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From experience to modelling: a Teaching-Learning sequence for studying surface phenomena in liquids through experiments and mesoscopic simulations

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Summary

This doctoral dissertation investigates the teaching and learning of surface phenomena in liquids through an integrated approach that combines macroscopic observations, microscopic models, and mesoscopic simulations. Phenomena such as surface tension and capillarity provide a fertile educational context for developing skills in observation, analysis, and modelling, and for fostering deep and lasting learning. The research is situated within a constructivist theoretical framework, informed by the paradigm of Educational Reconstruction and by the ISLE (Investigative Science Learning Environment) approach, both of which emphasise active learning, conceptual change, and scientific modelling as means of integrating theory and experience. From this perspective, students are guided to gradually build knowledge starting from their initial conceptions, through engagement with experimental data, multiple representations, and iterative modelling processes.

The project was developed around a carefully designed Teaching-Learning Sequence (TLS) aimed at promoting autonomous construction of meaning through a coherent set of macroscopic activities, microscopic conceptual models, and mesoscopic simulations based on the Smoothed Particle Hydrodynamics (SPH) method. This sequence was implemented within a teaching intervention involving fourth-year students from a state secondary school specialising in scientific studies. The initial research hypothesis, namely that students hold mixed cognitive models, was subsequently confirmed by the data analysis, highlighting the need for instructional interventions capable of supporting the integration and negotiation of different forms of knowledge. To address this need, the TLS was designed as a progressive pathway beginning with direct experience and gradually guiding students towards more abstract and formalised forms of representation.

The sequence begins with a set of macroscopic activities that serve as the first conceptual exploration ground. These qualitative experiments provide immediate contact with surface phenomena, stimulate accurate descriptions, and encourage the emergence of spontaneous questions. The experiences collected in this phase generate productive cognitive conflicts and serve as essential anchors for naturally introducing modelling practices. These modelling concepts are not intended to offer direct explanations of invisible processes, but rather to prepare students to interpret, in an informed manner, what they will encounter at the subsequent level.

Mesoscopic simulations play a crucial role as an epistemic bridge between the observable and the invisible. Through the SPH method, otherwise inaccessible processes are rendered visible and manipulable, enabling students to explore emergent dynamics, vary parameters, and observe the effects of interparticle forces. This interactive experience allows macroscopic observations to be reinterpreted in light of processes situated between the perceptible world and more abstract theoretical models, thereby facilitating the transition from intuitive conceptions to formalised representations. In doing so, the mesoscopic level not only provides operational access to what is otherwise invisible, but also creates the conditions for microscopic modelling, introduced as conceptual tools, to be understood, contextualised, and integrated in a more mature and scientifically grounded manner.

To thoroughly document the effects of this integrated pathway, from macroscopic experience to mesoscopic modelling, the teaching intervention was supported by a systematic collection of both qualitative and quantitative data, gathered through questionnaires, worksheets, clinical interviews, researcher diaries, and students' spontaneous feedback. The qualitative analysis was conducted on two levels: a phenomenographic approach applied to the questionnaires, designed to identify distinct epistemological profiles within students' mental models, and a thematic analysis of the remaining instruments, which made it possible to trace the complexity of the cognitive, social, affective, and metacognitive processes activated by the TLS. The integration of multiple qualitative methods provided a rich and multifaceted account of the conceptual transformations and interactive dynamics promoted by the sequence. In parallel, the quantitative analysis based on Likert-scale data offered insights into students' satisfaction, perceived impact, and level of engagement with the proposed pathway, thus providing meaningful triangulation with the qualitative evidence.

The findings show significant progress in conceptual understanding, in the ability to connect theoretical models with experimental observations, and in the development of metacognitive, collaborative, and reflective competences. The use of mesoscopic simulations emerged as particularly effective in supporting the conceptualisation of complex processes, in increasing students' participation, and in promoting active and informed learning. Overall, the TLS contributed to strengthening students' ability to adopt a scientific perspective in interpreting phenomena, while enhancing their autonomy in the process of knowledge construction.

Finally, the study acknowledges several limitations, mainly related to the composition of the sample, the specificity of the educational context, and the technical resources required for the simulations. These elements suggest the need for further research exploring applications in more diverse contexts, the replicability of the approach in other educational and academic settings, and the potential extension of the analysis to additional observables included within the dimensions of learning. Future perspectives also include the refinement of modelling tools, integration with emerging technologies, and investigation of the role of collaborative modelling as a means of developing transversal competences. In this sense, the study provides a significant contribution to contemporary science education and to the design of instructional interventions grounded in robust empirical evidence, outlining a promising trajectory for the innovation of physics teaching.

Acknowledgment

Reaching this milestone has not been merely the outcome of academic endeavour: it has been a significant chapter of my life, marked by change, new responsibilities, and challenges that have helped me grow more than I could have imagined. If I can present this work today, it is thanks to the people who, either quietly or steadfastly, have accompanied me throughout these three years. To them, I extend my deepest gratitude.

My most sincere and heartfelt thanks go to my supervisor, Professor Claudio Fazio. To call him a "supervisor" does not fully capture what he has represented for me. He was the first to believe in my abilities, to perceive what I had ceased, or was no longer able, to recognise in myself. Through his guidance and support, he indicated a path that I now truly feel as my own, shaped by my inclinations and a more confident and mature professional awareness. He was present in the most challenging and complex moments of this journey, always welcoming me with patience, trust, and quiet yet unwavering encouragement. For all this I can genuinely consider him a mentor in the truest sense of the word.

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A special thanks goes to my family. To my mother, father, and uncle: you are my safe harbour, my constant source of support and affection. Thanks to you, I have been able to pursue my dreams and realise my aspirations. You were the first to share in my joys and struggles, to endure my mood swings, and you have never withheld understanding, patience, or encouragement. Thank you for helping me to balance everything and for making this journey possible through your quiet but ever-present affection.

Thanks to the friends and confidants who have accompanied me along this path. Being able to discuss, seek advice, and find sincere listening is one of the most precious gifts friendships can offer. Thank you for granting this to me.

A particular thank you goes to Francesca, a trusted friend and companion in confidences. You have listened to and supported every stage of these years, never hesitating to offer advice, even when a frank and impartial opinion was needed. Thank you for always encouraging me to give my best and, when necessary, for helping me to let go of what could not be controlled. Your wisdom as an older sister has been a priceless gift.

Finally, but by no means least, I wish to dedicate thanks to myself. Thank you for continuing to show that you can prevail, despite everything. You know how to face obstacles, find compromises where they seem impossible, and rise again even on the hardest days. Tenacity, resilience, and courage define you: always cherish them. Be yourself, with pride, beyond what others think you can or cannot achieve. And, as someone once told you, "learn to acknowledge your own merits, every now and then."

Dedication

To the path travelled and to the one yet to be travelled, amidst cherished memories and dreams still to be charted.

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Introduction

Understanding surface phenomena in liquids, such as surface tension, wetting and capillarity, poses well-documented conceptual challenges for students across different levels of physics education. These phenomena are inherently multiscale: they emerge from molecular interactions while manifesting themselves through observable macroscopic effects. As a consequence, learners often struggle to reconcile everyday experiential observations with formal physical explanations, oscillating between phenomenological descriptions and fragmented microscopic interpretations. Despite their central role in physics, chemistry, biology, and engineering, surface phenomena remain conceptually opaque and resistant to instruction based solely on either macroscopic experimentation or microscopic theoretical models.
Traditional instructional approaches frequently exacerbate these issues by privileging either mathematical formalism or qualitative descriptions without providing learners with epistemic tools to connect different levels of description in a coherent manner. As a result, students' reasoning often remains compartmentalised, unstable, or context-dependent.

In recent years, modelling has gained increasing prominence in science education as a central epistemic practice rather than a mere representational tool. From this perspective, learning physics involves not only acquiring conceptual knowledge but also engaging with models as simplified, purpose-driven constructions that mediate between theory, empirical evidence, and interpretation. However, while modelling is widely acknowledged as a core scientific practice, its instructional implementation, particularly in relation to multiscale phenomena, remains challenging. Learners are rarely supported in navigating the epistemic status of models, their assumptions, limitations, and the specific kinds of explanations they afford.
Mesoscopic modelling offers a promising yet underexplored avenue in this regard. By operating at an intermediate level between microscopic particles and macroscopic continua, mesoscopic simulations can make visible the emergence of collective behaviour from local interactions without requiring the full complexity of molecular dynamics. In particular, particle-based approaches such as Smoothed Particle Hydrodynamics (SPH) allow surface phenomena to be represented

dynamically, enabling learners to explore how macroscopic properties arise from interaction rules rather than being imposed a priori.

Although mesoscopic and particle-based simulations have been increasingly employed in scientific and educational contexts, their integration into school physics instruction raises open theoretical and didactic questions. In particular, less attention has been devoted to analysing how such simulations function as epistemic tools within structured learning pathways, how students interpret their representational status, and how these representations mediate the transition between observable phenomena and more abstract explanatory models.
Addressing these questions requires moving beyond the mere use of simulations as visualisation devices and examining their role within coherent instructional designs that explicitly foreground modelling as a scientific practice.

Against this background, the present doctoral thesis addresses the following overarching problem: how can a teaching-learning sequence be designed to support students' conceptual understanding of surface phenomena by integrating macroscopic experimentation with mesoscopic modelling, while explicitly engaging them in modelling as an epistemic practice? The study responds to a gap in the literature concerning the educational use of mesoscopic representations and their capacity to mediate between experiential knowledge and formal physical explanations. Rather than treating simulations as illustrative add-ons, this work conceptualises them as central components of a learning environment aimed at fostering meaningful conceptual change.

The thesis is situated within the framework of design-oriented research in physics education and is grounded in constructivist theories of learning, with particular reference to the paradigm of Educational Reconstruction and to modelling-oriented instructional approaches. It adopts the notion that students' reasoning about complex physical phenomena often involves hybrid or mixed knowledge models, in which everyday intuitions, phenomenological observations, and elements of formal physics coexist and interact. Understanding how such knowledge structures evolve requires fine-grained qualitative analysis of students' discourse, representations, and activities over time.

The main contribution of this thesis lies in the design, implementation, and in-depth analysis of a teaching-learning sequence focused on surface phenomena in liquids, combining hands-on experiments with mesoscopic SPH simulations. Through a rich empirical corpus, the study investigates how students appropriate mesoscopic representations, how they negotiate the meaning and status of model entities, and how their explanatory frameworks evolve as they move across representational levels. In doing so, the thesis aims to contribute both to the theoretical understanding of modelling as an epistemic practice in physics education and to the development of instructional approaches capable of addressing the multiscale nature of complex physical phenomena

Chapter 1

Physical foundations of surface phenomena

Since ancient times, the observation of liquid behaviour has aroused wonder and deep questions. The natural tendency of water droplets to assume a spherical shape, the resistance that water offers to the immersion of light objects, or the rapid absorption of a liquid by a specific fabric are phenomena that have fascinated generations of scientists. The science of surfaces arose precisely from that ancient need to understand what happens where direct observation ends, or where it begins to change shape.

During the 19th century, as the great theories of energy and electromagnetism were being developed, some physicists began to formulate more precise hypotheses on the behaviour of liquids at their interfaces. A powerful and intuitive idea then emerged: that the surface of a liquid behaves like a kind of stretched elastic film, capable of exerting a force that seeks to minimize the exposed area. In this image, the surface became the seat of tension, almost as if it were a living entity that reacts, contracts, and defends itself against intrusions. Although today we have more refined models, the legacy of that interpretation remains in the language of modern physics. The term "surface tension" has become an integral part of the description of surface phenomena, even though its historical origin initially confused it with the concept of surface free energy (Ip & Toguri, 1994).

Yet, despite the initial imprecision of the terminology, that intuitive vision of a liquid surface has inspired deep reflection, ingenious experiments, and a long-standing tradition of study that has continued, with renewed rigor, to the present day. One could say that surface tension has silently but inexorably accompanied the maturation of modern physics.

Surface tension is, in every respect, the tangible result of organized disorder: molecules at the interface adopt new arrangements, more energetic, more unstable, more complex. Here, physics meets chemistry, and collective behaviour emerges as a measurable macroscopic phenomenon. However, it is essential to clarify that such "tension" should not be understood in the mechanical sense of the term, as in the case of a stretched rope or an elastic membrane. Rather, it is an emergent property that arises from the microscopic

asymmetry of interactions between the molecules located at the interface and those immersed in the bulk of the liquid. It is precisely this symmetry breaking that generates an energetic tension, which manifests macroscopically in the system's tendency to minimize its exposed surface. At the molecular level, surface tension can be interpreted as the work required to increase the contact area between two phases (Rusanov, 1996). In parallel, fluid mechanics has provided a complementary interpretation of the phenomenon, formalizing the relationships between surface tension, curvature, and pressure difference through the Young-Laplace equation.
With the advent of molecular modelling, surface tension has become a testing ground for the validity of microscopic models. Theoretical physicists use it to investigate the nature of intermolecular interactions; engineers manipulate it to design functional surfaces and smart materials. From this, a multifaceted vision has emerged, in which surface tension is not only the result of molecular dynamics, but also a macroscopic variable that governs the shape, motion, and equilibrium of fluid systems (Adam, 1941).

Today, the concept of surface tension is no longer merely a natural mystery to be explored, but also a powerful tool at the service of science and technology. Yet, it has lost none of its power to astonish. Every drop rolling on a leaf, every thread of water climbing along a capillary wall, every cell shaping its own membrane, continues to tell that invisible and profound story, which began centuries ago when humanity looked at water with new eyes and began to wonder what really happens... on the surface.

1.1 Didactic framing of the physical content

The detailed physical framework presented in this chapter is not intended to offer an exhaustive disciplinary treatment of surface phenomena, nor to reproduce the level of formalisation typical of advanced fluid mechanics or physical chemistry. Its inclusion is motivated by a specific didactic need within the structure of the thesis: to make explicit the physical assumptions and conceptual distinctions that underpin the subsequent instructional design and analysis of learning.

Surface phenomena in liquids represent a paradigmatic case of multiscale systems, in which macroscopic behaviours, such as capillary rise, wetting, or surface tension effects, cannot be interpreted without reference to interactions occurring at smaller, non-directly observable scales. For this reason, the design of a Teaching-Learning sequence on these topics necessarily requires a careful selection and organisation of physical concepts, variables, and mechanisms, in order to avoid oversimplified macroscopic descriptions.

The physical analysis developed in this chapter identifies those elements that are essential for an educational treatment of surface phenomena, with particular attention to the role of cohesive and adhesive interactions and to the interpretation of surface tension as an emergent collective effect. These aspects directly inform the choice of experimental situations and modelling activities proposed in the Teaching-Learning Sequence, as well as the criteria used to delimit the scope of the phenomena addressed. By clarifying which physical factors are relevant and how they contribute to the observable behaviour of liquids, this chapter establishes a shared conceptual ground that constrains both instructional design and the interpretation of explanations. In this sense, the physical detail presented here is functional to ensuring coherence between the phenomena proposed in the Teaching-Learning Sequence and the analytical framework adopted to examine how students make sense of surface phenomena.

1.2 The nature of liquids: surfaces and interfaces

When describing matter and its states of aggregation, liquids occupy an intermediate and conceptually complex position. Unlike gases, where molecules move freely and interact only during brief collisions, or solids, where particles occupy fixed positions within regular structures, liquids are characterised by stronger cohesion between molecules while retaining a certain degree of freedom of movement. This combination of order and disorder makes liquids challenging to describe with a simple and complete theoretical model.

A liquid can be described as a fluid with a compact structure, in which intermolecular forces play a central role in determining its behaviour.
When such forces act between molecules of the same substance, they are referred to as cohesive forces. They are responsible for the tendency of a liquid to remain united and to resist separation, as occurs within a droplet. Adhesive forces, on the other hand, act between molecules of different substances, such as water molecules adhering to a glass surface.
The balance between cohesion and adhesion determines how a droplet behaves on a surface. If cohesive forces are stronger than adhesive ones, the molecules tend to stay within the liquid, and the droplet retains a nearly spherical shape. Conversely, if adhesive forces prevail, the energy required to spread the droplet into a thin film can be supplied by the work performed by the droplet itself as it collapses and spreads over the surface (Petrucci et al., 2011).
The presence and interplay of cohesive and adhesive forces are crucial when examining phenomena that occur at the boundaries between different phases of matter. It is precisely at these interfaces, or separation surfaces, that the most relevant macroscopic and microscopic effects related to surface tension are concentrated.

