interaction between science content and student perspectives, with the aim of optimizing learning outcomes and facilitating knowledge construction [5]. TLSs and LPs consist of carefully sequenced blocks of learning that students can master on

their way to achieving broader educational goals. By designing and implementing TLSs and LPs, teachers can tailor their instruction to meet the diverse learning needs of their students, ultimately enhancing the overall learning experience.

Recent research in education and cognitive psychology has emphasized the importance of the student role and of its beliefs, motivation, confidence, and mindset in learning. The Investigative Science Learning Environment approach [9], for example, immerses students in activities that resemble real scientific inquiry, emphasizing collaboration and reflection. Psychological research, particularly the work of Carol Dweck, has highlighted the significance of students’ beliefs about their abilities. A “growth mindset” encourages learners to view their abilities as malleable, motivating them to engage in sustained and deliberate efforts to improve [10–12].

Although Dweck’s approach has faced criticism, especially concerning how teacher beliefs influence classroom practice [13,14], studies have shown that mindset interventions can lead to improved outcomes across different contexts [15,16].

This integrated perspective informs many contemporary strategies for planning and implementing TLSs and LPs [17].

Within this broad framework, our research aims to explore what it means to promote science learning, particularly in terms of how students engage with and make sense of scientific concepts.

To address this complex and multifaceted question, we designed and implemented two teaching-learning sequences (TLSs) focused on surface phenomena in liquids.

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The educational value of exploring surface phenomena in liquids remains largely underinvestigated, especially from the perspective of modeling and student engagement with different descriptive scales. While these phenomena have significant practical implications in disciplines such as biology, chemistry, and materials science, they are often introduced in educational settings through traditional, macroscopic descriptions that may fail to foster deep conceptual understanding. Moreover, these descriptions are often paired with transmissive teaching methods characterized by frontal lessons, textbook reading, and limited laboratory time, which hardly support the development of meaningful learning [18–20].

Starting from these observations, our research aimed to explore alternative approaches, in terms of both didactic methodologies and descriptive scales, to the teaching of surface phenomena, capable of promoting a deeper and more active student engagement. Specifically, we sought to understand how different modeling scales (macroscopic and mesoscopic) might influence students' reasoning processes, conceptual development, and participation in scientific practices.

To this end, we formulated the following research question: *In which terms and to what extent can the two approaches trialed—macroscopic and mesoscopic—promote science learning?*

This question guided the design of our study, the development of the TLSs, and the collection and analysis of data.

II. THEORETICAL FRAMEWORK

Although the process of *promoting science learning* may appear straightforward, it presents a complex, multilayered challenge in practice. Drawing on the literature [21,22], we identified three overarching dimensions central to this process: (i) *Acquisition of conceptual knowledge*; (ii) *Intellectual growth*, and (iii) *Development of habits of mind suited to learning science* (see Fig. 1). These dimensions reflect the multifaceted nature of science education, encompassing cognitive, metacognitive, affective, and attitudinal components.

Referring to Fig. 1, the *conceptual knowledge* dimension involves not only mastering scientific content but also meaningfully applying and connecting ideas. This is strictly related to the *intellectual growth* dimension, which includes the development of higher-order thinking skills such as analysis, synthesis, problem solving, and scientific inquiry, along with the ability to communicate and transfer knowledge across contexts. Interwoven with these cognitive dimensions is the *Development of habits of mind suited to learning science*, encompassing students' attitudes, motivation, self-efficacy, and metacognitive awareness that influence how they engage with, interpret, and reflect on their learning experiences.

While these three dimensions represent distinct aspects of learning, they are deeply interconnected and mutually reinforcing. A solid grasp of conceptual knowledge supports the development of advanced thinking skills, which in

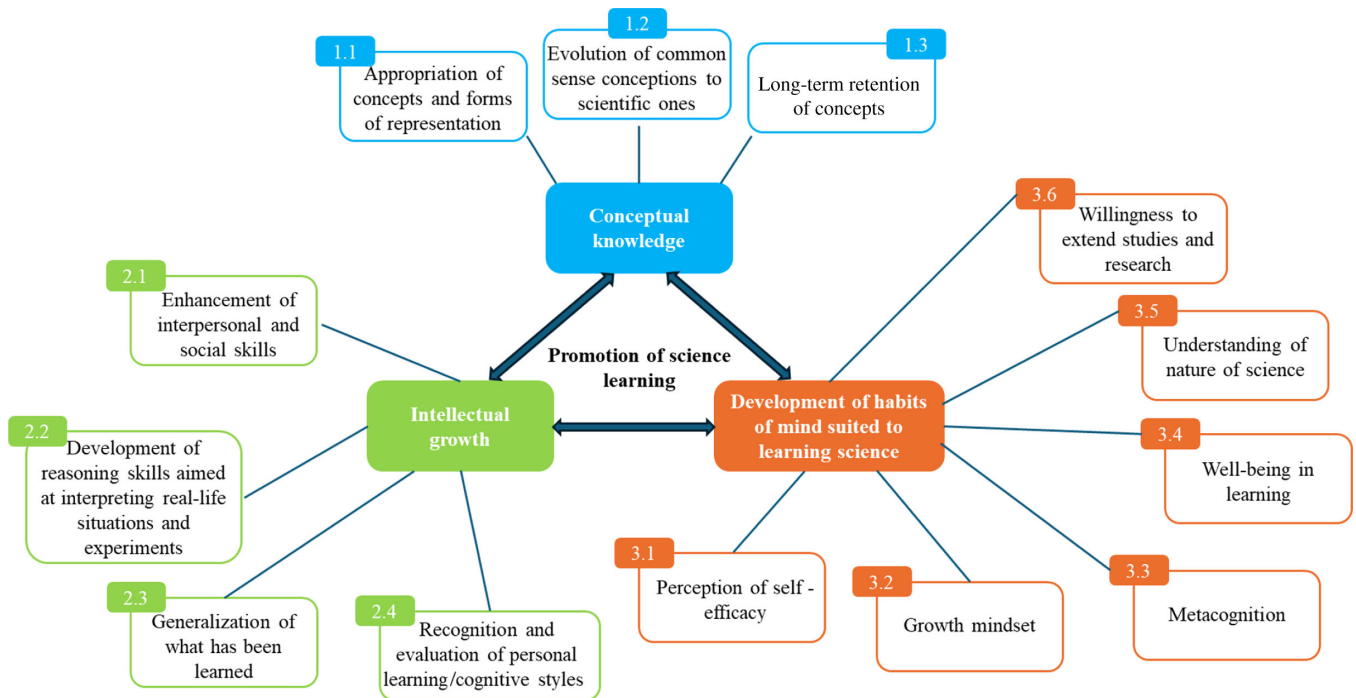


FIG. 1. Map illustrating the three overarching dimensions of science learning and their corresponding subdimensions, identified through a comprehensive analysis of the literature. This research-informed framework underpins the study and provides a lens for examining how different educational strategies can foster meaningful and enduring science learning.