Systems involving an interface are often metastable, meaning that they are essentially in equilibrium in some respects but still subject to slight perturbations; the result is a slow evolution towards a final state of global equilibrium. Such systems are real systems, where there will always be an interface between two phases and whose properties will depend on the physical or chemical changes of either phase involved. Subsequently, we shall address, with varying degrees of detail, all possible interfaces among the three states of matter: solid, liquid, and gaseous.

A phase is defined as a form of matter that is uniform in chemical composition and physical state (Clarke et al., 1994).
An interface is the physical boundary between two adjacent bulk (condensed) phases. The interface must have a thickness of at least one molecular diameter, measurable in ångström (Å); however, in some cases, its thickness may extend to several molecular layers.
The term surface is used, instead, to define the plane marking the physical boundary of a single phase, or more simply, the plane separating the phase from its environment, such as a solid surface, a liquid surface, or a gas surface (Erbil, 2006).
In practice, however, an interface is involved in all cases other than conditions of absolute vacuum, since every single phase is in contact with another phase; an example is the solid-air or liquid-air contact (Trasatti & Parsons, 1986). In many standard textbooks on chemistry, physics, surface chemistry, or surface physics, the terms "surface" and "interface" are used interchangeably because authors often overlook the slight differences between the air phase and absolute vacuum conditions (Everett, 1972).

Molecules located at the phase boundaries, that is, at solid-gas, solid-liquid, liquid-gas, and liquid-liquid interfaces, behave differently from those within the bulk phase. This rule generally does not apply to solid-solid and gas-gas interfaces: in the former, atomic and molecular bonds inherent to the solid structure limit the reorientation of interfacial molecules; in the latter, the ease of gas molecule mixing in free space prevents the formation of a true interface.
Molecules within liquids behave differently depending on their position within the liquid itself; those located at or near the liquid's surface will be oriented differently relative to one another compared to those in the bulk phase. Any molecule at the liquid surface experiences an asymmetric force field, resulting in surface or interfacial tension. The closer a molecule is to the interfacial boundary, the greater the effect of this asymmetry. As the distance from the boundary increases, the effect of the force field diminishes and vanishes beyond a certain distance.

For solid surfaces, only the uppermost monolayer of atoms and molecules, that is, the interface immediately in contact with other phases, is considered the surface.

The study of surfaces and interfaces has shown that, at the molecular level, matter exhibits structural configurations different from those observables within the bulk material. In particular, the disruption of symmetry generates an imbalance in intermolecular forces, leading to phenomena observable on the macroscopic scale. Among these, surface tension is one of the most significant effects, as it reflects the collective behaviour of molecules near the surface. Based on these considerations, we can now introduce the concept of surface tension, before exploring its more formal and specific descriptions within thermodynamics and fluid mechanics.

1.3 Surface tension: energetic and mechanical perspectives

Surface tension is a complex physical phenomenon which, as previously discussed, emerges at the interface between two phases, particularly in liquid-gas or liquid-liquid systems. It represents one of the most evident macroscopic manifestations of molecular interactions and plays a crucial role in numerous natural and technological processes.
The first to hypothesise the existence of interfacial energy between two materials were Thomas Young (1805) and Pierre Simon Laplace (1808), who laid the theoretical foundations for the understanding of surface tension and for modelling the interaction between a droplet and a solid surface. This quantity, generally denoted by the Greek letter γ, can be interpreted from two different perspectives.

Within the framework of thermodynamics, it is conceived as a scalar quantity, that is, the surface free energy: a measure of the energy required to create a new unit of interfacial area, expressed in joules per square meter $[J/m^2]$. In this view, surface tension reflects an energy change associated with changes in the separating area between two phases, without implying any directionality. Conversely, in fluid mechanics, surface tension assumes a tensorial character, describable as a force per unit length $[N/m]$, acting tangentially along a line located on the surface. This dual nature, both scalar and tensorial, highlights the complexity of the phenomenon and accounts for the fact that surface tension can be approached either from an energetic perspective or a mechanical one, depending on the theoretical or practical context.

Surface tension manifests itself in many situations observable even in everyday life, allowing for an immediate connection between the microscopic behaviour of molecules and the visible effects at the macroscopic scale. Several emblematic examples are presented below.

- A classic example of the effect of surface tension can be observed in the case of a metal needle carefully placed on the surface of water (Figure 1.1). Although the material of the needle, steel, has a density significantly higher than that of water, the needle can remain suspended in equilibrium on the liquid surface. This phenomenon is attributable to surface tension, which generates a cohesive force among water molecules sufficient to counteract the weight of the needle, thereby preventing the surface from being pierced. In this instance, water behaves like an elastic membrane capable of supporting a load distributed over a sufficiently small area.

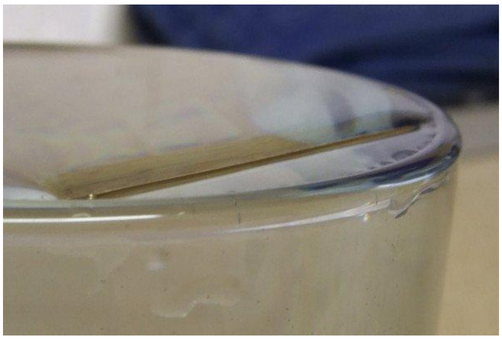

Figure 1.1: A metal needle suspended on the surface of water: despite the density of steel being greater than that of water, surface tension prevents the rupture of the liquid interface, maintaining the needle in equilibrium. The water surface metaphorically behaves like an elastic membrane capable of supporting the load, provided it is distributed over a sufficiently small area (ProblemDestroyer, 2022).

- Water striders (Figure 1.2), insects belonging to the suborder Gerromorpha, provide a further example of the relevance of surface tension in biological systems. These organisms can support themselves and move across the surface of water without sinking, thanks to the distribution of their body weight and the morphology of their legs. The extremities of their limbs are covered with microscopic hairs possessing hydrophobic properties, often coated with waxy or oily substances, which increase the contact angle and prevent the rupture of the liquid surface (Hu et al., 2003). The static forces associated with surface tension, acting perpendicularly to the liquid surface, balance the weight of the insect and enable its gliding locomotion.

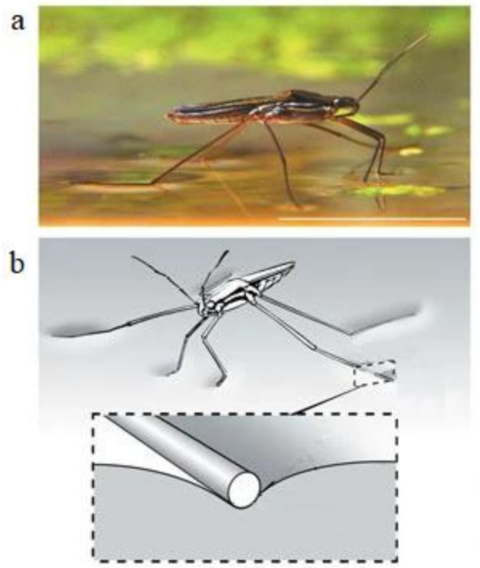

Figure 1.2: (a) Gerris remigis, an adult water strider that exploits surface tension to walk on water; (b) the deformation of the liquid interface, induced by the weight of the strider, generates a curvature force balanced by surface tension, sufficient to support the insect without breaking the surface (Hu et al., 2003).

- An extraordinary example of the interaction between muscular force and the property of a liquid surface is provided by the locomotion of the basilisk lizard (Figure 1.3), a reptile belonging to the Iguanidae family. This animal is renowned for its ability to run across the surface of water, a behaviour made possible by exploiting the dynamic forces induced by surface tension (Glasheen & McMahon, 1996). During running, the basilisk adopts a bipedal posture, lifting itself onto its hind legs and using its tail as a stabiliser. The mechanics of movement are based on a coordinated threefold action: in the initial phase of the step, the limb strikes the liquid surface forcefully, expanding the interdigital flanges and generating a contact area sufficiently large to support the body weight (frame D). This impact forms an air-filled cavity which, together with Archimedes' buoyant force and the inertia of the water, counteracts sinking (frame E). Immediately afterwards, the basilisk swiftly retracts the limb, closing the flanges (frame F); the withdrawal occurs before the cavity collapses, thus minimising liquid resistance and preventing water ingress. The overall result is a sequence of rapid steps in which the reptile appears to “walk” on water.

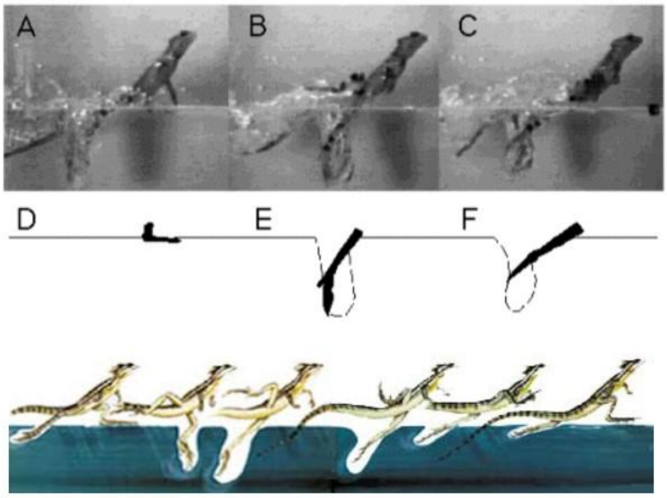

Figure 1.3: The basilisk lizard, through rapid and coordinated muscular action, manages to run across the surface of water by exploiting the interaction between surface tension, hydrostatic thrust, and the dynamics of movement (Glasheen & McMahon, 1996; Fioravanti, 2018).

- The effects of surface tension become particularly evident under microgravity conditions, where liquids spontaneously assume a spherical shape, forming nearly perfect droplets (Figure 1.4). In the absence of gravitational force, the only forces responsible for the equilibrium of the droplet are intermolecular: each molecule of the liquid exerts attractions on others, causing the system to adopt a configuration that minimises the surface free energy. The spherical geometry represents the most energetically favourable solution, as it maximises the internal volume while minimising the exposed surface area.
  A similar behaviour is observed in certain liquid emulsions, such as oil-water systems, where small unstable droplets tend to coalesce into larger structures. This process, known as Ostwald ripening (Kahlweit, 1975), is favoured by the fact that a larger droplet, for the same overall volume, possesses a smaller total surface area compared to the sum of the areas of the smaller droplets, thus leading to a reduction in the system's free energy.

Figure 1.4: In microgravity, the absence of gravitational force allows surface tension to freely shape liquids, which spontaneously assume a spherical form, the configuration of minimum energy (NASA, 2015).

In ordinary conditions, such as with raindrops, the situation becomes more complex. Here, the ideal spherical shape is altered by aerodynamic forces acting during the fall through the atmosphere. The airflow impacts the droplet unevenly: it is greater at the base than at the top. This asymmetry causes the droplet to flatten at the bottom while maintaining a convex curvature at the top. This effect is related to the local variation in surface tension, which decreases in the lower region due to the greater dynamic stress and remains relatively high at the upper region, where perturbations in the airflow are less pronounced. The result is an oblate shape, far from the spherical symmetry observed in microgravity droplets.

These empirical observations provide a starting point for deepening our understanding of the phenomenon, linking the theoretical principles of condensed matter physics with concrete and everyday experience.

1.3.1 Microscopic origin of surface tension

To deepen the understanding of phenomena related to surface tension, it is now useful to shift the focus from the descriptive and macroscopic level towards a deeper perspective, the microscopic one. Observing how molecules behave within the liquid compared to those located near the surface allows us to grasp the origin of the forces responsible for these effects.

Through molecular-level analysis, it becomes clear that surface tension arises from an imbalance in intermolecular interactions: molecules within the bulk, surrounded symmetrically by others, are in equilibrium, whereas those at the surface experience a net resultant force directed inwards. This imbalance generates a force that acts tangentially to the surface of the liquid, manifesting in the macroscopic behaviours observed.

In liquids, cohesive forces between molecules ensure that they remain close to one another, allowing them a certain degree of translational and rotational freedom. In the bulk phase, each molecule is symmetrically surrounded by other molecules that attract it in all directions, resulting in a net vectorial force of zero acting on it ($\boldsymbol{R} = 0$). In contrast, molecules near the surface of the liquid are subjected to an asymmetric distribution of forces, as no external molecules exist to balance the attractions from the interior molecules (Berry, 1971). This imbalance leads to a net force directed towards the interior, perpendicular to the free surface of the liquid ($\boldsymbol{R} \neq 0$), as illustrated in Figure 1.5.

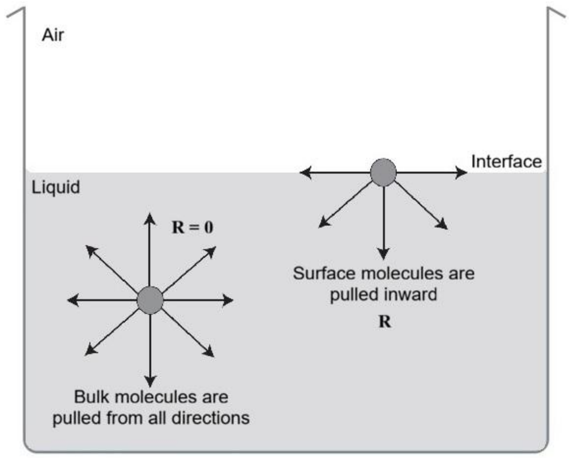

Figure 1.5: Distribution of intermolecular forces in the bulk phase and near the free surface. While molecules immersed in the volume of the liquid experience symmetrically distributed forces with a resultant equal to zero ($\boldsymbol{R} = 0$), those close to the surface experience a net resultant directed inwards ($\boldsymbol{R} \neq 0$), due to the absence of external molecules capable of balancing the internal attractions (Erbil, 2006).

Due to this attractive force, surface molecules tend to migrate inward of the liquid more rapidly than bulk molecules can rise to fill the vacated spaces. This results in a reduction in the number of molecules at the surface and, consequently, a contraction of the overall surface area. The process continues until a configuration is reached in which the internal volume accommodates the maximum possible number of molecules. As a result, the liquid surface is subjected to a state of lateral tension, schematically represented in Figure 1.6. In this depiction, surface molecules are likened to pulleys which, rather than merely experiencing vertical traction, redistribute this force along the direction tangential to the surface. This analogy serves to introduce the idea that interactions between surface molecules are not limited to a perpendicular

attraction but also generate a lateral component: an effective force distributed along the edges of the interface, tending to contract the surface of the liquid. It is precisely this lateral component that is interpreted, at the macroscopic scale, as surface tension: a force per unit length acting tangentially along any imaginary line drawn on the liquid's surface (Erbil, 2006).
This force is the macroscopic manifestation of the unbalanced interactions between molecules at the interface, which will be further analysed in the following sections.

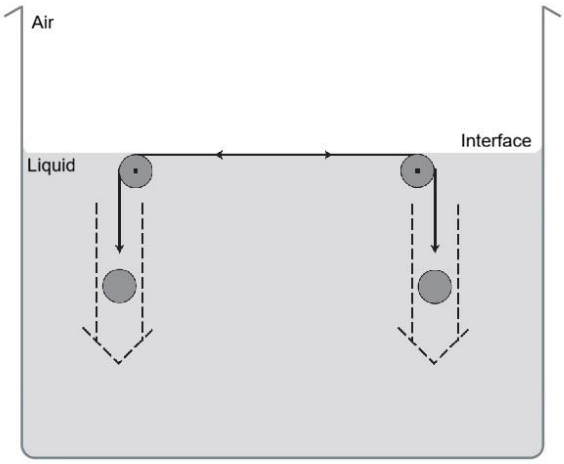

Figure 1.6: Surface molecules act as elements capable of redistributing the exerted forces, generating a tangential traction along the interface: it is this component that manifests macroscopically as surface tension (Erbil, 2006).

Although surface tension is sometimes described, particularly in educational or popular contexts, as a sort of "film" or "elastic membrane" covering the surface of the liquid, it is important to regard this image as a simplifying metaphor, useful for intuitively grasping macroscopic effects but not fully exhaustive from a physical standpoint (Thoburn, 1977).
In thermodynamic terms, surface tension expresses an energy associated with the presence of the interface: more precisely, it represents the free energy per unit area required to create a new interface between two phases, such as between a liquid and a gas, or between two immiscible liquids. In this context, the simplifying metaphor introduced earlier is valid only when surface tension is positive, that is, when a certain energy expenditure is required to create surface by separating molecules that, within the liquid, are in a more stable energetic state.
Let us now consider the hypothetical case in which surface tension assumes a negative value, that is, where the free energy associated with the interface between two phases becomes negative. In such a scenario, the interface would no longer be stable but would instead tend to expand spontaneously, as

increasing the surface area would result in a decrease in the system's total energy. However, this theoretical prediction does not align with experimental observations in systems composed of completely miscible liquids: the interface between two such liquids does not deform or bend in an unstable manner but rather tends to gradually vanish through molecular diffusion until complete homogenisation of the mixture is achieved.
This apparent paradox suggests that the concept of surface tension should be attributed not to a purely geometric or mechanical property of the surface but to the nature of molecular interactions (Grekov, 2021). A positive surface tension reflects the existence of a net inward attractive force exerted by the bulk molecules on those at the surface. Conversely, a hypothetical negative surface tension would imply that repulsive forces prevail and push molecules outward, a condition compatible only with the absence of a true interface, that is, complete miscibility between the two phases. In such a case, the interface does not simply deform but loses its physical meaning altogether, as the two substances spontaneously mix without any barrier (Adamson & Gast, 1997).

1.3.2 Modelling interactions: introduction to the Lennard-Jones potential

The macroscopic behaviour of liquids and particularly, the presence of an energy associated with an interface can be better understood by adopting a microscopic perspective, one that focuses on the interactions between individual molecules rather than treating the fluid as a homogeneous continuum. In this view, a molecule immersed within the bulk of the liquid interacts with all its neighbours through a molecular potential, reflecting the nature of the electromagnetic forces to which it is subjected. These forces may take various forms, Coulombic interactions, dipolar interactions, van der Waals forces, depending on the nature of the liquid under consideration (Butt & Kappl, 2018; Israelachvili, 2011).

To describe these molecular interactions in a simplified manner, prototypical models are often employed, such as the Lennard-Jones potential (Lennard-Jones & Dent, 1928). Although originally developed for apolar molecules and noble gases, this potential is widely used for educational and computational purposes, owing to its ability to essentially capture the attractive-repulsive behaviour between particles. Therefore, although this potential is not among the most accurate for reproducing the complex interactions between water molecules, it will be adopted here as a simplified model, with the aim of qualitatively representing the cohesive and adhesive forces that give rise to surface phenomena.

The general form of the Lennard-Jones potential (Figure 1.7) is given by:

$$V(r) = 4\varepsilon \cdot \left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right] \quad (1.1)$$

where r is the distance between two molecules, ε is the depth of the potential well, representing the strength of the attractive interaction at the energy minimum, and σ is the distance at which the interaction between molecules becomes zero, that is, where attraction and repulsion are balanced.

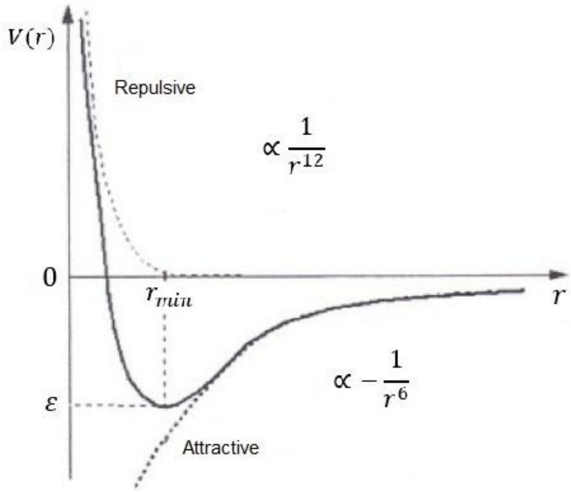

Figure 1.7: Lennard-Jones potential as a function of the intermolecular distance r. The curve shows two main components: a short-range repulsion (proportional to r^{-12}) and a long-range attraction (proportional to r^{-6}) associated with van der Waals forces.

This potential consists of two distinct terms (Stone, 2013). The first term represents short-range repulsion (proportional to r^{-12}) and describes the increase in energy that occurs when two molecules approach each other too closely. This repulsive behaviour arises from the fact that two atoms cannot occupy the same space: when they come within very small distances, repulsion between their nuclei, no longer shielded by electrons, and between the electrons themselves, becomes predominant. Electrons repel each other due to the Pauli exclusion principle, which prevents two electrons from occupying the same set of quantum numbers. The second term of the Lennard-Jones potential, by contrast, represents a long-range attraction (proportional to r^{-6}). This component accounts for van der Waals interactions, which are attractive forces between molecules that, although relatively weak, act over greater distances than short-range repulsion.

Within this framework, surface tension and adhesion work emerge as macroscopic outcomes of a microscopic balance between cohesive and adhesive forces.

Through this potential, one can observe how the equilibrium between attraction and repulsion gives rise to an equilibrium distance between molecules, corresponding to an energetically favourable configuration. When a molecule is located within the bulk of a liquid, it interacts with a spherical arrangement of nearby molecules, defined within the range of the potential, and these interactions determine the cohesive energy per molecule, which constitutes the reference energy state of the system. The effects of these interactions are therefore balanced in all directions.
Conversely, a molecule situated near the surface experiences a lack of neighbouring molecules on the outer side: its binding energy is lower than that of molecules fully immersed in the bulk, resulting in a net force directed inward. It is precisely this imbalance of molecular forces that gives rise to surface tension, understood as the macroscopic manifestation of uncompensated potential energy.

In this context, the Lennard-Jones potential becomes a valuable tool for linking the microscopic and macroscopic levels, making explicit the connection between molecular interactions and phenomena observable at the visible scale.

1.3.3 Surface tension in thermodynamics

The microscopic description allows one to grasp the origin of surface tension as the result of a balance between attractive and repulsive forces among molecules, highlighting how the differing distribution of interactions within the liquid and at its surface gives rise to an energy associated with the interface. However, to fully appreciate the role that such energy plays in the behaviour of real systems, it is helpful to adopt a broader perspective, namely that of thermodynamics. This approach allows surface tension to be considered not only as the product of forces between particles but also as a quantity that enters the energy balances of the system, influencing its stability and transformations. In this context, the interface is no longer merely the site where microscopic symmetry is broken but also becomes an active location for energy exchange and transformation.

At the interface of a real system, there exists a finite distance over which properties gradually change from those of one bulk phase to those of the adjacent one. The three-dimensional region of contact between two phases is referred to as the interphase region or interfacial layer. It is generally assumed that, due to geometrical constraints, only an extremely small fraction of molecules in the system, covering a thickness of approximately $1-2\,nm$, are present in the interfacial region.

It is known that intermolecular interactions lower the internal energy, and molecules at the surface of a liquid in contact with its vapour possess a higher average internal energy compared to those in the bulk phase; this is because surface molecules experience fewer attractive forces than those located within the bulk liquid. Indeed, the only action felt by molecules at the liquid surface, when the system is closed and not in equilibrium, consists of thermal agitation, determined by the vapour pressure or equilibrium vapour pressure, namely, the pressure exerted by a vapour in thermodynamic equilibrium with its condensed phase (in this case, the liquid) at a given temperature (Speight, 2018). In other words, it reflects the tendency of a liquid to evaporate or sublimate. When the system is open, however, equilibrium vapour pressure will never be reached, as the liquid will tend to evaporate completely over time (Atkins & De Paula, 2006).

Since interfacial internal energy cannot be measured by any direct experimental method, it is necessary to employ indirect approaches. One practical option would be to treat the interface as a very thin layer and to define the properties of this thin layer. Nevertheless, this is not an easy task because it raises a significant problem: namely, determining how much of the system's total energy should be attributed to the interface and how much to the two bulk phases of the substances involved.

This difficulty is substantial because the interfacial layer is not infinitely thin, and free energy is stored within it. No sharp boundary exists between the phases; rather, there is a molecular gradient (Figure 1.8) that affects not only the density or orientation of interfacial molecules but also intrinsic properties of the liquid, such as molecular composition, enthalpy, entropy, or electric potential (in the case of charged molecules).

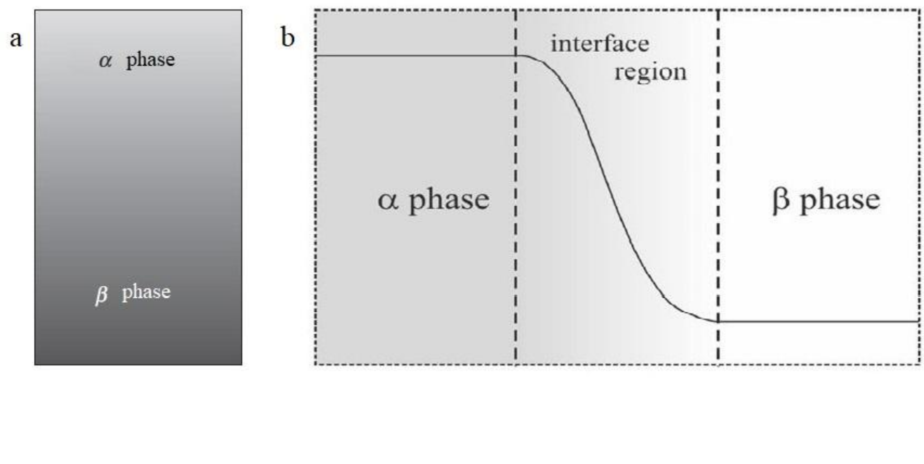

Figure 1.8: (a) Schematic representation of the interfacial region layer between phases α and β for a real system; (b) diagram of the variation of properties as a function of distance near the two phases for a real system (Erbil, 2006; Láng, 2015).

Some assumptions must therefore be made if one wishes to define the free energy of this interfacial layer in thermodynamic terms; otherwise, it would be physically impossible to determine where one phase ends and the other begins. The thickness of the interfacial layer will depend on the molecular nature of the phases involved, as well as external factors such as temperature and pressure. Taking these considerations into account, the interfacial layer typically comprises only a few molecules, usually between one and five monomolecular layers for liquid-vapour interfaces.

In 1878, Josiah Willard Gibbs was the first to propose a method to idealise the interface as an imaginary mathematical dividing surface, known as the *Gibbs dividing surface* (Radke, 2015). He suggested treating the interface as an infinitely thin boundary layer, devoid of thickness and volume ($V^S = 0$), serving as a separation between two distinct phases (Gibbs, 1928). However, it is important to note that this conceptualisation of a dividing surface, idealised as a quasi-two-dimensional entity, inevitably departs from physical reality and represents a purely theoretical construct.
To apply thermodynamics, Gibbs compared a real system to a reference system consisting of this imaginary dividing surface, where it is assumed that all extensive properties of the two bulk phases, α and β, remain unchanged up to the dividing surface (Gibbs, 1928), as illustrated in Figure 1.9. One drawback of this approach is that the position of the dividing surface varies depending on the substances under consideration.

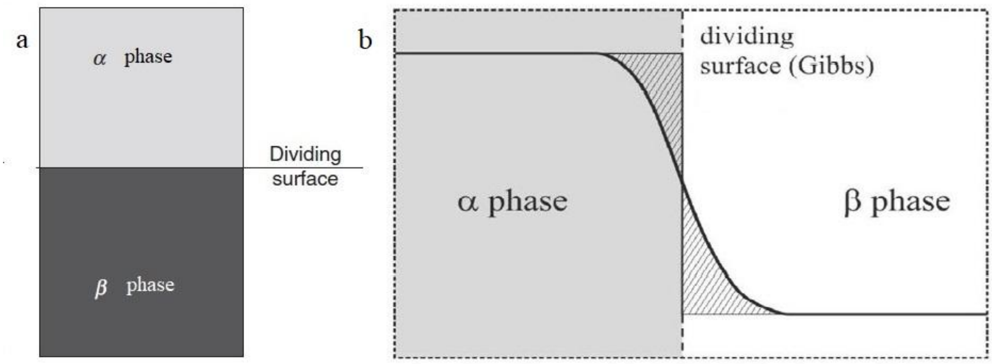

Figure 1.9: (a) Schematic representation of the interfacial region layer between phases α and β after the determination of the imaginary Gibbs dividing surface; (b) diagram of the variation of properties as a function of distance after the determination of the imaginary Gibbs dividing surface (Erbil, 2006; Láng, 2015).

There will be an excess number of moles of each component, of energy, and of entropy in the real system compared to the Gibbs reference system; all these excess quantities are known as the surface excesses of the system's extensive properties and are denoted by a superscript S (Guggenheim & Adam, 1933). The surface excess of any component is defined as the difference between the value of that component in the real system and its value in the idealised system.

The various properties of the real system are therefore given by:

$$V = V^{\alpha} + V^{\beta} \tag{1.2}$$

$$U = U^{\alpha} + U^{\beta} + U^{S} \tag{1.3}$$

$$S = S^{\alpha} + S^{\beta} + S^{S} \tag{1.4}$$

$$n_i = n_i^{\alpha} + n_i^{\beta} + n_i^{S} \tag{1.5}$$

where V, U, S and n_i represent, respectively, the total volume, internal energy, entropy, and number of moles of the i-th component, while the superscripts α and β refer to the two bulk phases of the reference system. Finally, U^S, S^S and n_i^S are all excess quantities (Rowlinson & Widom, 2003).

When phases α and β are in contact, it is assumed that α, β, and the interface are in mutual equilibrium. It is always possible to measure the difference in internal energy between the two contacting phases, but this does not help to define which part of the system's total energy is attributable to the interface U^S and which parts to the bulk phases U^{α} and U^{β}.
Regarding the value of the interfacial excess of a given component, n_i, it will depend on the position of the Gibbs dividing plane.

In differential form, equation (1.3) can be written as:

$$dU = dU^{\alpha} + dU^{\beta} + dU^{S} \tag{1.6}$$

By combining it with the fundamental thermodynamic equation for open systems ($dU = TdS - PdV + \sum_i \mu_i dn_i$, where μ_i is the chemical potential of the i-th substance), it is possible to rewrite equation (1.6) as:

$$dU = T^\alpha dS^\alpha - P^\alpha dV^\alpha + \sum_i \mu_i^\alpha dn_i^\alpha + T^\beta dS^\beta - P^\beta dV^\beta + \sum_i \mu_i^\beta dn_i^\beta + dU^S \tag{1.7}$$

However, to solve it, it is necessary to find a thermodynamic expression for the internal energy in the interfacial region, dU^S.

In thermodynamics, particularly when considering the compression and subsequent expansion of a gas confined within a closed cylinder and piston, the work performed depends solely on two quantities: pressure and volume. This type of work is referred to as W_{PV}. All other types of work can be collectively classified under the general term of non-pressure-volume work, $W_{non\ PV}$. Thus, when multiple types of work are operative in a process, W can be expressed as the sum of pressure-volume work, W_{PV}, and non-pressure-volume work, $W_{non\ PV}$:

$$dW = dW_{PV} + dW_{non\ PV} = -PdV + dW_{non\ PV} \tag{1.8}$$

By combining equation (1.8) with the First Law of Thermodynamics ($dU = dQ + dW$, where Q is the heat exchanged with the environment), we obtain:

$$dU = dQ - PdV + dW_{non\ PV} \tag{1.9}$$

For a reversible system in equilibrium, $dQ = dQ_{rev} = TdS$, and thus equation (1.9) becomes:

$$dU_{rev} = TdS - PdV + dW_{non\ PV} + \sum_i \mu_i dn_i \tag{1.10}$$

Every interfacial region has a natural tendency to spontaneously reduce its surface area. The system possesses free energy and performs work to reduce its interfacial area; since $dA < 0$ for the decrease of area, it follows that $dW_{non\ PV}$ will be negative, as expected for a system doing work. Therefore, the work performed by the system to decrease the surface by a unit area ($1\ m^2$) is given by:

$$dW_{non\ PV} = \gamma dA \tag{1.11}$$

By combining equations (1.10) and (1.11), a general expression for the surface excess of internal energy can be written as:

$$dU^S = T^S dS^S - P^S dV^S + \gamma dA^S + \sum_i \mu_i^S dn_i^S \tag{1.12}$$

From which it is possible to extract the thermodynamic expression for surface tension:

$$\gamma = \left(\frac{\partial U^S}{\partial A^S}\right)_{S^S,V^S,n_i^S} \tag{1.13}$$

Recalling that $V^S = 0$ for the interfacial region, the volume terms in equation (1.12) can thus be disregarded.