turn prompt students to refine and reorganize their conceptual frameworks. Meanwhile, habits of mind sustain this ongoing learning process: motivated and self-efficacious students are more likely to persevere through challenges, reflect critically on their thinking, and take ownership of their educational journey, thereby deepening both conceptual understanding and intellectual capacities.

Each dimension includes a range of subdimensions that can be used as “study variables” to have a more granular view of how students engage with scientific content, develop reasoning skills, and adopt productive learning behaviors. This layered framework allows for a nuanced analysis of educational strategies and student learning outcomes, enabling researchers to trace how different teaching approaches influence not only students’ conceptual understanding but also their engagement, reasoning processes, and the development of transversal skills such as critical thinking and collaboration. By examining learning through multiple dimensions—cognitive, social, and affective—this framework provides a comprehensive perspective on the effectiveness and impact of instructional interventions.

A brief description of the learning subdimensions involved in our research, along with selected bibliographic references, is provided in Sec. II A. While not exhaustive, the references included offer a broad overview of the key concepts most relevant to fostering science learning, highlighting how these learning dimensions are interrelated and play a central role in supporting the development of meaningful and effective science education. The map in Fig. 1, highlighting the key dimensions and subdimensions that shape our research on science learning and supporting the investigation of how various instructional practices can either promote or hinder learning in educational settings, serves as the conceptual framework of the study presented in this work.

A. Learning variables

In this paragraph, we provide a brief description of the subdimensions of learning identified as particularly relevant to our research, supported by selected literature references. These references provide theoretical grounding for our conceptual framework and inform the analysis of science learning processes.

1.1. Appropriation of concepts and forms of representation: Achieving a deep and meaningful understanding of scientific concepts requires that students take ownership of the content. This means they must be able to express it through multiple forms, actively reshaping and adapting the reasoning structures underlying their knowledge. Appropriating content involves not only solid conceptual understanding but also a reflective effort to transform scientific discourse into something personally meaningful and authentic. In parallel, the appropriation of representational forms pertains to students’ ability to

navigate and employ various modes of expression and communication. Among the most frequently used in science are verbal, iconic, tabular, graphical, and analytical representations [23–25].

1.2. Evolution of common-sense conceptions to scientific ones: Students begin the process of acquiring and organizing knowledge by forming beliefs based on their everyday experiences and cultural influences, which they then structure into patterns and models of reality. In learning science, students should recognize the underlying assumptions and epistemological commitments that shape their intuitive theories, while also acknowledging the differences from, and limitations of, these theories compared to scientific theories. This entails becoming aware of their experience-based beliefs and developing new belief systems grounded in scientific reasoning and executive function skills [26–28].

1.3. Long-term retention of concepts: Memory is a dynamic and evolving process, rather than something static or fixed. The ability to store new information in long-term memory requires the capacity to integrate and adjust one’s existing knowledge network. It is widely recognized that the value of education is strongly linked to the long-term retention of what has been learned [29,30].

2.1. Enhancement of interpersonal and social skills: The development of students’ social and interpersonal skills should be a key educational goal. Transversal abilities such as working effectively in teams, cooperating, offering help and support to those in need, and recognizing and respecting differences serve as the foundation upon which all other competencies are built [31] and represent the key to effective intellectual growth [32].

2.2. Development of reasoning skills aimed at interpreting real-life situations and experiments: In physics, an explanation of a system or situation/observation differs from a description because it suggests that the system possesses properties that are not directly observable but contribute to the observed patterns. Constructing and validating explanations involves developing different types of hypotheses: empirical law hypotheses, synthesis of regularities (derived from phenomenological observations and condensed into rules), and hypotheses for building explanatory models, which introduce theoretical representations and often include nonobservable entities [33–35].

2.3. Generalization of what has been learned: The generalization of what has been learned is often linked to the systematization of knowledge. By organizing knowledge about facts, phenomena, laws, and principles into a cohesive system, students can uncover new connections and relationships between concepts. Generalizing knowledge can be viewed as a shift to a higher level of abstraction, emphasizing common features (such as properties and relationships) of objects and phenomena. This process of generalization not only enhances the quality of knowledge but also facilitates its transfer [36–38].

2.4. Recognition and evolution of personal learning/cognitive styles: Meaningful didactics aimed at fostering effective and personalized learning should be guided by an analysis of students' learning and cognitive styles. Learning styles refer to a combination of cognitive, emotional, and physiological factors that serve as stable indicators of how a learner perceives, interacts with, and responds to the learning environment. Cognitive styles reflect consistent individual differences in preferred methods of organizing and processing information and experiences [39–44].

3.1. Self-efficacy: Self-efficacy refers to the belief in one's ability to influence personal motivation, actions, and social interactions. Self-assessments of cognition affect several aspects of human experience, including the goals individuals set, the effort they invest in achieving those goals, and the likelihood of reaching performance levels [45–49].

3.2. Growth mindset: Learning is shaped by individuals' beliefs about their own abilities and dispositions. When students view their abilities as adaptable and capable of development, they tend to engage more positively and actively with learning tasks, embracing feedback and recognizing opportunities for growth. Adopting a growth mindset enables students to break free from limiting thought patterns and take ownership of their learning journey. It also helps them avoid settling into a “cognitive comfort zone,” a space defined by skills they believe they have already mastered, which can hinder meaningful cognitive advancement [10,11,50].