Although equation (1.13) is mathematically correct, it is unfortunately impractical from an experimental standpoint, as expanding the surface area under constant volume and entropy conditions is extremely challenging in a real experiment. The selection of independent variables chosen is, therefore, not the most convenient. It is generally preferable to use T, temperature, as the independent variable instead of S (Láng, 2015).

If the system is such that external conditions maintain constant pressure, temperature, and number of moles, the function that best describes the energy is the Gibbs free energy function $G(T, P, n_1 \dots n_i)$, which is obtained from $U(S, V, n_1 \dots n_i)$ through two successive Legendre transformations (Tulczyjew, 1977).

The Gibbs free energy function is defined as $G = U + PV - TS$, which can be expressed as:

$$dG = dU + PdV + VdP - TdS - SdT \tag{1.14}$$

The excess Gibbs free energy, G^S, of the interfacial region during a reversible process is then:

$$dG^S = V^S dP^S - S^S dT^S + \gamma dA^S + \sum_i \mu_i^S dn_i^S \tag{1.15}$$

The total Gibbs free energy of the entire system is the sum of the Gibbs free energy of phases α, β, and the interface, $dG = dG^\alpha + dG^\beta + dG^S$.

Consequently, the expression for defining the surface tension in terms of the Gibbs free energy can be written as:

$$\gamma = \left(\frac{\partial G^S}{\partial A^S}\right)_{P^S,T^S,n_i^S} = \left(\frac{\partial G}{\partial A}\right)_{P,T,n_i} \tag{1.16}$$

Thanks to thermodynamics, it is also possible to predict the effects that temperature variation induces on surface tension and on the surface excess internal energy. At constant pressure, $dP = 0$, and variable temperature, equation (1.15) can be rewritten as:

$$(dG^S)_P = \left[\gamma dA^S - S^S dT^S + \sum_i \mu_i^S dn_i^S\right]_P \tag{1.17}$$

Similarly to the derivation of the Maxwell relations through the application of Euler's reciprocity theorem (Prausnitz et al., 1999), for $G^S = f\left(T^S, A^S, n_i^S\right)$, one obtains:

$$\left(\frac{\partial \gamma}{\partial T}\right)_{A^S,\, n_i^S} = -\left(\frac{\partial S^S}{\partial A}\right)_{T^S,\, n_i^S} \tag{1.18}$$

As temperature increases, the interactions between molecules weaken, resulting in a decrease in surface tension. The component $\left(\frac{\partial \gamma}{\partial T}\right)_{A^S,\, n_i^S}$ is almost always negative; thus, the right-hand side of equation (1.18) becomes positive. In this case, when the surface area expands at constant temperature, an increase in entropy will occur. Consequently, equation (1.18) becomes:

$$dS^S = -\left(\frac{\partial \gamma}{\partial T}\right)_{A^S,\, n_i^S} dA^S \tag{1.19}$$

Recalling that, according to the Gibbs convention, $V^S = 0$, and combining equation (1.12) with the above when n_i^S is constant, one obtains:

$$dU^S = \left[\gamma - T^S \left(\frac{\partial \gamma}{\partial T^S}\right)_{A^S,\, n_i^S}\right] dA^S \tag{1.20}$$

Finally, it can be shown that the surface excess internal energy U^S is almost always greater than the surface tension γ, by integrating equation (1.20) for a surface expansion from 0 to 1 m^2 at constant temperature:

$$U^S = \gamma - T^S \left(\frac{\partial \gamma}{\partial T^S}\right)_{A,n_i} \quad (1.21)$$

Surface tension, γ, represents the work that must be supplied to transfer molecules from the bulk phase to the surface, thereby creating a new surface of unit area ($1\ m^2$). Its dimension is energy per unit area, $[J/m^2]$, according to the International System of Units (SI). Surface tension and surface excess internal energy U^S are dimensionally equivalent $[N/m = J/m^2 = kg/s^2]$, and for pure liquids in equilibrium with their vapour, the two quantities are numerically equal (Gray, 1965).

The Gibbs convention was chosen as the reference framework for describing surface phenomena because it is considered a more effective and practical methodological choice for introducing and discussing the fundamental concepts related to surface tension. The assumption of an interface with no real volume allows excess quantities to be treated clearly and straightforwardly, facilitating the physical interpretation of phenomena and the derivation of fundamental equations. However, another interpretation exists, namely that proposed by Guggenheim in 1936 (Guggenheim, 1988), which suggests a model in which the interface has a small but finite thickness, and therefore a real volume. In this case, the quantities associated with the interface are no longer "excess functions" but actual variables of the intermediate phase.

1.3.4 Surface tension in fluid mechanics

After having examined surface tension as an energetic manifestation from the thermodynamic point of view, and as an effect of unbalanced molecular interactions at the microscopic level, we can now move towards a more operational and quantitative description. Fluid mechanics provides the tools to formalize this interfacial force, integrating it into models that describe the equilibrium and motion of fluids. From this perspective, surface tension is no longer merely a consequence of molecular configurations, but a well-defined force that acts tangentially along the surface and can be treated according to the same principles governing other mechanical forces. To make this vision more concrete, we shall now examine a classical experiment that effectively represents surface tension as a mechanical force tangential to the interface.

Let us consider immersing a rectangular metallic frame into a liquid (Birdi, 2015). Three sides of the metallic frame are rigid and fixed, while the fourth side, corresponding to one of the shorter sides of length l, is made of a movable rod. Once immersed into the liquid and subsequently extracted with care, a liquid film will form stretched between the sides of the frame. If a soap solution is used, a soap film will be obtained (Figure 1.10).

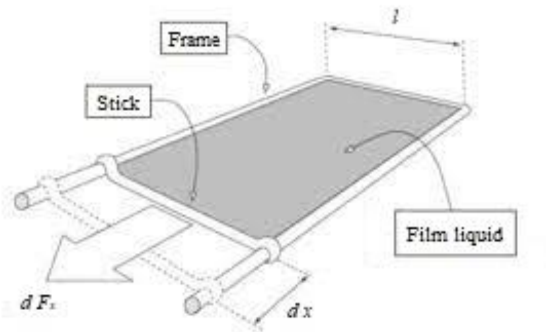

Figure 1.10: Partially mobile rectangular frame immersed in a liquid: three sides are rigid and fixed, while the fourth consists of a movable rod. After immersion and withdrawal, a liquid film forms between the sides of the frame, allowing the direct observation of surface tension effects (Fioravanti, 2018).

Controlled expansion of this surface area can be achieved by applying an infinitesimal force dF_x, perpendicular to the direction of the movable wire, thus causing an infinitesimal increase of the interfacial area dA. If the force is applied sufficiently slowly, the newly formed area will have time to reach equilibrium, and the local value of surface tension can be considered constant and equal to γ^{film}. In the case where the liquid film is sufficiently thick, the distance between the two surfaces exposed to air, the front and the back, is large enough for the interactions between them to be negligible. In such circumstances, the two interfaces can be considered independent, and thus:

$$\gamma^{film} = 2\gamma \tag{1.22}$$

From a mechanical point of view, the infinitesimal work required to displace the movable rod by a distance dx is:

$$dW = F_x dx \tag{1.23}$$

The force F_x required to keep the rod in equilibrium against the contraction of the film is provided by the surface tension along the mobile edge, namely:

$$F_x = \gamma^{film} l = 2\gamma l \tag{1.24}$$

According to the geometry of the system, the variation of the interfacial area is $dA = (2l)dx$, since the film presents two surfaces (front and back). Substituting into the formula for work (1.23):

$$dW = (2\gamma l)dx = \gamma dA \tag{1.25}$$

By combining equations (1.24) and (1.25), an operational definition of surface tension as work per unit area is obtained:

$$\gamma = \frac{dW}{dA} = \frac{F_x}{2l} \tag{1.26}$$

This relationship can also be conceptually justified: the number of molecules present in the interfacial region is proportional to the surface area. Therefore, an infinitesimal increase in the area, dA, implies the addition of molecules to this region. Since transferring molecules from the interior of the liquid to the interface requires positive work, the work required will be proportional to the area increment dA, with a constant of proportionality. This constant is γ, which thus represents both the surface free energy per unit area and the surface tension (Bormashenko, 2019). In general, the stronger the attractive forces between the molecules of a liquid, the higher the value of γ.
However, for this definition to have physical meaning and for the measurement of surface tension to be reliable, it is necessary for the system to be in thermodynamic equilibrium. In other words, any variation of the free surface area of the liquid (for example, during an expansion or deformation of the surface) must occur slowly enough to allow the system to fully relax and redistribute the molecules according to the new interface–volume configuration (Lyklema, 2000). Only under these conditions can one correctly speak of equilibrium surface tension (or static interfacial tension).

In the case of low-viscosity liquids, this relaxation is usually rapid, and equilibrium conditions are easily achieved. However, in high-viscosity liquids, surface relaxation can be very slow, and the system may fail to reach equilibrium within the timescale of the measurement. In such cases, one refers to dynamic or non-equilibrium interfacial tension, distinguishing it from the static case (Lyklema, 2000).

Another useful example to visualize the forces related to surface tension is provided by a simple yet effective experimental apparatus often cited in fluid mechanics. Imagine having a rigid frame of closed shape, such as square, rectangular, or circular (De Gennes et al., 2004). A flexible loop, for instance oval-shaped, is attached to this frame using two cotton threads.
By immersing the system thus constructed into a surfactant solution (such as a soap solution) and then extracting it, a thin liquid film will form covering the entire structure: both the outer frame and the inner boundary formed by the cotton loop. In this initial configuration, as long as the film covers both surfaces, the inner thread remains free to assume various shapes (Figure 1.11a). However,

if the film enclosed by the loop is punctured, the system loses its symmetry: the surface tension forces that previously acted on both sides of the thread are no longer balanced. As a result, the thread tightens and forms an almost perfect circle (Figure 1.11b), a configuration corresponding to the minimum possible surface for the remaining liquid film.

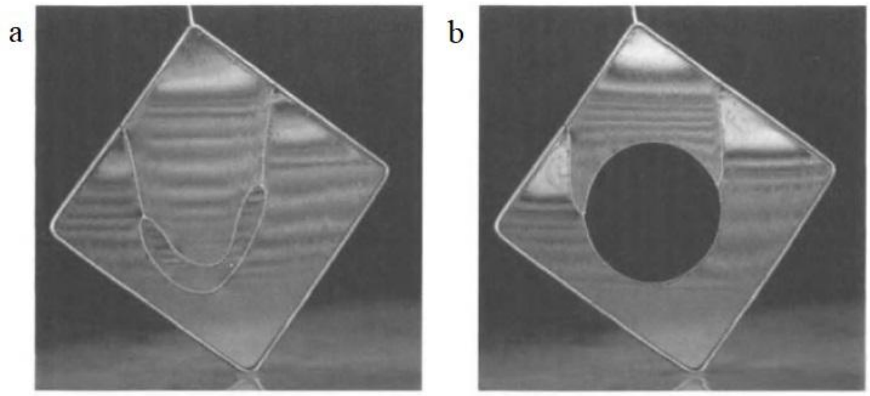

Figure 1.11: Configuration of a frame immersed in a surfactant solution, with a cotton loop placed inside it: (a) in the absence of disturbances, the liquid film uniformly covers both the outer frame and the inner contour, leaving the thread free to adopt arbitrary shapes; (b) after the film inside the loop breaks, surface tension is no longer balanced, and the thread is drawn inwards, adopting a circular shape corresponding to the configuration of minimum area (De Gennes et al., 2004).

In practical experimentation, measurements of surface tension are always carried out between the liquid and air, that is, at the liquid-air interface. It is not possible to directly measure the surface tension of a liquid in the presence of a vacuum, because under such conditions the liquid would rapidly evaporate, making stable observation impossible. Although air is not a vacuum, it is often considered chemically inert with respect to most liquids, at least at low or moderate pressures. The interactions between liquid molecules and air molecules are generally negligible, which is why the interfacial tension measured between liquid and air is taken as a good approximation of the true surface tension of the liquid, namely that which would ideally exist between the liquid and vacuum.
Because of this approach, the values of surface tension reported in the literature (Wohlfarth & Lechner, 2016; Jasper, 1972; Batchelor, 2000) almost always refer to measurements made between liquid and air, under thermodynamic equilibrium and controlled temperature conditions.

In solids, the situation is different: it is not possible to continuously and reversibly expand a surface, because the solid tends to break or fracture rather than deform as a liquid does. This does not mean that solids lack surface tension, but rather that its experimental determination requires indirect methods, such as measuring the contact angle between a liquid droplet and the solid surface or through specific mechanical models (see Section 1.5).

1.4 Curved liquid surfaces

In the context of interface physics, interfacial tension and the morphology of the surfaces separating two phases play a crucial role in determining the mechanical and thermodynamic properties of systems. Curved liquid surfaces, such as spherical droplets, bubbles, or menisci observable in capillaries, are macroscopic manifestations of the principle of minimisation of surface free energy. In the presence of surface tension, the system spontaneously tends to arrange itself to minimise the area of the separating surface, while maintaining a constant volume. This behaviour often results in geometries exhibiting spherical or cylindrical symmetry. The presence of curvature implies a discontinuity in pressure across the interface, a discontinuity which is functionally linked to the surface tension and the local geometry of the surface. Specifically, within a curved surface, such as the interior of a bubble, the pressure is higher by a value ΔP compared to the exterior. This pressure gradient is a direct consequence of the curvature of the interface, which acts as an elastic surface capable of sustaining pressure differences under static equilibrium (Erbil, 2006).
It is essential to emphasise that pressure is always greater on the concave side of the surface, regardless of the nature of the phases involved. This principle holds true both for condensed phases and for systems where one of the two phases is gaseous, as in the case of bubbles or suspended droplets.

However, the formation of curvature is not an obligatory consequence: two phases in perfect hydrostatic equilibrium may also be separated by a planar interface, which represents an ideal limiting case, rarely encountered under real laboratory conditions.

From a geometrical perspective, curvature constitutes a quantitative measure of the deviation of a surface from a planar configuration. Intuitively, one distinguishes between concave surfaces, resembling the inner surface of a sphere, and convex surfaces, analogous to the outer surface of the same sphere. Nevertheless, a rigorous treatment requires adopting the mathematical definition of curvature, which, in a two-dimensional context, can be understood as the variation of the slope of a curve with respect to arc length. If a curve lies below all its tangents, it is concave; conversely, if it lies above all its tangents, it is convex (Figure 1.12).

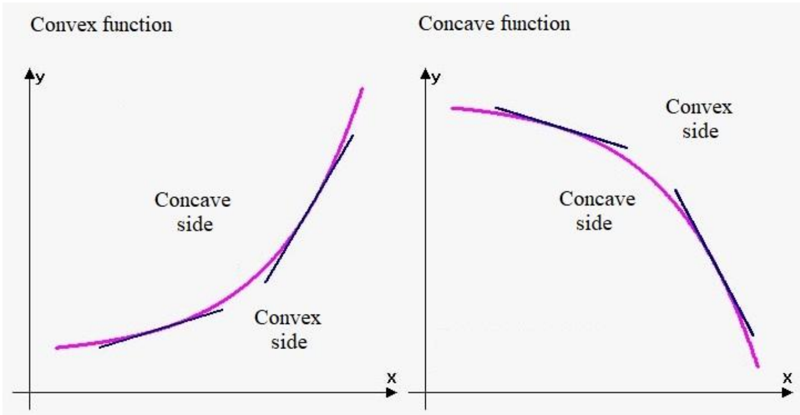

Figure 1.12: Schematic representation of curved surfaces: the curvature determines the direction of the slope variation along the surface and directly influences the pressure distribution, which is greater on the concave side (eMathHelp, n.d.).