3.3. Metacognition: The main components of metacognition include several interconnected processes [51–53]. Metamemory refers to the ability to accurately assess one's own knowledge state, while metacomprehension involves judging how well one understands written or spoken information. Problem solving is another key aspect, characterized by the pursuit of a goal when the path to it is not immediately clear. This involves continuously generating and weighing options, exploring alternatives, and evaluating outcomes. Finally, critical thinking plays a central role, requiring individuals to assess the quality of ideas by analyzing whether they are coherent and logically sound.

3.4. Well-being in learning: Well-being should be understood as an active and dynamic process that plays a central role in shaping meaningful and effective learning experiences. While it is essential for educators to create a supportive, inclusive, and emotionally safe environment, one that encourages openness, collaboration, and respect, well-being should not be seen solely as the responsibility of the teacher or the school context. Rather, it must also be cultivated by students themselves through active participation, self-reflection, and engagement in their educational journey. This dual perspective recognizes well-being not only as a precondition for learning but also as a skill to be developed, a personal and social resource that evolves as students grow, take responsibility, and shape their identity as learners [54–57].

3.5. Understanding of the nature of science: Effectively learning science involves more than acquiring content knowledge; it requires students to develop a clear understanding of the nature of science itself, i.e., its aims, its methods, and its distinctive ways of constructing knowledge. This includes becoming familiar with scientific procedures, such as formulating hypotheses, designing experiments, and interpreting data. At the same time, students must learn to revise how they represent and explain physical phenomena, gradually aligning their intuitive reasoning with the logical and evidential standards of scientific thinking [58–60].

3.6. Willingness to learn and extend: It can be described as an internal drive or desire to continuously seek out information and deepen understanding, particularly when this pursuit is motivated by personal growth and self-improvement. This kind of curiosity reflects an active engagement with learning, where individuals are intrinsically motivated to explore new ideas, question assumptions, and expand their knowledge beyond immediate goals or external rewards [18,19].

III. METHODS

A. Designing TLSs to investigate science learning processes

In response to the limitations of traditional teaching methods such as frontal lectures, textbook-based learning, and minimal laboratory work, we designed two TLSs centered on surface phenomena in liquids, integrating interactive, student-centered strategies, including laboratory activities, computer-based simulations, and cooperative learning.

The two TLSs differ primarily in the modeling scale they adopt. One sequence (TLS-A) uses a macroscopic approach, typically employed in traditional physics curricula, while the other (TLS-B) employs a mesoscopic approach, which aims to bridge the gap between macroscopic observables and microscopic mechanisms. When discussing surface phenomena, macroscopic and microscopic descriptions often appear to be in contrast or even contradictory, as highlighted by Marchand *et al.* [20], who emphasize the complex interplay between observable behaviors and molecular-level interactions at interfaces. As highlighted by the literature [61], mesoscopic modeling can help students identify causal mechanisms and dynamic interactions that underlie observable effects.

Both sequences are structured around active involvement: students engage in hands-on experiments and use simulations that allow real-time manipulation of model parameters. This interactivity helps make abstract concepts more tangible and supports a deeper understanding of the physical processes involved. Crucially, students are also guided to compare experimental data with simulation outputs, promoting reflection on the nature and role of scientific models.

B. Population and data collection

The TLSs were trialed during the 2021/22 school year with two groups of upper secondary school students enrolled in a science-oriented curriculum. Each group consisted of 20 students, all attending the fourth year of the same high school. All students came from two classes whose physics teachers graduated in physics.

Students were randomly assigned to two groups (group A and group B) so that each group would be as heterogeneous as possible in terms of prior scientific preparation, interest in and attitudes toward scientific subjects, and learning dispositions. This arrangement was intended to ensure that any observed differences in learning processes or outcomes could be attributed more confidently to the modeling scale and pedagogical design of the TLSs, rather than to initial group characteristics.

Group A participated in the TLS based on the macroscopic approach, while group B engaged in the TLS structured around the mesoscopic approach. Both groups engaged in collaborative learning environments that emphasized peer interaction, shared exploration, and discussion. Students were encouraged to reflect on experimental outcomes, theoretical models, and the interplay between them. These collaborative dynamics created a supportive atmosphere in which students could exchange ideas, confront misconceptions, and develop a deeper and more nuanced understanding of the phenomena under study. More details on the TLSs are presented in Refs. [62,63].

The data collected during the implementation of the TLSs included:

- Students' responses to content questionnaires.
- Students' worksheets.
- Students' interviews.
- Transcripts and audio recordings of students' discussions.
- School teachers and researchers' observations.

The data analyzed in this study consist of students' responses to an interview on surface phenomena conducted both before and after the instructional intervention (database 1), as well as their written reflections in the open-ended section of a feedback questionnaire regarding the activities they participated in (database 2).

The variety of data sources enabled a rich, multifaceted analysis of how students made sense of surface phenomena and interacted with the proposed modeling tools and approaches. Most importantly, the breadth and depth of the collected data allowed us to address our central research question: *in which terms and to what extent the two approaches trialed—the macroscopic and the mesoscopic—can promote scientific learning?* The qualitative nature of the data, combined with the diversity of learning experiences documented, provided the basis for an in-depth exploration of this question from multiple perspectives, with attention to both individual and collective learning trajectories.

C. Thematic analysis of the data

To explore how students learn in rich and meaningful ways, it is crucial to adopt analytical tools capable of capturing the complexity of learning processes. In this regard, thematic analysis (TA) [64,65] provides a flexible and robust approach that is particularly well-suited for investigating such multifaceted dynamics. Unlike approaches constrained by predefined categories or strictly quantitative data, TA enables the inductive identification of patterns and meanings within qualitative sources such as interviews, classroom observations, and reflective journals.

This method is particularly well suited for exploring the cognitive, affective, social, and metacognitive dimensions of learning, which often surface in context-specific and nuanced ways. In recent years, TA has also gained traction in PER [64–66], where it has been increasingly employed to investigate how students build knowledge, regulate their learning, and engage emotionally and socially within their learning environments. Its iterative and interpretive nature aligns with constructionist views of knowledge and supports contextually grounded interpretations, an essential foundation for designing effective instructional interventions and advancing educational research.

We adopted an inductivelike approach to coding [67], meaning that codes were not predetermined but developed through repeated readings of the data. The raw data, i.e., the full, unaltered student responses, were systematically examined line by line to identify patterns and emergent concepts.