The phenomena that arise as a direct consequence of the presence of curved liquid surfaces are generally classified as capillary phenomena. These phenomena, besides being relevant to the understanding of microscopic and biological physical systems, play a central role in numerous technological applications, ranging from materials engineering to microfluidics.

The quantitative relationship between the curvature of a liquid surface and the associated pressure discontinuity is expressed by the Young–Laplace equation. This formula, independently derived by Thomas Young (1805) and Pierre Simon Laplace (1808) in the early 19th century, provides a fundamental description of the mechanical equilibrium between surface tension, curvature, and pressure. It constitutes a conceptual bridge between fluid mechanics and the differential geometry of surfaces.

In the simplest case, where perfectly spherical surfaces are considered (such as isolated droplets or bubbles), the equation can be derived through an approach based on Newtonian mechanics, by evaluating the forces acting on an infinitesimal surface element (Siqveland & Skjæveland, 2021). For more complex surfaces, such as asymmetric menisci or irregular interfaces, the treatment requires a generalised formulation involving concepts of mean curvature and Gaussian curvature. Such more abstract treatments lie beyond the objectives of the present discussion; however, it will still be shown that the generality of the Young-Laplace equation precisely stems from its dependence on the principal radii of curvature, which are equal only in the case of a sphere.

1.4.1 The Young–Laplace equation in Newtonian mechanics

The simplest and most intuitive form of the Young-Laplace equation is obtained by considering the ideal case of a perfectly spherical vapour bubble in equilibrium with a surrounding liquid, or a suspended liquid droplet in air. In this context, it is assumed that there are no external fields, such as gravitational, magnetic, or electric forces, that might alter the symmetry of the configuration. In the absence of such perturbations, the bubble naturally tends to adopt a spherical shape, as this geometric configuration minimises the surface area for a given volume, in accordance with the principle of minimisation of surface free energy.

Under these conditions, the total force exerted by the internal pressure of the bubble on its surface can be expressed as:

$$F_{interior} = A_{bubble}P_{interior} = 4\pi R_{sph}^2 P_{interior} \tag{1.27}$$

where R_{sph} is the radius of the spherical bubble and $A_{bubble} = 4\pi R_{sph}^2$ represents its surface area.

To describe the resultant force acting on the bubble surface from the exterior, it is necessary to consider, in addition to the external pressure exerted by the surrounding medium, an additional contribution due to surface tension. This force denoted F_γ, functions to reduce the surface area and therefore opposes the expansion of the bubble. The complete equation for the force acting on the exterior side is thus:

$$F_{exterior} = A_{bubble}P_{exterior} + F_\gamma = 4\pi R_{sph}^2 P_{exterior} + F_\gamma \tag{1.28}$$

According to Newtonian mechanics, the work dW_γ associated with the variation of the bubble radius can be expressed as:

$$dW_\gamma = F_\gamma R_{sph} \tag{1.29}$$

and, knowing from equation (1.25) that $dW_\gamma = \gamma dA$ and that the surface area of a sphere is $A = 4\pi R_{sph}^2$, it follows that:

$$F_{\gamma} = \gamma\left(\frac{dA}{dR_{sph}}\right) = \gamma(8\pi R_{sph}) \quad (1.30)$$

By imposing the condition of mechanical equilibrium, that is, equating the internal and external forces ($F_{interior} = F_{exterior}$) and combining equations (1.27), (1.28), and (1.30), one obtains:

$$4\pi R_{sph}^2 P_{interior} = 4\pi R_{sph}^2 P_{exterior} + 8\pi\gamma R_{sph} \quad (1.31)$$

Rewriting equation (1.31) in terms of the pressure difference between the inside and outside of the bubble, the well-known form of the Young–Laplace equation for the spherical case is obtained:

$$\Delta P = P_{interior} - P_{exterior} = \gamma\left(\frac{2}{R_{sph}}\right) \quad (1.32)$$

This equation highlights that the pressure difference between the interior and exterior of the bubble is directly proportional to the surface tension of the liquid and inversely proportional to the radius of curvature. As the radius increases, the pressure difference decreases, ultimately vanishing in the limit where $R_{sph} \rightarrow \infty$. In this condition, the curvature tends to zero, and the surface approaches a flat Euclidean geometry, corresponding to a hydrostatic equilibrium interface between two phases.

Although the treatment thus far has referred to the ideal case of a perfectly spherical surface, many physical systems exhibit curved interfaces that cannot be described by a single radius of curvature. In such situations, the surface presents different curvatures along two principal orthogonal directions, necessitating a more general formulation of the Young-Laplace equation. This generalisation introduces the so-called principal radii of curvature, each contributing to the capillary pressure according to a relationship that upholds the principle of surface force balance. The following section will therefore examine the Young-Laplace equation in its extended form, suitable for describing systems in which the local curvature of the surface varies from point to point.

1.4.2 Young-Laplace equation in planar geometry

In the previous subsection, the pressure difference under equilibrium conditions was analysed for a perfectly spherical bubble, where the curvature is isotropic and described by a single radius. However, in many physical systems, it may occur that the internal pressure is significantly greater than the external pressure. In such circumstances, the bubble, or a liquid droplet, will tend to expand to reduce the existing pressure gradient. This expansion results in an increase in the system's surface area and will continue until the cohesive forces exerted by surface tension become sufficiently strong to balance further expansive forces. Throughout this process, the geometry of the interface changes: the shape of the bubble is no longer spherical but evolves towards configurations characterised by non-uniform curvatures.

To describe such situations, one considers an infinitesimal portion of an arbitrarily curved surface, as illustrated in Figure 1.13 (Rapp, 2016; Butt et al., 2023). The principal radii of curvature, R_1 and R_2, are determined by intersecting the surface with two orthogonal planes, corresponding to the principal directions of curvature. Defining x and y as the arc lengths along these directions, it is assumed that the surface is displaced by an infinitesimal outward increment, dz, thereby increasing the arc lengths to $(x + dx)$ and $(y + dy)$.

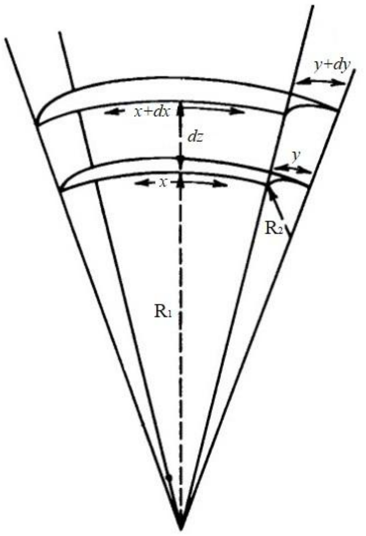

Figure 1.13: Schematic representation of an infinitesimal element of an arbitrarily curved surface. The two principal radii of curvature, R_1 and R_2, are obtained by sectioning the surface along two mutually orthogonal planes. The initial arc lengths x and y, corresponding to the principal directions, increase to $(x + dx)$ and $(y + dy)$ following an infinitesimal outward displacement dz from the surface (Adamson & Gast, 1997).

The corresponding increment in surface area associated with this displacement is given by:

$$dA = (x + dx)(y + dy) - xy \approx xdy + ydx \tag{1.33}$$

where second-order differential terms have been neglected.

The corresponding increase in Gibbs free energy, at constant temperature and pressure, due to the increase in area against the surface tension γ, is:

$$dG = \gamma(xdy + ydx) \tag{1.34}$$

This energy increase must be balanced by the mechanical work produced by the pressure difference ΔP, acting through the displaced volume element. Since $dG = \Delta P dV$ and $dV = xy\, dz$, it follows that:

$$\Delta P dV = \Delta P xydz = \gamma(xdy + ydx) \tag{1.35}$$

At this point, considering geometric relations derived from similar triangles, one can write:

$$\frac{x + dx}{R_1 + dz} = \frac{x}{R_1} \text{ simplifying to } \frac{dx}{xdz} = \frac{1}{R_1} \tag{1.36}$$

$$\frac{y + dy}{R_2 + dz} = \frac{y}{R_2} \text{ simplifying to } \frac{dy}{ydz} = \frac{1}{R_2} \tag{1.37}$$

Substituting expressions (1.36) and (1.37) into Equation (1.35), one arrives at the most general form of the Young-Laplace equation for surfaces with double curvature:

$$\Delta P = \gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{1.38}$$

At equilibrium, the capillary pressure ΔP is constant throughout the fluid, implying that the liquid surface must exhibit uniform curvature everywhere. Otherwise, a spontaneous flow of liquid would occur from regions of higher curvature (and thus higher pressure) towards regions of lower curvature, to restore hydrostatic equilibrium.

This expression, also known as the fundamental equation of capillarity, describes the pressure difference across the two sides of a curved surface in terms of its principal curvatures. In the presence of non-zero curvature, a pressure difference is necessary to maintain mechanical equilibrium. It should be noted that Equation (1.38) reduces to Equation (1.32) when the principal radii of curvature are equal, as in the case of a sphere.

1.5 Theory of wettability

The wettability of a solid surface by a liquid is a complex phenomenon involving thermodynamic, mechanical, and microstructural aspects (Eustathopoulos et al., 1999). Understanding this phenomenon first requires a reflection on the nature of surface tension in solids, a quantity that cannot be determined directly due to the elastic and viscous constraints present in the bulk phase. Unlike liquids, where molecules are free to move and reorganise in response to external perturbations, the mobility of molecules near the surface of a solid is extremely limited. Consequently, solid surfaces do not easily adopt the geometrical configurations required to minimise the surface free energy on a macroscopic scale. Indeed, most solids are unable to spontaneously reorganise into equilibrium conformations, and their surfaces effectively represent a kind of "frozen snapshot" of their thermal and mechanical history, often marked by irregularities, inhomogeneities, and defects.
The only generalised approach available for calculating surface tension in solids is therefore empirical, based on estimating the solid's surface tension from that of a liquid in contact with it.

Consider a liquid droplet placed on a solid surface, as shown in Figure 1.14. The equilibrium of the droplet is determined by the balance between three interfacial tensions: that between the solid and the liquid (γ_{SL}), the solid and the gas (γ_{SG}), and the liquid and the gas (γ_{LG}). The contact angle, denoted by θ, represents the angle formed at the point of contact between the three phases (liquid, solid, and gas), and is defined between the plane tangent to the liquid surface and that tangent to the solid surface at the point of intersection. This angle provides a quantitative measure of the degree of wettability of a solid by a given liquid.

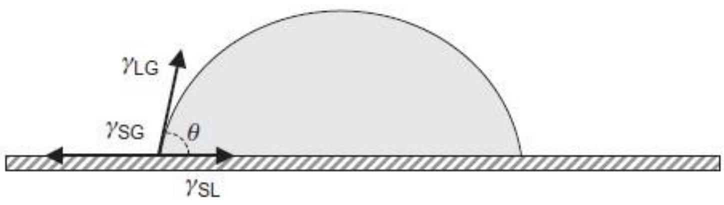

Figure 1.14: Diagram of the forces acting on the triple contact line between liquid, solid, and gas. The figure shows the balance of interfacial tensions between solid-liquid (γ_{SL}), solid-gas (γ_{SG}), and liquid-gas (γ_{LG}), which determines the equilibrium of the droplet on a solid surface. The contact angle θ, formed at the meeting point of the three phases, provides a measure of the degree of wettability of the solid (Berthier, 2012).

Unless the liquid is highly volatile, any low-viscosity fluid can be used for such measurements.

In describing the interaction between a liquid droplet and a solid surface immersed in a gaseous atmosphere, the mechanical equilibrium at the point where the three phases meet, known as the triple contact line, can be represented by a vector balance of interfacial tensions (Berthier, 2012). This equilibrium is expressed as:

$$\vec{\gamma}_{SG} = \vec{\gamma}_{SL} + \vec{\gamma}_{LG} \quad (1.39)$$

Two distinct scenarios are possible depending on the nature of the interactions between the liquid and solid molecules: partial wetting and complete wetting (Figure 1.15).

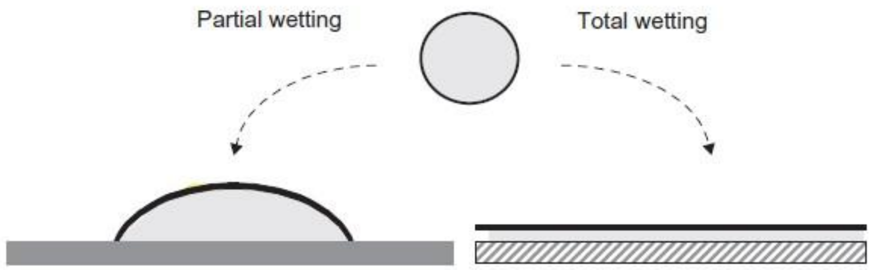

Figure 1.15: Two wetting scenarios depending on the interactions between liquid and solid molecules. Partial wetting occurs when the liquid forms a droplet on the solid surface, with a finite contact angle. In contrast, complete wetting occurs when the liquid spreads as a uniform film over the solid surface without forming a droplet (Berthier, 2012).

In the first case, known as partial wetting, the liquid assumes the shape of a droplet with a finite contact angle, defined at the triple interface between the solid, liquid, and gas. This behaviour indicates that the cohesive forces within the liquid are comparable to or greater than the adhesive forces between the liquid and the solid. Under such conditions, the system's total free energy is minimised when the liquid limits its contact area with the solid surface (Bonn et al., 2009). Two main regimes can be distinguished: if the contact angle θ is less than 90°, the contact is referred to as hydrophilic, and more generally, as wetting behaviour (Figure 1.16a). Conversely, if the contact angle θ is greater than 90°, the liquid tends to remain cohesive rather than spreading across the surface, and the behaviour is termed hydrophobic (Figure 1.16b).

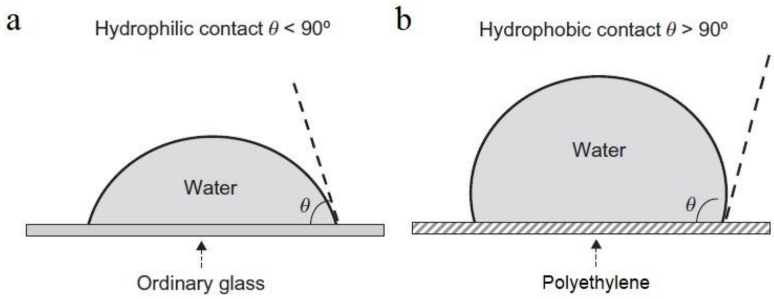

Figure 1.16: Two wettability regimes as a function of the contact angle θ. (a) Wetting behaviour (hydrophilic) with a contact angle $\theta < 90°$, where the liquid spreads across the solid surface; (b) non-wetting behaviour (hydrophobic) with a contact angle $\theta > 90°$, where the liquid tends to form a droplet and remains cohesive rather than spreading over the surface (Berthier, 2012).

These definitions are useful for describing a liquid's tendency to interact with a given surface and depend on both the chemistry of the surfaces involved and their microscopic structure, as well as environmental conditions such as temperature or the presence of contaminants. Smooth, high-energy surfaces tend to promote wetting, whereas rough surfaces or those chemically modified with non-polar groups can enhance hydrophobic behaviour.

In the second case, complete wetting is observed, where the liquid does not retain the shape of a droplet but instead spreads spontaneously over the solid surface to form a thin film whose height tends towards zero in the limit, while its lateral extent depends solely on the initial available volume of the liquid. In this condition, the contact angle tends to zero ($\theta \rightarrow 0°$), indicating that the adhesive forces between the solid and the liquid greatly exceed the cohesive forces between the liquid molecules (Figure 1.17). Thermodynamically, this scenario occurs when $\vec{\gamma}_{SG} > \vec{\gamma}_{SL} + \vec{\gamma}_{LG}$ indicating that the system can reduce its free energy by increasing the contact area between the liquid and the solid (Marchand et al., 2011).