Initial codes were generated based on recurrent expressions and ideas found in the data segments. These codes were iteratively refined through multiple rounds of analysis. Ultimately, this process led to the definition of six overarching codes (A–F), presented in Table I. These overarching codes were obtained by grouping initial codes that conveyed similar meanings. It is worth noting that the overarching codes identified in our research represent the main themes that emerged from the data, capturing recurring patterns and meaningful insights related to students' learning processes. Themes are not merely topics or

TABLE I. The letters A–F indicate the codes also named overarching codes, obtained by merging the initial codes reported in the first column.

Initial codes	Overarching codes
Procedure-methodology understanding/ tools-skills/theory vs practice/traditional lecture vs innovative lecture	A
Content understanding	B
Debate/perspective/role	C
Language	D
Reflection/acknowledgment	E
Engagement-interest/comfort/proactiveness	F

TABLE II. Code-variables correspondences that help us in tracing the information on specific aspects of learning carried by a given segment of text labeled with a given code.

Overarching codes	Variables												
	Conceptual knowledge			Intellectual growth				Development of habits of mind suited to learning science					
	1.1	1.2	1.3	2.1	2.2	2.3	2.4	3.1	3.2	3.3	3.4	3.5	3.6
A					X	X			X	X		X	X
B	X	X	X		X	X							
C		X		X	X		X	X	X	X	X	X	X
D	X	X		X		X				X		X	
E					X	X	X	X	X	X			X
F									X		X		X

categories, but rich, interpretative constructs that reflect significant features of the data in relation to the research questions [68,69].

To enhance the rigor and reliability of the analysis, three researchers independently coded the data and subsequently engaged in collaborative discussions to reach consensus. This triangulated approach minimized individual biases and promoted intersubjective agreement, ensuring that the final coding scheme accurately reflected the content and structure of the data. The associations between the identified codes and the learning variables investigated in this study are detailed in Table II. This table represents a key tool for mapping which aspects of learning emerge from each code. While Table II provides an overall picture of these correspondences, it is important to note that not all code-variable relationships necessarily appear in our datasets. Therefore, in the following sections, we will show how Table II is used to analyze the specific datasets under examination (see Tables V and VII).

For example, referring to Table II, data segments labeled with the overarching code “A” can provide information about students’ intellectual development (variables 2.2 and 2.3) and the development of scientific habits of mind

(variables 3.2, 3.3, 3.5, and 3.6). Each code defined in Tables I and II serves to synthesize the key information conveyed by the associated data segments and reflects one or more dimensions of learning addressed in this research.

The decision to merge codes and to associate each with specific variables was the result of negotiated agreement among the researchers involved. This collective process, based on shared expertise and mutual validation, enhances both the consistency and validity of the final coding scheme. The key steps of the analysis process are summarized in Table III.

D. Overarching codes and their relationship with learning dimensions

In this section, we describe the overarching codes (or themes) (A–F) that were developed through repeated readings of the data. Each code is accompanied by a definition that explains its meaning and identifies the specific aspects of the data it highlights. These definitions are informed by both the manifest content (i.e., verbatim student quotes) and the researchers’ interpretations, particularly where implicit meanings were strongly conveyed.

TABLE III. Main steps followed to conduct the thematic analysis of the data.

Step 1.	Familiarization with the data	We reviewed all the data collected to become familiar with their content and context.
Step 2.	Selection of the data	We recognized inside the data text segments suitable for achieving the research purposes.
Step 3.	Raw data coding	We identified some preliminary codes, also named initial codes (first column of Table I), i.e., keywords that helped us to synthesize the information provided by the data.
Step 4.	Advanced data coding	After repeated readings, we decided to introduce some overarching codes (second column of Table I) embedding all the information carried by more than one initial code.
Step 5.	Data labeling	We labelled the text segments of analytic interest identified in step 2, initially using the codes developed in step 3, and subsequently refined them through the codes found in step 4.
Step 6.	Code-variable correspondence table	We built a table containing code-variable correspondences (see Table II). This correspondence clearly shows what kind of information related to a variable is carried by a given segment of text labeled with a given code (or overarching code).
Step 7.	Post-coding exploration	At this stage, thanks to the code-variable correspondences table (see Table II), we can navigate our dataset and efficiently identify the segments that provide meaningful insights into the learning dimensions we aim to explore (see Fig. 1), even long after the coding process has been completed.

1. Overarching code A

Students engage with a variety of tools, materials, and learning scenarios during the TLSs, which can either support or hinder their understanding of specific topics. Facilitating factors include interactive activities, visual supports, and a positive learning environment. Obstacles include complex language, limited prior knowledge, low engagement, or cognitive overload. Students also reflect on the usefulness of theoretical-practical connections and distinguish between traditional and innovative teaching methods, typically favoring the latter for their interactivity, engagement, and use of multimedia.

2. Overarching code B

Student responses reveal varying degrees of understanding. Some students demonstrate strong comprehension, accurately explaining key concepts, while others show limited or partial understanding, often accompanied by misconceptions. A middle group displays a basic grasp of the topic but lacks the ability to provide detailed explanations.

3. Overarching code C

Students value debate-based activities, recognizing their benefits for developing critical thinking, communication skills, and confidence. Engaging with diverse perspectives fosters empathy, tolerance, and reflective thinking, encouraging students to refine their ideas and become more aware of cognitive biases. These experiences contribute to both academic and personal growth.

4. Overarching code D

Students employ technical language at varying levels of complexity. They often recognize the importance of scientific terminology and mathematical expressions for conveying intricate ideas accurately, interpreting experimental outcomes, and engaging in precise communication. This specialized language not only strengthens formal reasoning but also nurtures critical thinking and enables meaningful participation in scientific discourse.

5. Overarching code E

Students engage in reflective practices to evaluate their learning progress, identify challenges, and appreciate the value of various activities. Through self-assessment, they become more aware of their learning processes, set personal goals, and take greater responsibility for their development, both in academic and real-world contexts.

6. Overarching code F

Students express preference for specific didactic tools and/or methodologies. They frequently provide constructive feedback on the TLSs, demonstrating their awareness of the importance of timely feedback and iterative improvement.

IV. THEMATIC ANALYSIS OF THE DATA

In this section, we present the analysis of the data according to a structured scheme that guides our study. For each case, we report:

- The choice of one or more variables of interest.
- The corresponding text excerpts selected for the analysis.
- The thematic analysis of the data, carried out according to our research framework.

After identifying the information conveyed by the data, i.e., after recognizing the variables emerging from specific text segments, we proceeded to label those segments using overarching codes. As previously explained, these codes allow us to navigate more efficiently within our dataset whenever we seek insights related to specific aspects of learning.

For each dataset, we provide both the table containing the analyzed text segments and the corresponding code-variable table associated with the data of interest.

A. Database 1—Interview excerpts: Macroscopic vs mesoscopic approach

Here we present the TA of some excerpts from student interviews about surface phenomena conducted before and after the didactic intervention (Table IV). The interviews explore two key aspects of learning: the appropriation of concepts and forms of representation (variable 1.1), and the evolution of common-sense conceptions to scientific ones (variable 1.2) (Table V). Comparisons are drawn between students who trialed the macroscopic approach (labeled with “M”) and those who experienced the mesoscopic approach (labeled with “S”).

The selected excerpts effectively illustrate the differences in learning outcomes associated with the modeling approach proposed, specifically in relation to variables 1.1 and 1.2. These examples represent the broader range of student responses recorded, highlighting how the different modeling approaches implemented influenced students’ understanding and engagement in the TLSs. To provide a more comprehensive view of our findings, we also included additional data in the Appendix. This supplementary material offers further evidence supporting the observed differences in learning outcomes between the two groups, reinforcing the validity of our conclusions regarding the impact of the modeling approach on student learning.

The data show a marked progression in students’ conceptual understanding from pre- to postintervention interviews, suggesting that both approaches had a positive impact, although in different ways and degrees.

1. Macroscopic approach

The responses from students M1, M2, and M3 suggest that the macroscopic TLS supports scientific learning by helping students transition from intuitive, perceptual explanations to descriptions that incorporate formal physics

TABLE IV. Excerpts from student interviews conducted before and after the didactic intervention. The table includes responses to two interview questions aimed at probing students' conceptual understanding of surface phenomena and their ability to represent the underlying mechanisms. The letter "M" denotes students who participated in the group employing the macroscopic approach, whereas "S" designates those who engaged with the mesoscopic approach.

Learning dimension		Variables		Codes
Conceptual knowledge		1.1 ("Appropriation of concepts and forms of representation") and 1.2 ("Evolution of common-sense conceptions to scientific ones")		B–D
Student	Interview moment	Response to Q1: What keeps a water droplet in shape on a surface?	Response to Q2: How would you represent what's happening inside the droplet?	
M1	Pre	<i>"I think it's because there's not much gravity pulling it down. Maybe air helps it stay round."</i>	<i>"I'd draw the drop like a little hill, maybe some arrows from the sides?"</i>	
M1	Post	<i>"Surface tension pulls the molecules together, and the contact angle with the surface matters too."</i>	<i>"I'd show forces with arrows from outside and maybe the contact angle at the base."</i>	
M2	Pre	<i>"Maybe the surface is waterproof, so the water can't spread out."</i>	<i>"Just a drop shape, maybe with a shiny top."</i>	
M2	Post	<i>"It's due to cohesion within the liquid and adhesion to the surface which affect the drop's shape."</i>	<i>"I'd sketch the droplet and label the angles, with arrows showing cohesive and adhesive forces."</i>	
M3	Pre	<i>"Maybe water is just sticky? Like, it wants to stay together."</i>	<i>"I would draw a water drop with a little curved line on top to show it's round."</i>	
M3	Post	<i>"Cohesion makes the water molecules attract each other, and adhesion with the surface affects the shape too. The balance between them creates the curved surface."</i>	<i>"I'd show the drop touching the surface with a labeled contact angle and arrows showing cohesion pulling inward and adhesion pulling sideways."</i>	
S1	Pre	<i>"I think it's the shape of the surface or gravity ... I'm not sure."</i>	<i>"Maybe just a blob with some arrows?"</i>	
S1	Post	<i>"The molecules inside the liquid attract each other. On the surface, there's an imbalance, and those molecules experience surface tension."</i>	<i>"I'd draw particles interacting, equal pulls inside, unbalanced on the surface. Like in the animation we saw."</i>	
S2	Pre	<i>"Because it's water? It just does that normally. Like in raindrops."</i>	<i>"I would draw a round drop with a little sparkle maybe."</i>	
S2	Post	<i>"Surface tension comes from molecular forces. Molecules at the surface experience less neighboring interactions, so they create a sort of 'film.'"</i>	<i>"I'd zoom in and draw molecules showing different interaction vectors in the bulk vs surface."</i>	
S3	Pre	<i>"I think it's because the water is thick? Like it holds itself up."</i>	<i>"Just a circle of water. Maybe with some lines showing it's heavy?"</i>	
S3	Post	<i>"At the molecular level, particles in the center are pulled in all directions, but those at the surface are pulled inward more, which creates surface tension."</i>	<i>"I'd draw molecules, with arrows showing forces acting equally inside and unbalanced at the surface. Maybe a zoom-in panel too."</i>	

terminology and principles, such as surface tension, cohesion, adhesion, and contact angle. For instance, M1 initially hypothesizes that the shape of the droplet is due to "not much gravity" and vaguely references "air." After the intervention, M1 refers explicitly to surface tension and contact angle, both of which are central to macroscopic models of fluid behavior on surfaces. This shift indicates an improvement in the use of scientifically accepted language and an understanding of surface phenomena more related to interactions and measurable physical quantities.

M2's and M3's responses show similar progression. M3, for example, moves from the idea that water is "just

sticky" to a more articulated explanation based on the balance between cohesive and adhesive forces. Their postintervention drawings also improve in precision and relevance: from generic drop shapes to labeled diagrams with vectors and angles that visually represent the physical forces at play. This suggests that the macroscopic approach effectively supports representational competence, enabling students to translate conceptual understanding into visual terms.

The macroscopic approach improves learning by making observable effects (e.g., droplet shape and contact angle) intelligible in terms of named forces and interactions, even

TABLE V. Table showing code variables correspondences found for the text segments analyzed.