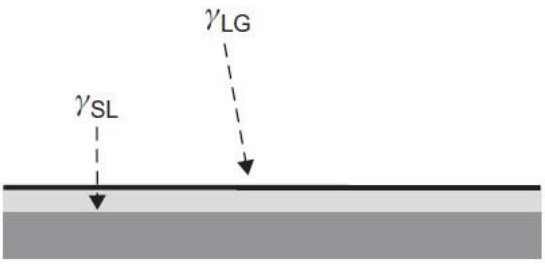

Figure 1.17: Complete wetting, in which the liquid spreads over the solid surface forming a thin film, with a contact angle $\theta \to 0°$. In this condition, adhesive forces between the solid and the liquid prevail over cohesive forces between the liquid molecules, allowing a greater extension of the contact area (Berthier, 2012).

The transition between partial and complete wetting can be influenced by factors such as temperature, pressure, the chemical composition of the phases involved, and the microstructure of the solid surface (Quéré, 2008).
Finally, it is important to highlight that these two configurations represent the extremes of a continuous behaviour. In experimental practice, intermediate situations are often observed, where contact angles vary depending on local conditions, leading to complex droplet boundary dynamics. In this context, phenomena such as contact angle hysteresis (Marmur, 1994; Gao & McCarthy, 2006) and pinning (De Gennes, 1985) may occur, although they will not be discussed in this work. For a more detailed treatment, the reader is referred to the cited references.

Within the context of wettability, a rigorous formulation of the problem is obtained by considering the energy balance of the system at equilibrium. Suppose we analyse a droplet of liquid of constant volume placed on a rigid solid surface and immersed in a gaseous atmosphere. In this configuration, the system presents three distinct interfaces, each associated with a specific free energy per unit area: γ_{SG} for the solid-gas interface, γ_{SL} for the solid-liquid interface, and γ_{LG} for the liquid-gas interface. When the droplet undergoes a slight deformation, changing its contact area with the solid by an infinitesimal amount dA, the system's surface free energy changes according to the expression:

$$dG = \gamma_{SL} dA + \gamma_{LG} dA \cos\theta - \gamma_{SG} dA \qquad (1.40)$$

where the term $\gamma_{LG}\cos\theta$ represents the contribution of the liquid-gas tension projected in the direction tangential to the solid. Setting the mechanical equilibrium condition, namely $dG = 0$, yields Young's law (1805), further specified by Bangham and Razouk (1937):

$$\gamma_{SG} = \gamma_{SL} + \gamma_{LG} \cos\theta \qquad (1.41)$$

or, solved for the contact angle:

$$\theta = \cos^{-1} \frac{\gamma_{SG} - \gamma_{SL}}{\gamma_{LG}} \qquad (1.42)$$

This relation establishes that the equilibrium contact angle is a function of the surface free energies of the three interfaces involved. It is important to stress that this equation derives from the balance of the horizontal components of the surface tensions at the triple contact point. The vertical components are not balanced between the surface tensions and are generally absorbed by slight local deformations of the solid, which, in the case of rigid substrates, are negligible.

1.5.1 Phase interactions: adhesion work, cohesion work, and the Young-Dupré law

In the field of the physics of interfacial phenomena, it is essential to understand the energetic mechanisms governing the interactions between different phases, such as liquids, solids, and gases. Two fundamental concepts that enable us to describe these interactions are the work of adhesion and the work of cohesion. These concepts provide a measure of the energy required to create or destroy contact surfaces between materials and are applicable both to pairs of immiscible liquids and to interactions between a liquid and a solid.

In this section, we formally introduce the concepts of adhesion work and cohesion work, illustrating how, in the case of a system consisting of a liquid in contact with a solid, applying the concept of adhesion work in combination with Young's law naturally leads to the Young-Dupré formula (Wang et al., 2012). The latter represents a fundamental link between the mechanics of interfaces and thermodynamics, highlighting how the macroscopic behaviour of a droplet (the contact angle) is governed by energy balances at the molecular level.

The adhesion work, W_A, represents the energy required to separate a unit area of two contacting phases, for instance, a solid and a liquid, and transform them into two new surfaces, each in contact with the gaseous phase or another phase (Figure 1.18).

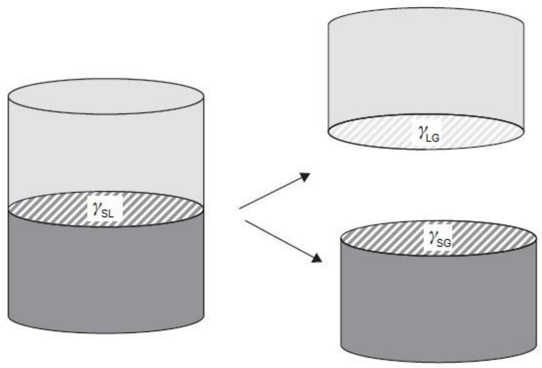

Figure 1.18: Schematic representation of the work of adhesion between a liquid and a solid. The work of adhesion corresponds to the energy required to separate a unit area of two contacting phases (solid and liquid), creating two new interfaces (Berthier, 2012).

According to Dupré's equation (Dupré, 1869), this work is expressed as:

$$W_A = \gamma_{LG} + \gamma_{SG} - \gamma_{SL} \quad (1.43)$$

By substituting Young's equation (Equation 1.41) into this expression, the Young-Dupré relation is obtained (Schrader, 1995):

$$W_A = \gamma_{LG}(1 + \cos\theta) \quad (1.44)$$

This establishes a quantitative link between the work of adhesion and the experimentally measurable contact angle. From this equation, it emerges that the smaller the contact angle, the greater the thermodynamic affinity between liquid and solid, that is, the greater the work required to separate the two phases. In the limiting case of complete wetting ($\theta \to 0°$), one obtains $W_A = 2\gamma_{LG}$; conversely, for non-wetting conditions ($\theta \to 180°$), $W_A = 0$.
It is thus evident that the contact angle is not merely a geometric parameter, but rather a macroscopic manifestation of molecular interactions and profound thermodynamic equilibria that govern adhesion, cohesion, and interfacial stability phenomena. The treatment outlined above constitutes the fundamental conceptual basis for the study of interfacial phenomena in numerous application domains, ranging from microfluidics to the biocompatibility of materials, from industrial adhesion to the design of functionalised surfaces.

The work of cohesion, W_C, instead measures the energy required to separate a unit area of a homogeneous phase to create two identical new surfaces, as in the case of two portions of the same liquid, each in contact with a different phase, generally air or another gaseous phase (Figure 1.19).

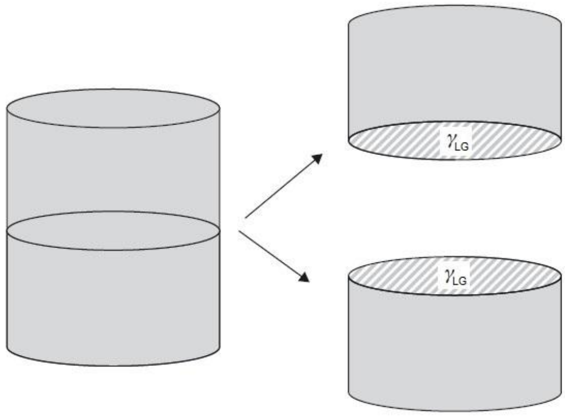

Figure 1.19 Schematic representation of the work of cohesion. The energy required to separate a unit area of the same liquid phase and to form two new liquid surfaces in contact with the gaseous phase (Berthier, 2012).

The work of cohesion represents a fundamental thermodynamic quantity for describing the internal stability of a substance and the strength of the intermolecular forces that determine its internal cohesion. It can be expressed as:

$$W_C = 2\gamma_{LG} \tag{1.45}$$

where γ_{LG} is the interfacial tension between the liquid and the gas. The factor 2 reflects the formation of two identical surfaces upon separation.
This concept has significant practical and experimental relevance, as it allows the behaviour of liquids under different conditions to be understood, such as spreading on surfaces, droplet formation, or resistance to separation. High values of work of cohesion are typical of liquids with strong intermolecular bonds (e.g., hydrogen bonds) and are associated with high surface tension.

1.6 Capillarity: theoretical and applied aspects

Continuing the analysis of interactions between liquids and solids, it is natural to consider phenomena where more complex geometries or confinement conditions emerge. The behaviour of a liquid in contact with thin solid surfaces reveals fundamental aspects of the molecular interactions that govern interfacial phenomena. When variations in the liquid level inside very narrow tubes are observed, one enters the domain of capillary phenomena, in which forces such as adhesion, cohesion, and surface tension play crucial roles. This section explores the mechanisms underlying the rise or depression of liquids in capillaries, the experimental conditions necessary to observe them in a controlled manner, and the role of the meniscus shape in the balance of pressures acting on the system (Sophocleous, 2010). Particular attention will be given to the description of the Jurin-Borrelli law, its relationship with the Young-Laplace equation, and the implications of the contact angle between the liquid and the solid wall.

To understand these phenomena in depth, let us consider the case in which a tube with a diameter smaller than approximately $0.1\ mm$, that is, a capillary, is immersed in a liquid. In this configuration, a variation of the liquid level inside the tube with respect to that in the container is observed: specifically, the liquid may rise or be depressed within the capillary. This phenomenon, known as the capillary effect, is attributable to the combination of surface tension, adhesive forces between the liquid and the tube wall, and cohesive forces between the liquid molecules. The extent of the level change depends on the physicochemical nature of the liquid and the geometry of the tube: the smaller the radius of the capillary, the more pronounced the observable effect will be.
If a tube larger than capillary dimensions is used, the rise of the liquid inside will be negligible and will coincide with the liquid level in the container, with no observable rise or depression phenomena. Capillaries are generally made of glass, a material that exhibits two fundamental properties: transparency, which is useful for direct observation, and high wettability by many liquids, a necessary condition to promote adhesion to the inner wall.
As is well known, capillary rise results from the adhesive interactions between the liquid and the capillary wall, which are stronger than the cohesive forces between the molecules of the liquid itself. This condition allows the liquid to "adhere" to the inner walls of the tube and spontaneously rise. One interpretative hypothesis, advanced but not yet definitively confirmed experimentally, proposes that the rise process begins with the formation, upon initial contact between the liquid and the tube, of a thin film of liquid along the inner walls of the capillary (Leger et al., 1988; Xu et al., 2004). This film would form due to the strong adhesive attraction between the liquid molecules and those of the solid surface, generating an extensive new liquid-solid interfacial area. The creation of such a film initially increases the surface free energy of the system, but this configuration is not stable. The system spontaneously tends to minimise its total free energy: this results in a rapid rise of the liquid within the capillary, driven by the reduction of the liquid-vapour interface in favour of the liquid-solid interface, which is energetically more favourable.
The rise continues until the capillary force pushing the liquid upwards, associated with surface tension and the curvature of the meniscus, is exactly balanced by the weight of the formed liquid column, that is, by the hydrostatic pressure exerted by the fluid itself. At equilibrium, the height reached by the column represents the point at which the capillary pressure and the hydrostatic pressure exactly compensate each other. Capillary rise or depression thus results

from a delicate balance between these opposing contributions, directly reflecting the molecular interactions at the liquid-solid interface (Rodríguez-Valverde & Tirado Miranda, 2011; McCaughan, 1987, 1988).

The height reached by the liquid in a capillary tube can be quantitatively described by the Jurin-Borrelli law, according to which the height h is directly proportional to the surface tension γ and inversely proportional to the density ρ, gravitational acceleration g, and the radius r of the capillary (Jurin, 1718):

$$h = \frac{2\gamma}{\rho g r} \tag{1.46}$$

A fundamental element in describing the phenomenon is the shape of the liquid surface inside the tube, which assumes a curved configuration known as the meniscus. The curvature of the meniscus is determined by the competition between adhesive and cohesive forces and is characterised by the contact angle θ, defined as the angle between the tangent to the liquid profile near the wall and the internal surface of the tube. When the liquid completely wets the wall ($\theta = 0^\circ$), the meniscus assumes a hemispherical shape.

The hydrostatic equilibrium of the liquid column in a capillary tube can be formally described by the Young-Laplace equation (Equation 1.38), which relates the pressure difference ΔP across the curved interfacial surface (meniscus) to its curvature and the surface tension γ of the liquid. In a capillary tube with a circular cross-section and sufficiently small radius, if the meniscus adopts a hemispherical shape (that is, the principal radii of curvature are both equal to the tube radius, $R_1 = R_2 = r$), the equation simplifies to:

$$\Delta P = \frac{2\gamma}{r} \tag{1.47}$$

As illustrated in Figure 1.20, the pressure at point a, just above the meniscus, corresponds to the atmospheric pressure. The height h of the liquid column will be such that the pressure at point c, at the base of the tube, will also match the atmospheric pressure, due to the balance between hydrostatic pressure and capillary pressure. The pressure at point b, immediately below the meniscus, will be lower than the atmospheric pressure by an amount equal to $2\gamma/r$ (Durand, 2021).

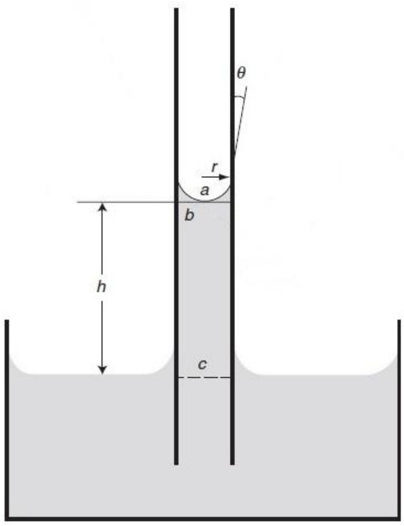

Figure 1.20: Concave meniscus of a liquid in a capillary tube during a surface tension measurement. The angle θ represents the contact angle between the liquid and the wall of the capillary. Point a, just above the meniscus, is at atmospheric pressure, as is point c, at the base of the tube, due to the balance between hydrostatic and capillary pressures. Point b, immediately below the meniscus, has a pressure lower than atmospheric by an amount equal to $2\gamma/r$. The height h indicates the column of liquid sustained by the capillary effect (Erbil, 2006).

At equilibrium, the pressure difference described by the Young-Laplace equation must balance the pressure drop caused by the hydrostatic column of the liquid, according to the relation:

$$\Delta P = \Delta\rho g h = \frac{2\gamma}{r} \tag{1.48}$$

where $\Delta\rho$ represents the density difference between the liquid and the gaseous phase. From this expression, it follows that, in the case of a hemispherical meniscus and perfect wetting ($\theta = 0^\circ$), the height of the capillary column can be expressed as:

$$rh = \frac{2\gamma}{\Delta\rho g} = a_0^2 \tag{1.49}$$

where a_0^2 is the capillary constant for zero contact angle, and a_0 (its square root) has the dimension of a length.
In more general conditions, the liquid may interact with the capillary wall with a finite contact angle θ. In these cases, if the tube radius is sufficiently small to render curvature distortions due to gravity negligible, the geometry of the

meniscus allows the relation between tube radius and meniscus curvature radius to be approximated as:

$$\cos\theta = \frac{r}{R} \quad \Rightarrow \quad R_1 = R_2 = \frac{r}{\cos\theta} \tag{1.50}$$

From this, the equilibrium equation is generalised into the form:

$$rh = \frac{2\gamma\cos\theta}{\Delta\rho g} = a_0^2 \tag{1.51}$$

The shape of the meniscus and, consequently, the behaviour of the liquid column depend on the balance between adhesive forces (between the liquid molecules and the solid wall) and cohesive forces (between the molecules within the liquid itself). When adhesive forces exceed cohesive forces, the contact angle satisfies $0^\circ \leq \theta \leq 90^\circ$, resulting in a concave meniscus and consequent capillary rise. Conversely, when cohesive forces dominate ($90^\circ \leq \theta \leq 180^\circ$), the meniscus is convex, and a depression of the liquid level within the capillary is observed (De Gennes et al., 2004).