Overarching codes	Variables												
	Conceptual knowledge			Intellectual growth				Development of habits of mind suited to learning science					
	1.1	1.2	1.3	2.1	2.2	2.3	2.4	3.1	3.2	3.3	3.4	3.5	3.6
B	X	X											
D	X	X											

if it does not directly address the underlying microscopic mechanisms. It thus offers meaningful conceptual scaffolding for students at an intermediate level of abstraction.

2. Mesoscopic approach

The students in the mesoscopic group (S1, S2, S3) exhibit a different kind of learning progression, one that is more focused on the molecular-level mechanisms responsible for surface tension. Their postintervention explanations consistently refer to intermolecular forces, interaction imbalance at the surface, and the idea that surface molecules are pulled inward due to fewer neighboring interactions. For example, S3 moves from a vague explanation involving the “thickness” of water to a precise description of how force vectors differ between bulk and surface particles.

This approach appears particularly effective in fostering mechanistic reasoning and encouraging students to visualize interactions at a particle level. The use of arrows and enlarged panels in their representations, such as those mentioned by S1 and S3, shows that the students are beginning to integrate abstract molecular concepts into their explanations, a shift from phenomenological to causal reasoning.

Moreover, the references to classroom tools (e.g., “like in the animation we saw”) suggest that the mesoscopic intervention, which included dynamic visualizations, plays a key role in supporting students’ ability to internalize and express complex, invisible interactions.

3. Implications for the research question

These data show that both approaches facilitate significant learning, but in distinct ways. The macroscopic approach enhances understanding by connecting visible phenomena with physical principles and by strengthening students’ ability to produce structured scientific representations of what they observe. The mesoscopic approach promotes deeper conceptual learning, allowing students to construct causal explanations based on molecular interactions and to build mental models of systems not directly accessible to the senses.

Across both groups, students’ answers move from vague, everyday language and simplistic drawings toward more elaborate, physics-based accounts that include

appropriate terminology, reasoning, and visual representation. Therefore, the data substantiate that both approaches can significantly improve scientific learning, albeit through different cognitive and representational pathways. These findings support the idea that both perspectives, the macroscopic and the mesoscopic, are valuable, and possibly complementary, in fostering comprehensive scientific understanding.

B. Database 2—Students’ feedback on the activities carried out during the TLSs

Here we present the TA of some excerpts from the open-ended responses students provided at the end of the satisfaction questionnaire (Table VI). This database explores four key aspects of learning: the perception of self-efficacy (variable 3.1), the development of a growth mindset (variable 3.2), the activation of metacognitive processes (variable 3.3), and students’ well-being in learning (variable 3.4) (Table VII). To further elucidate the impact of the modeling approach on students’ affective and metacognitive dimensions of learning, we selected representative excerpts that highlight differences in outcomes related to variables 3.1, 3.2, 3.3, and 3.4. These excerpts reflect the broader spectrum of student responses, illustrating how the distinct modeling strategies employed influenced learners’ self-perceptions, cognitive processes, and emotional engagement within the TLSs. Additional supporting data are provided in the Appendix, offering further evidence of the observed variations between the two groups and reinforcing the validity of our conclusions regarding the modeling approach’s effect on student learning.

1. Macroscopic approach

The macroscopic approach effectively promoted perception of self-efficacy (variable 3.1) in students, as seen in the feedback from M1 and M6. M1 highlighted the utility of modeling activities, especially in understanding the phenomena studied, which strengthened their belief in their ability to understand complex scientific concepts. This reflects an increase in self-efficacy, as the student felt more capable of engaging with and understanding the science involved. Similarly, M6’s comment about how thinking in terms of a macroscopic model helped solidify

TABLE VI. Excerpts from students' interviews illustrating perceptions of modeling practices within macroscopic and mesoscopic approaches. Comments highlight aspects of conceptual understanding, modeling engagement, cognitive challenge, and emotional response relevant to the study's key variables. The letter "M" denotes students who participated in the group employing the macroscopic approach, whereas "S" designates those who engaged with the mesoscopic approach.

Learning dimension		Variables	Codes
Development of habits of mind suited to learning science		3.1 (“Perception of self-efficacy”), 3.2 (“Growth mindset”), 3.3 (“Metacognition”), and 3.4 (“Well-being in learning”)	E–F
Student		Feedback	
M1	“Modeling activities were useful because we usually do not focus on this aspect. We use models to describe a lot of things but thinking about the type of model used, its advantages and disadvantages and asking questions about how it was built helped me a lot to better understand the phenomena we studied.”		
M6	“Thinking in terms of a macroscopic model of a liquid helped me to better fix the ideas on some behaviors of the liquid such as the formation of menisci. However, I would have liked to see something different from simple diagrams or graphic representations, such as videos or animations that would make the lesson less monotonous.”		
S1	“Let’s say that in general none of us were very familiar with the use of models. We use models in mathematics, physics and science but there is usually no time to focus on how they work and why those models are used. For me it was interesting to see that there exist other models different from the usual ones such as the mesoscopic model. The most difficult part was the computer-based simulation because it was a completely new thing to modify a code based on the phenomenon we wanted to analyze. The best thing was the output of the simulation, that is a graph or a movie that showed us in real time how our physical system changed based on the chosen parameters. However, we had difficulties when we had to modify the code, and some of us were quite confused.”		
S13	“At the beginning, I was scared by the idea of using a simulation. I thought I wouldn’t understand how it worked. But when we started changing the parameters and seeing the graph changing in real time, I realized I was actually getting the logic behind it. I wouldn’t say I’m good with coding, but now I think I could try similar things again. However, I think I need more time to get used to this approach. It’s a new way of thinking, and I feel like it takes time to really absorb the concepts, and the technical skills involved.”		

their ideas about liquid behaviors (such as meniscus formation) aligns with the idea that students who perceive themselves as successful in learning are more likely to engage deeply with the material. However, the desire for more dynamic tools, such as animations, hints at a need for more interactive forms of learning, which could potentially enhance engagement and perception of well-being in learning (variable 3.4).

The macroscopic approach also facilitated the development of metacognitive awareness (variable 3.3). By encouraging students to think critically about the models they were using and to evaluate the advantages and disadvantages of each model, students engaged in reflective thinking about the nature of scientific models. This

kind of reflection allows for a deeper understanding of the processes behind scientific reasoning. M1's comment about being prompted to think about the type of model used, how it was built, and why it was effective is a prime example of metacognitive engagement.

However, as the macroscopic approach appeared to provide more immediate, observable learning outcomes, it may not have fully tapped into the growth mindset (variable 3.2). Since the approach was less challenging in terms of cognitive load, students may not have been pushed to extend their abilities beyond their current understanding. It may, therefore, be less effective in fostering a growth mindset compared to the more demanding mesoscopic approach.

TABLE VII. Table showing code-variables correspondences found for the text segments analyzed.

Overarching codes	Variables												
	Conceptual knowledge			Intellectual growth				Development of habits of mind suited to learning science					
	1.1	1.2	1.3	2.1	2.2	2.3	2.4	3.1	3.2	3.3	3.4	3.5	3.6
E								X	X	X			
F									X		X		

2. Mesoscopic approach

The mesoscopic approach, which focuses on molecular-level interactions and often requires the use of simulations, fostered significant growth in growth mindset (variable 3.2). Students like S13 reflected a shift in attitude toward the challenges involved in simulations and coding. Initially intimidated by the idea of using simulations, S13's feedback demonstrated a positive change in their approach to learning. The realization that they were getting the logic behind the simulations and could attempt similar tasks again reflects an important development in their growth mindset. This attitude aligns with the research suggesting that students with a growth mindset are more resilient in the face of challenges, more likely to persist through difficulty, and believe that their abilities can improve with effort.

Moreover, the mesoscopic approach strongly encouraged metacognitive reflection (variable 3.3). As students had to modify and interact with simulations, they needed to think critically about the phenomena they were observing and reflect on how their actions (such as changing parameters in the simulation) influenced the results. S1's statement about learning from the real-time graphs and simulations suggests an ongoing process of metacognitive development, as the student considered both the content of the simulation and their strategies for modifying it. This also extended to the technological tools, where students like S13 expressed the need for more time to fully absorb the new skills and concepts.

In terms of self-efficacy (variable 3.1), the mesoscopic approach was initially challenging but ultimately led to increased confidence in students' abilities to understand complex systems and utilize computational tools. However, as S13 mentioned, more time would be needed to gain proficiency, pointing to the fact that while the approach nurtured confidence, it also highlighted the importance of feeling well in learning (variable 3.4). The process of engaging with new technologies and ideas could have been overwhelming for some students, but the ability to reflect on this difficulty and engage in subsequent learning is a sign of developing well-being in learning environments. While the mesoscopic approach was challenging, it supported students' growth in terms of self-efficacy and confidence over time.

3. Implications for the research question

The macroscopic and mesoscopic approaches offer complementary contributions to scientific learning, each supporting different aspects of students' cognitive and emotional development. The macroscopic approach fosters immediate gains in self-efficacy and metacognition through accessible modeling tasks, though it offers limited stimulation for developing a growth mindset. Conversely, the mesoscopic approach, while more demanding, promotes deeper conceptual understanding, metacognitive reflection,

and the development of a growth mindset through engagement with simulations and coding. Although it may initially challenge students' self-efficacy, it ultimately supports confidence and well-being when adequate time and support are provided. Also, these data show that integrating both approaches can enhance science learning by addressing diverse student needs across various dimensions.

V. CONCLUSION

A. Implications

The TA of the data analyzed in this paper indicates that fostering meaningful learning of surface phenomena, in terms of both conceptual understanding and the development of cognitive, social, and affective competences, requires the integration of complementary modeling strategies. Data from database 1 indicate that both macroscopic and mesoscopic approaches significantly enhance scientific learning, each through distinct cognitive and representational pathways. The macroscopic approach strengthens students' ability to produce structured scientific representations by connecting visible phenomena with physical principles. In contrast, the mesoscopic approach promotes deeper conceptual understanding, enabling students to construct causal explanations based on molecular interactions and to build mental models of systems not directly accessible to the senses.

Across both groups, students' responses evolved from vague, everyday language and simplistic drawings to more elaborate, physics-based accounts that incorporate appropriate terminology, reasoning, and visual representation. This progression underscores the effectiveness of both approaches in fostering scientific understanding.

Data from database 2 reveal that these approaches complement each other by supporting different aspects of students' cognitive and emotional development. The macroscopic approach fosters immediate gains in self-efficacy and metacognition through accessible modeling tasks, though it offers limited stimulation for developing a growth mindset. Conversely, the mesoscopic approach, while more demanding, promotes deeper conceptual understanding, metacognitive reflection, and the development of a growth mindset through engagement with simulations and coding.

These findings suggest that a revised and expanded "TLS 2.0" should embed the strengths of both approaches to create a more comprehensive and impactful learning experience. Increasing the time devoted to mesoscopic modeling and computer-based simulations may enhance students' confidence and autonomy [70] in exploring the underlying mechanisms of surface phenomena.

Although students tend to use tools and strategies that are habitual for them [71], these findings suggest that balancing familiarity and challenge is key to maintaining

emotional engagement, as moderate levels of difficulty can optimize both motivation and performance.

This multidimensional engagement contributed to the development of interpretative and reasoning skills, reinforcing the potential of a well-designed TLS to foster scientific literacy and advanced scientific thinking [72].

Across both TLSs, students exhibited meaningful changes in their learning processes, particularly in the dimensions explored by this study. Activities promoting active participation, collaboration, and critical reflection contributed to a dynamic and inclusive learning environment in which students were encouraged to take ownership of their learning. Such an environment supported the acquisition of transversal competences such as problem solving, collaboration, and critical thinking that are applicable beyond physics education and relevant to real-world contexts.

B. Limitations and future perspectives

The study presented in this paper has certain limitations related to the size of the research sample. Specifically, the TLSs were trialed with a group of 40 upper secondary school (science oriented) students, which restricts the generalizability of the findings to broader samples and different school curricula. An additional limitation of this study lies in the fact that the data analysis discussed in this study focused on a selected subset of the collected data, which does not allow for a comprehensive view of all the findings. While the materials examined provided valuable insights into students' learning processes, a fuller understanding of the effectiveness of the TLSs requires the integration of results from additional datasets, which is currently underway. These will offer complementary perspectives that, when combined, will support a deeper and more complete understanding of how the TLSs contribute to promoting students' learning.