A representative example of the first condition is provided by water in glass tubes (typically $\theta \cong 0^\circ$), whereas an example of the second case is mercury in contact with glass, where the contact angle is approximately $\theta \cong 140^\circ$, leading to a pronounced capillary depression (Figure 1.21).

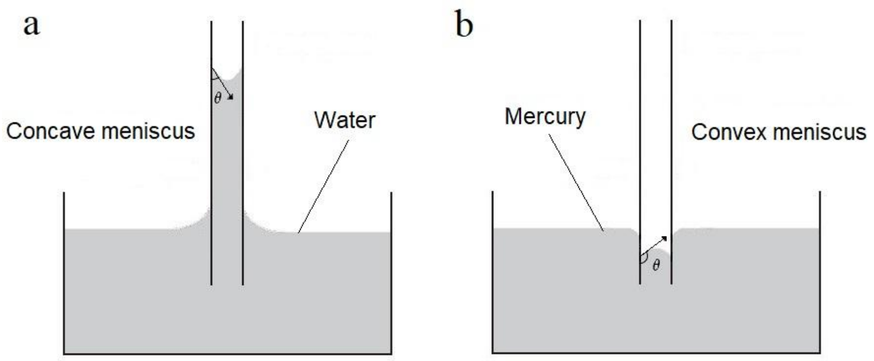

Figure 1.21: (a) Concave meniscus of water: observed when adhesive forces between the liquid molecules and the solid surface prevail over cohesive forces between the liquid molecules themselves ($\theta < 90^\circ$); (b) convex meniscus of mercury: occurs when cohesive forces between the liquid molecules exceed adhesive forces with the solid surface ($\theta > 90^\circ$) (Erbil, 2006).

In the theoretical analysis of the capillary rise phenomenon, a commonly adopted approximation involves neglecting the contribution of the weight of the

liquid contained within the crown of the concave meniscus, that is, the portion of liquid between the apex and the base of the meniscus. This simplification allows for a more straightforward treatment but inevitably introduces a significant approximation in the experimental estimation of surface tension. To account for the gravitational contribution of the meniscus crown, various correction methods have been proposed in the literature. Among the most notable is that introduced by Jurin, which assumes a hemispherical shape for the meniscus; subsequently, more refined approaches, such as that developed by Rayleigh (1899), sought to model the deviations of the meniscus profile from the ideal spherical shape more accurately.
When the radius of the capillary is no longer negligible, and the contact angle between the liquid and the wall differs from zero, the effect of gravity can no longer be ignored: the curvature of the meniscus is deformed, and the height of the liquid column can no longer be accurately described by simplified expressions. In such cases, a more precise description of the meniscus profile requires combining the equilibrium between hydrostatic pressure and surface tension (Liu et al., 2018). However, the resulting equation does not admit a general analytical solution and must instead be solved numerically.
Finally, qualitative criteria can be established to assess whether the effect of gravity on the meniscus shape can be neglected: generally, if the radius of curvature of the meniscus is significantly smaller than the square root of the capillary constant of the liquid (approximately at least an order of magnitude smaller), the influence of gravity can be considered negligible. Conversely, for larger capillaries, the gravitational effect must be considered to obtain an accurate estimate of the surface tension.

1.7 The role of surfactants in surface phenomena

An additional perspective on the interaction between liquids and surfaces arises when considering the mechanisms through which surface tension can be controlled. After analysing wetting and capillarity phenomena, it is natural to explore how the introduction of chemical substances enables the modification of the interfacial properties of a liquid. Among these substances, surfactants represent an extremely important class due to their ability to reduce surface tension and to significantly influence the macroscopic behaviour of liquid systems, both under static and dynamic conditions.
In scientific and technical literature (Myers, 2005; Rosen & Kunjappu, 2012), surfactants are sometimes referred to as wetting agents, detergents, soaps, emulsifiers, or dispersants, although the term surfactant remains the most widely used.

Surfactants are molecules characterised by an amphipathic structure, consisting of a hydrophilic (water-affine) part and a hydrophobic (apolar) chain. This distinctive structure gives them the ability to spontaneously position themselves at the interface between a liquid and a gas (such as water and air) or between two immiscible phases, thereby altering their physical properties. Once dissolved in a liquid, surfactants initially tend to diffuse throughout the bulk of the solution following a concentration gradient. However, due to their amphipathic nature, they exhibit a marked tendency to migrate towards interfaces, such as that between the liquid and air. Upon reaching the interface, these molecules become energetically "trapped" (Figure 1.22): their peculiar structure prevents a spontaneous return to the bulk of the liquid, as this would entail an increase in the system's free energy.

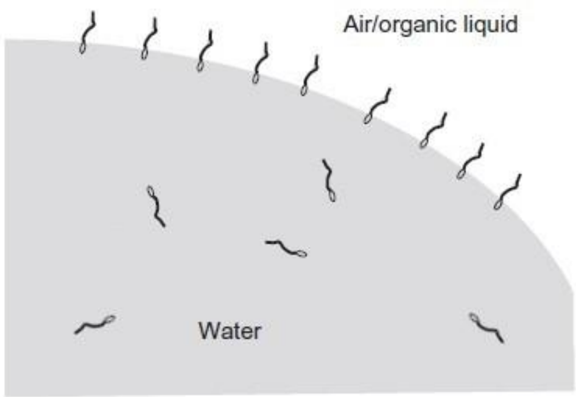

Figure 1.22: Arrangement of surfactants at the water-air interface. Thanks to their amphiphilic structure, the molecules spontaneously migrate towards the interface, where they become "trapped" in an energetically stable configuration: the hydrophilic heads remain immersed in the liquid, while the hydrophobic tails orient themselves towards the gaseous phase, reducing the system's free energy (Berthier, 2012).

This behaviour can be attributed to the principle of minimisation of interfacial free energy, whereby a system tends naturally towards a configuration that minimises its total energy. The presence of surfactants at the interface thus allows for a more energetically stable molecular arrangement: the hydrophobic tail orients towards the non-polar phase (such as air), whilst the hydrophilic head remains immersed in the liquid, thereby reducing the inhomogeneity between the two phases (Manikantan & Squires, 2020). In thermodynamic terms, this means that the free energy associated with the interface is lowered. The reduction in interfacial free energy thus translates directly into a decrease in surface tension, which represents the work required to expand the interfacial area between two phases. By making such expansion energetically less costly, surfactants facilitate phenomena such as dispersion, foam formation, and wetting.

In other words, the accumulation of surfactants at the interface is not only a consequence of their molecular structure but also a spontaneous response of the system to reach a lower energy state. This process renders the interface thermodynamically more stable while simultaneously modifying the macroscopic properties of the liquid. From a macroscopic perspective, the introduction of surfactants alters not only the surface tension between liquid and air but also that between liquid and solid, with direct repercussions on the contact angle and, thus, on the wetting regime according to Young's Law (Equation 1.41). The resulting effect is a change in the configuration of the liquid interface, which may lead to a transition from partial to complete wetting, depending on the molecular structure of the surfactant and the physicochemical nature of the solid surface (Shen et al., 2005).

Chapter 2

Computational modelling with SPH

What does it mean to observe a phenomenon? Where does direct experience end, and where does the need arise to construct representations to grasp what cannot be touched or seen? In physics, these questions are far from trivial: they become urgent whenever we confront fluid matter, with its silent metamorphoses, with transitions that elude intuition and can only be captured by the tools of thought.
We cannot look inside a drop to see the forces at work. We cannot pause a meniscus and measure, one by one, the pressures shaping it. Yet, in fluid physics, it is precisely there, in the interstitial space between one particle and another, between internal cohesion and adhesion to surfaces, between pressure and tension, that fundamental equilibriums are played out: invisible, yet decisive.

Experience teaches us that water wets, that a drop falls, that a liquid rises by capillarity. But physics demands more: it asks to explain, to describe, to predict. And when direct observation is insufficient, modelling intervenes: a bridge between reality and abstraction, between the observable world and the calculable one. It is in this transitional space that one of the silent revolutions of contemporary science takes shape: the use of computational simulations as tools for scientific exploration. Not mere graphical aids, but conceptual environments where theory and experience merge, where the laws of mechanics become visible dynamics, where every simulated instant is also a hypothesis in action, a visualisable interpretation of reality.
Computational fluid modelling is not merely an extension of calculation: it is a new way of seeing. It is a lens to observe the invisible, a form of dynamic reasoning, a means to manipulate conditions, vary parameters, and explore possible worlds. It is the concrete answer to a classical challenge of physics: how to represent what changes, what flows, what cannot be held still?

Within the educational context, these simulations prove to be extraordinary tools: no longer closed models, but open environments in which the student can explore, question, and hypothesise. Computational modelling fosters a new form of learning: active, visual, exploratory. It does not merely display results, but

reveals dynamics in real time, makes the process transparent, and invites discovery.
The Smoothed Particle Hydrodynamics (SPH) method stands at the heart of this revolution with a particular strength. Not only because it enables the simulation of fluid dynamic phenomena with high precision, but because it does so from a radically different perspective: a physics composed of mobile particles that attract, repel, and distribute themselves through space to generate shapes, pressures, and surfaces.

This chapter is an invitation to explore this frontier: to enter a world where classical fluid dynamics concepts are reinterpreted through the prism of particle-based computation, where theory takes shape in animations that narrate, step by step, the emergence of forms and forces. In this scenario, SPH is not merely a numerical method, but an epistemological key to accessing a physics that no longer just describes what happens but makes it experientially accessible in the very process of its becoming.

2.1 Simulations: epistemology, models, and dynamics of scientific exploration

The study of fluid dynamics constitutes a privileged domain for analysing how scientific knowledge is constructed, explored, and transformed in the presence of highly complex systems. Fluid phenomena, ranging from atmospheric motions to flows in microsystems, are governed by strongly non-linear equations, in which minimal variations in initial conditions, geometries, or physical parameters may generate turbulent, chaotic, and emergent behaviours that are difficult to predict. This intrinsic complexity has made evident, throughout the historical development of the discipline, the impossibility of relying on a single methodological approach, instead favouring an interdisciplinary articulation based on the integration of three complementary strands: the theoretical, the experimental, and the numerical–computational approaches.

The theoretical approach, beginning with the foundational contributions of Euler, Navier, and Stokes, provided the first formal framework for the description of fluid motion by translating fundamental physical principles, such as the conservation of mass, momentum, and energy, into continuous mathematical models. The Navier-Stokes equations represent, in principle, a complete and deterministic description of the system’s evolution. However, their analytical tractability is limited to highly idealised cases, characterised by simple geometries, steady conditions, and laminar regimes (Batchelor, 2000; Chorin & Marsden, 2000). As geometric or dynamical complexity increases, theoretical analysis encounters structural limitations that require simplifications which significantly reduce the transferability of the models to complex real-world systems.

Experimental investigation provides direct access to the behaviour of real flows and plays a crucial role in validating theoretical models. Nevertheless, the three-dimensional, turbulent, and often transient nature of fluid-dynamic phenomena makes measurements extremely challenging, particularly in the presence of complex geometries, microscopic scales, or multiphysical interactions (Pope, 2000). Despite advances in acquisition and visualisation techniques, experimentation remains constrained by high costs, a limited range of explorable configurations, and difficulties in control and reproducibility (Tropea et al., 2007). While these limitations do not undermine the epistemic value of empirical evidence, they highlight the need for alternative tools capable of exploring otherwise inaccessible scenarios.

It is within this context that numerical methods have progressively established themselves as the third pillar of scientific research. These methods enable approximate solutions to the differential equations describing continuous systems through the discretisation of space, time, and relevant physical quantities. The transformation of differential equations into algebraic systems solvable computationally makes it possible to address problems characterised by non-linearity, irregular domains, and realistic boundary conditions (Chapra & Canale, 2021). The multiplicity of numerical methods reflects the absence of a universally valid solution and underscores the adaptive and situated nature of scientific modelling.

For numerical methods to acquire operational and epistemic significance, they must be embedded within complex computational environments: simulations. Simulations do not coincide with the numerical methods they implement; rather, they represent the process through which such methods are employed to construct dynamic, controllable, and repeatable scenarios. As evolving modelling environments, simulations constitute an operational interface between theory and phenomenology, capable of generating data, exploring hypotheses, and rendering observable spatio-temporal dynamics that would otherwise remain inaccessible. They do not merely execute formalised models automatically, but entail modelling choices, computational trade-offs, and continuous interaction between mathematical representation, algorithmic implementation, and physical interpretation (Magnani & Bertolotti, 2017).
From an epistemological perspective, the simulation process unfolds through three interdependent phases: the construction of the formal model, its computational implementation, and the critical analysis of the results. At each of these stages, simulation transforms the initial model by exposing it to temporal

dynamics, emergent interactions, and systematic comparison with empirical evidence. In this sense, simulations do not function merely as verification tools, but as generative devices capable of producing unexpected behaviours, revealing emergent patterns, and triggering conceptual revisions. This exploratory dimension is particularly salient in the study of complex systems, in which global properties emerge from the local interaction of multiple components.

These characteristics also confer a central cognitive and educational value upon simulations. Simulations function as learning tools insofar as they make explicit the model-based nature of scientific knowledge, engaging users in an active process of model construction, manipulation, and revision. Through interaction with parameters, initial conditions, and dynamic representations, learners are placed in a position to confront their intuitions with the behaviour of the simulated system, thereby fostering processes of conceptual change and deeper understanding of emergent dynamics. Interactive visualisations and animations do not merely serve an illustrative function, but operate as genuine inferential tools that provide cognitive scaffolding (Podolefsky et al., 2013), supporting exploration, interpretation, and meaning-making.

2.1.1 The role of simulations in fluid mechanics

The behaviour of fluids represents one of the most pervasive yet least directly observable manifestations of nature. Unlike solids, fluids neither retain shape nor leave stable traces of their passage; their essence resides in motion, dynamic interactions, and invisible fields of pressure, velocity, and stress that govern their behaviour. To simulate a fluid therefore means to construct an artificial world in which such dynamics, though not directly observable, are rendered accessible through a rigorous reconstruction grounded in mathematical models and algorithmic implementations, endowed with explanatory and predictive power comparable to that of real experimentation.
In this sense, fluid-dynamic simulations do not merely display the behaviour of a fluid, but enact the profound interaction between physical models, mathematical structures, and computational realisations. Every simulation arises from a compromise between theoretical fidelity, idealisation of the real system, and computational constraints, thereby constituting not only a computational tool but also a conceptual construction device capable of linking the macroscopic level of phenomenological experience with the abstraction of equations. To speak of simulations in fluid mechanics therefore entails referring to a specific way of doing physics, in which the invisible takes form through computational language.

The numerical methods most traditionally employed in Computational Fluid Dynamics and Computational Solid Mechanics are mesh-based approaches,

particularly Finite Difference Methods (FDM) (LeVeque, 2007; Strikwerda, 2004) and Finite Element Methods (FEM) (Logan, 2022; Liu et al., 2022; Reddy, 2006). Both rely on the discretisation of the computational domain into nodes (Çengel & Cimbala, 2004), that is, points at which field quantities are evaluated, but they differ in conception and purpose. Grids, typical of FDM, are regular structures that prioritise efficiency in the computation of numerical derivatives and are particularly suited to simple domains and regular geometries. Meshes, characteristic of FEM, are more flexible structures composed of elements of variable shape and size, designed to faithfully follow the geometry of the physical domain even in the presence of curved surfaces or discontinuities. This distinction reflects different epistemic choices: grids embody a more abstract and computationally oriented view of the domain, whereas meshes operate as geometric mediations between the real physical system and its numerical representation.
Despite their theoretical robustness and wide applicability, mesh-based methods exhibit structural limitations related to discretisation quality and computational cost. Insufficient resolution compromises solution accuracy, whereas excessive refinement dramatically increases computational load. Moreover, the presence of a fixed lattice structure makes the treatment of free surfaces, moving interfaces, and large domain deformations particularly demanding, thereby motivating the development of alternative approaches.

From the 1970s onwards, mesh-free or particle methods progressively emerged, abandoning fixed grids in favour of representations based on coordinate systems and discrete sets of mobile entities. Within this framework, Eulerian approaches, based on a fixed reference frame (Smolianski, 2001; Price, 2006; Shadloo, 2013); Lagrangian approaches, in which computational elements follow the motion of the fluid while transporting its physical properties (Smolianski, 2001; Price, 2006; Shadloo, 2013) (Fig. 2.1); and mixed Eulerian-Lagrangian methods, seeking to combine geometric stability and deformative flexibility at the cost of increased computational complexity (Hirt et al., 1974; Shadloo, 2013), can be distinguished.