Another significant aspect to address is the adequate preparation of school physics teachers [73,74] to design, implement, and evaluate TLSs on surface phenomena, such as those outlined in this research. This highlights a broader need for professional development programs that equip teachers with the skills and confidence to create and execute pedagogical approaches grounded in active learning methodologies. Effective teacher preparation involves several key components. First, educators must be trained to integrate active learning strategies, such as collaborative problem solving, hands-on experiments,

and computer-based simulations into their lessons. These approaches have been shown to foster deeper student engagement, critical thinking, and comprehension of complex concepts. Additionally, teachers need guidance on designing TLSs that are adaptable to diverse learning environments and student needs, ensuring inclusiveness and accessibility. Implementing TLSs requires educators to develop robust assessment frameworks that evaluate not only student outcomes but also the efficacy of the methodologies used. This dual focus ensures that pedagogical practices remain evidence-based and continuously refined for effectiveness. Finally, the ability to evaluate and adapt teaching strategies based on real-world classroom feedback is essential. This iterative process supports a culture of reflective teaching, enabling educators to respond to challenges, develop successful practices, and innovate their approaches.

The two physics teachers who collaborated on this research with their students brought considerable expertise and enthusiasm for the study of surface phenomena. Both held advanced degrees in physics and actively contributed to the design and implementation of the TLSs, demonstrating a genuine commitment to innovative educational practices. Furthermore, they expressed interest in adapting the pedagogical methods utilized during the trial for their everyday teaching. This collaborative spirit greatly enhanced the research, as the activities introduced through the TLSs were thoughtfully revisited and extended during routine classroom instruction, enriching both the research process and the students' learning experiences.

Unfortunately, this is not common in Italian schools. Many teachers view the implementation of active learning methodologies as impractical, primarily due to time constraints associated with covering the prescribed curriculum and the substantial effort required to effectively engage students in laboratory and modeling activities based on inquiry and investigation.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX: ADDITIONAL DATA

1. Database 1—Interview excerpts: Macroscopic vs mesoscopic approach

Student	Interview moment	Response to Q3: Why does a liquid form a concave meniscus in a glass capillary tube? Explain in terms of forces.	Response to Q4: What happens when a few drops of soap are added to water, causing a small toy boat to move? Explain in terms of forces.
M1	Pre	<i>“Maybe it’s because the water sticks to the glass more than to itself, so it climbs up the sides.”</i>	<i>“The soap makes the water slippery, so the boat moves away from it.”</i>
	Post	<i>“The concave meniscus forms due to adhesion between water and glass being stronger than cohesion among water molecules, causing the water to climb up the walls.”</i>	<i>“Adding soap reduces surface tension behind the boat, creating an imbalance that propels the boat forward.”</i>
M2	Pre	<i>“I think the shape is just how water behaves in tubes.”</i>	<i>“Soap pushes the boat because it’s lighter than water.”</i>
	Post	<i>“Adhesive forces between water and glass pull the water up the sides, while cohesive forces pull it down, resulting in a concave meniscus.”</i>	<i>“Soap decreases the surface tension behind the boat, and the higher tension in front pulls the boat forward.”</i>
M3	Pre	<i>“Water curves in tubes because of gravity and the tube’s shape.”</i>	<i>“The soap acts like a fuel, pushing the boat.”</i>
	Post	<i>“The meniscus is concave because adhesive forces between water and glass are stronger than cohesive forces among water molecules.”</i>	<i>“The soap lowers surface tension behind the boat, causing a net force that moves the boat forward.”</i>
S1	Pre	<i>“Maybe the water molecules are attracted to the glass molecules, so they climb up.”</i>	<i>“Soap changes the water’s properties, making the boat move.”</i>
	Post	<i>“Water particles are attracted to glass particles more than to each other, so they climb up the walls, forming a concave meniscus.”</i>	<i>“Soap molecules disrupt the cohesive forces among water particles behind the boat, reducing surface tension and causing the boat to move forward.”</i>
S2	Pre	<i>“The water sticks to the glass, so it curves up.”</i>	<i>“Soap makes the water uneven, so the boat moves.”</i>
	Post	<i>“At the molecular level, adhesive forces between water and glass particles are stronger than cohesive forces among water particles, leading to a concave meniscus.”</i>	<i>“Soap molecules reduce the cohesive forces among water particles behind the boat, creating a surface tension gradient that propels the boat forward.”</i>
S3	Pre	<i>“Water likes glass, so it climbs up.”</i>	<i>“Soap pushes the boat by changing the water properties.”</i>
	Post	<i>“The imbalance between adhesive forces (water-glass) and cohesive forces (water-water) at the molecular level causes the concave meniscus.”</i>	<i>“Soap molecules decrease surface tension behind the boat by disrupting water particle interactions, resulting in movement due to the tension difference.”</i>

2. Database 2—Students' feedback on the activities carried out during the TLSs

Student	Feedback
M3	"The modeling activities were particularly valuable because we rarely examine how models work. While we often use them to describe concepts, reflecting on the model type, its strengths and limitations, and questioning its construction significantly deepened my understanding of the phenomena we studied."
M7	"The macroscopic model was effective in helping me grasp liquid behaviors more firmly. However, I would have appreciated the inclusion of multimedia elements instead of relying solely on static diagrams."
M8	"The graphical representations based on the macroscopic model of liquids made the understanding of surface phenomena quite clear, especially when we discussed contact angles or menisci. However, I would have liked to do something different, like my classmates who used simulations to study liquids through the mesoscopic model. I think it's more enjoyable to use different tools as well."
S2	"Honestly, none of us were very familiar with using models. We often use them in math, physics, and science, but we rarely have time to explore them. That's why discovering alternative models like the mesoscopic one was interesting. Initially, the hardest part was the computer-based simulation, in fact modifying code to represent the phenomenon felt completely new. Some of us got confused when coding. Yet, the highlight was seeing the simulation's output revealing in real time how the system changed with different parameters."
S15	"I was really intimidated at first by the idea of using a simulation, fearing I wouldn't grasp how they functioned. Yet, as we adjusted parameters and observed real-time changes in the graph, I began to understand the underlying logic. I recognize the need for more time to fully adapt to this approach, as it introduces a new way of thinking and requires time to master both the concepts and technical skills involved."

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