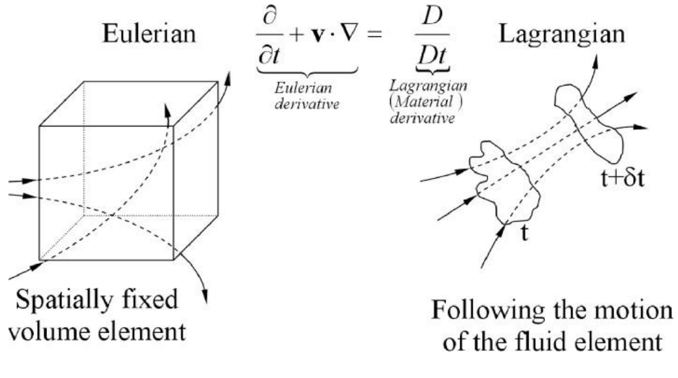

Figure 2.1: Eulerian and Lagrangian representation of fluid flow equations (Shadloo, 2013).

Among mesh-free methods, the Lagrangian approach proves particularly powerful for studying phenomena characterised by large deformations, moving interfaces, fragmentation, and multiphase flows. In these schemes, the computational domain is represented by mobile particles that interact locally according to interpolation laws based on smoothing functions, from whose interactions the global evolution of the system emerges. The Smoothed Particle Hydrodynamics (SPH) method constitutes a paradigmatic example of this approach, offering a flexible and adaptive theoretical and computational framework capable of overcoming many of the limitations inherent in traditional mesh-based methods (Gingold & Monaghan, 1977; Lucy, 1977).

The choice between mesh-based and mesh-free approaches is therefore not merely technical, but reflects a broader epistemological reflection on the type of representation of physical reality one intends to adopt. The former are more suitable for stationary domains and problems requiring precise control over local discretisation; the latter prove more effective in dynamic contexts, in which the topology of the domain evolves over time.

In all cases, fluid-dynamic simulations operate within a triangular dialogue with theory and experiment. Theory provides the laws and physical constraints, experiment offers the empirical reference for validation, and simulation acts as a bridge between mathematical abstraction and observation, generating predictions, suggesting new experiments, and triggering conceptual revisions. It is within this dynamic integration that the epistemic core of contemporary research in fluid mechanics is located.

2.2 The Smoothed Particle Hydrodynamics (SPH) method

Among the many developments in the field of numerical modelling of physical phenomena, the Smoothed Particle Hydrodynamics (SPH) method stands out as one of the most significant innovations for simulating complex fluid systems, particularly in contexts where conventional mesh-based methods prove inadequate or computationally prohibitive. Originally conceived within the framework of astrophysics (Lucy, 1977; Gingold & Monaghan, 1977), SPH has gradually expanded its scope, from free-surface fluid mechanics to transport modelling in porous media and numerous other domains in engineering and materials science. This broadening has been made possible by a fundamental structural analogy: in both the collective dynamics of celestial bodies and the behaviour of continuous fluids, the evolution of the system can be described using the same conservation equations of Newtonian hydrodynamics. This formal correspondence facilitated the methodological transfer from the astrophysical to the fluid dynamic context, significantly expanding the range of SPH applications.

In fact, the conceptual significance of the very name, *Smoothed Particle Hydrodynamics,* reflects its methodological essence: *smoothed* refers to the continuous interpolation of physical variables via kernel functions; *particle* highlights the discrete and Lagrangian nature of the approach, whereby particles follow the motion of the fluid; and *hydrodynamics* points to the original application domain, which today extends well beyond hydrodynamics to include solid mechanics, geophysics, biomechanics, and computational engineering.

One of the distinctive features of SPH is its natural capacity to handle complex geometries, moving interfaces, and evolving free surfaces, thereby avoiding the typical difficulties of grid-based methods, such as the need for remeshing or explicit treatments of discontinuities. This flexibility is further enhanced by the physical simplicity of the approach: the discretisation of the Navier-Stokes equations using SPH leads to a system of ordinary differential equations that take the form of Newton's second law for each particle.

In the simulations employed in this study (Battaglia et al., 2019), the SPH method has been implemented through a code developed entirely in FORTRAN (Kernighan & Plauger, 1976), a language historically well-established within the scientific community due to its efficiency in numerical processing and its optimised handling of large-scale simulations. The choice of FORTRAN reflects a methodological orientation aimed at robustness, computational reliability, and the maximisation of performance, critical aspects in simulation environments.

In the current landscape of numerical simulation, SPH thus emerges not merely as an effective computational technique, but as a genuine paradigm shift: an approach that places physical consistency, spatial adaptivity, and the ability to capture highly non-linear phenomena in geometrically complex domains at its core. The exact conservation of mass, momentum, and energy, ensured by the symmetry of interactions and the constancy of the particle number, confers an additional degree of robustness and reliability to the method.

2.2.1 Theoretical foundations of the SPH method

To fully grasp the functioning and potential of the SPH method, it is essential to examine the theoretical foundations upon which it is built.

SPH introduced a radical shift in how the discretisation of a continuous medium is conceived. Instead of relying on a static domain constrained by fixed lattice structures, the method proposes a dynamic and mobile representation free of

predefined connections, based on a discrete set of particles. These SPH particles embody a dual nature: on the one hand, they serve as computational elements; on the other, they represent portions of matter, following the fluid trajectories and carrying information about the system's physical properties.
The true conceptual strength of the method lies in its Lagrangian formulation. Within this framework, particles are not merely computational nodes, but entities endowed with fundamental physical properties (such as mass, position, velocity, and internal energy), which evolve over time under the influence of both local and non-local forces. Moving with the fluid, they form a system capable of reconstructing field variables through interpolation procedures based on smoothing functions (kernels), which operate over sets of neighbouring particles to provide continuous and regular local estimates. This structure renders the method intrinsically suited to the modelling of deformable domains, free surfaces, moving interfaces, and complex geometries, thereby significantly expanding its applicability beyond its original astrophysical context.
Another particularly distinctive feature of SPH is its inherent adaptivity, both in space and time. The absence of a computational grid enables the model's resolution to dynamically adapt to the local distribution of particles and to the smoothing length. When combined with individual or adaptive time-stepping strategies, the method proves capable of efficiently handling phenomena characterised by strongly varying spatial and temporal scales, such as shock waves, multiphase flows, hydrodynamic instabilities, and free surfaces (Springel, 2005; He et al., 2015). Moreover, the treatment of boundaries and interfaces, often problematic for grid-based methods, is greatly simplified in SPH.

Considering the above, it becomes evident that the conceptual structure of SPH rests on two fundamental pillars: on the one hand, the approximation of continuous functions through regularising kernels; on the other, the discretisation of the domain via a set of mobile particles.

2.2.1.1 Kernel approximation

One of the central aspects of the SPH method is the way physical quantities are approximated within the computational domain. Unlike mesh-based methods, in which field variables are computed at fixed grid nodes, SPH reconstructs these quantities via an interpolative approach based on moving particles. This necessitates the development of a mathematical strategy that allows the estimation of a continuous function at an arbitrary point from a discrete set of values associated with the surrounding particles.
This strategy is realised using a smoothing function, known as a kernel, which enables the approximation of physical variables to be reformulated as an integral representation. The transition from a continuous to a discrete formulation

represents one of the conceptual cornerstones of the SPH method, as it allows for a local estimation of physical properties even in the absence of a fixed grid structure. The following describes the mechanism by which this kernel-based approximation is constructed within the method.

The first conceptual step lies in the assumption that any continuous physical quantity can be approximated through a smoothing procedure, whereby the value of a function at a point is reconstructed as a weighted average of the values associated with neighbouring particles. The weight assigned to each particle depends on its distance from the reference particle: the closer the two particles are, the greater the contribution of the neighbouring particle to the local approximation (Monaghan, 1994).
The underlying idea of this strategy is that to accurately represent a physical property such as density, pressure, or velocity in each region of the domain, it is not necessary to know the exact value at every point, but rather to compute a controlled average over the values of nearby particles. This principle enables the replacement of the entire continuous representation of the function with a discrete sum of the contributions from neighbouring particles, each carrying its own material properties. In this way, the continuum is discretised into a set of moving points that represent a finite portion of the fluid.

It is important, however, to consider the specific use of the term "particle" in the SPH context. It does not denote an abstract point-like entity, but a computational unit associated with a finite volume and endowed with mass, position, velocity, and other thermophysical properties. The field quantities in the vicinity of a given particle are reconstructed from the characteristics of surrounding particles, but not from all of them: to ensure computational efficiency, the contribution is restricted to particles located within a certain distance, known as the smoothing radius. This radius is denoted by κh, where κ is a constant and h is the smoothing length. This interval defines the so-called support domain of the kernel function, i.e. the region of space in which the smoothing function assumes non-zero values.

The smoothing function thus plays a dual role: on the one hand, it mitigates potential discontinuities in the field, thereby enhancing the stability of the numerical simulation; on the other, it localises interactions, making them computationally tractable, by preventing the need to evaluate every possible interaction among all particles in the system. Furthermore, the choice of the kernel shape has a direct impact on the accuracy and stability of the approximation: its profile must ensure symmetry, regularity, and a monotonic decrease with distance, so that the most significant contributions come from regions that are genuinely close to the reference point.

At this stage, it is possible to formally introduce the function to be approximated, denoted as $f(x)$, where x represents the position in space at which the physical quantity of interest is to be estimated. This function may describe any field property, such as density, pressure, or temperature. The symbol x indicates a continuous vector variable that defines a generic point within the fluid domain (Benz, 1990).

For its conceptual formulation, we begin with a well-known integral identity from functional analysis, based on the Dirac delta function. The Dirac delta $\delta(|x - x'|)$ is a generalised function that selects the value of the integrand at the point $x = x'$, according to the relation:

$$f(x) = \int_{\Omega} f(x')\delta(|x - x'|)\, dx' \tag{2.1}$$

where Ω denotes the domain occupied by the fluid and $\delta(|x - x'|)$ is defined as:

$$\delta(|x - x'|) = \begin{cases} 1 & x = x' \\ 0 & x \neq x' \end{cases} \tag{2.2}$$

In the SPH method, identity (2.1) is reformulated by replacing the Dirac delta (Equation 2.2) with a kernel function $W(|x - x'|, h)$, which depends on the smoothing length h, a parameter that governs the spatial extent of the kernel's support. Unlike the Dirac delta, which is infinitely concentrated, the kernel has finite support and assumes non-zero values only within a limited region surrounding the point x. This substitution enables a regular and computationally manageable representation, endowing the SPH method with the ability to handle continuous functions in a stable and numerically efficient manner. In other words, the kernel function in SPH can be regarded as a regularised and smoothed version of the Dirac delta, hence the use of the term "kernel approximation" to denote that, insofar as the function W does not coincide with the Dirac delta, the integral representation remains an approximation of the actual value of the function.

By substituting the smoothing kernel function into the integral representation of $f(x)$ (Equation 2.1), we obtain:

$$f(x) = \int_{\Omega} f(x')W(|x - x'|, h)\, dx' \tag{2.3}$$

Within the SPH convention, Equation (2.3) is rewritten using angle brackets to emphasise that it does not represent the exact value of the function, but rather a smoothed approximation thereof (Fulk, 1994):

$$\langle f(x)\rangle = \int_{\Omega} f(x')W(|x - x'|, h)\, dx' \tag{2.4}$$

In this context, the angle brackets indicate a local weighted average around the point x, obtained through the kernel function W. This notation serves to distinguish between the original function $f(x)$ and its regularised representation, which is valid only to the degree of accuracy determined by the properties of the chosen kernel.

For the SPH method to be consistent, stable, and convergent, the kernel function must satisfy several fundamental conditions that ensure its mathematical and physical soundness (Liu & Liu, 2010).
The first is the normalisation condition, also referred to as the unity condition, which states:

$$\int_{\Omega} W(|x - x'|, h)\, dx' = 1 \tag{2.5}$$

Normalisation ensures that the kernel function behaves as a proper probability distribution centred at x. From both a physical and numerical standpoint, this condition guarantees that the weighted sum (or integral) of the contributions from neighbouring particles yields a consistent and conservative estimate of the quantity in question. Without proper normalisation, SPH approximations may systematically overestimate or underestimate field values.

The second condition is the Dirac delta property, which is observed in the limit as the smoothing length approaches zero:

$$\lim_{h \to 0} W(|x - x'|, h) = \delta(|x - x'|) \tag{2.6}$$

This condition requires that, as the smoothing length tends to zero, the kernel converges to a Dirac delta function, concentrating all contributions at the evaluation point. This ensures that the kernel approximation converges to the actual function, allowing increasingly precise and localised interpolation.

The third condition is the compact support requirement, where κ denotes a constant:

$$W(|x - x'|, h) = 0 \text{ when } |x - x'| > \kappa h \tag{2.7}$$

This implies that the kernel function is non-zero only within a finite radius, known as the support domain (or smoothing radius), and vanishes outside it. This property offers two main advantages. On one hand, it improves computational efficiency by limiting the number of particles involved in the calculations. On the other, it reflects the physical principle that significant interactions occur primarily between spatially proximate elements.

The fourth condition is that the kernel function must be even and spherically symmetric:

$$W(|x - x'|, h) = W(-|x - x'|, h) \tag{2.8}$$

Symmetry ensures that the interaction between two particles is reciprocal, i.e., the force or influence exerted by one particle on another is equal in magnitude and opposite in direction. This is essential for conserving physical quantities such as momentum and for preventing artificial directional bias in the distribution of forces.

In addition to these four principal conditions, the kernel function is typically required to be:

- smooth (continuously differentiable), to enable the approximation of derivatives of physical fields
- positive or non-negative within its support, to avoid unphysical behaviour (e.g., negative densities or energies)
- monotonically decreasing with distance, so that nearer particles exert a stronger influence, reflecting stronger physical interactions

The SPH literature consistently highlights that kernel-based approximations can, under appropriate conditions, achieve second-order accuracy. Foundational studies such as those by Monaghan (1982, 1992), Hernquist and Katz (1989), and Fulk (1994) demonstrate that the interpolation of physical quantities using smoothing functions ensures high numerical accuracy, provided that essential structural properties of the kernel are satisfied. These include normalisation, symmetry, compact support, and consistency in the Dirac delta limit, i.e., the ability of the kernel to approximate a delta function as the smoothing length tends to zero.
However, such accuracy is not guaranteed inherently: it critically depends on the mathematical properties of the chosen kernel. In particular, the ability of SPH to yield reliable numerical estimates is tied to the notion of consistency, inherited from classical numerical methods such as finite differences and finite elements. A formulation is considered consistent if it can exactly reproduce polynomials up to a certain order; for instance, reproducing a constant function implies zero-order consistency (C^0), while the exact reproduction of a linear or quadratic

polynomial corresponds to first (C^1) or second order (C^2) consistency, respectively. In the SPH framework, consistency refers to the kernel approximation's ability to faithfully reproduce the properties of the original continuous function. In other words, for the SPH approximation to converge to the exact solution, the smoothing function must meet specific polynomial reproducibility requirements, which in turn ensure the accuracy of interpolation and the physical and mathematical validity of the simulation. Should any of the kernel's fundamental conditions be violated, consistency deteriorates, thereby compromising both the numerical approximation and the overall stability of the model.

For this reason, the choice of kernel function is never a peripheral detail; rather, it constitutes a central element in the design of any SPH simulation and must be guided by rigorous theoretical criteria that ensure consistency and, consequently, method convergence.

While the smoothing function constitutes the core of continuous interpolation, the other indispensable component of the SPH method is the discretisation of the domain into a set of mobile particles. It is through these discrete entities, endowed with mass and physical properties, that the integral approximation is rendered computationally tractable.

2.2.1.2 Particle approximation

Once the kernel approximation has been established to interpolate the physical properties of a continuous medium, the next step in the SPH method involves the particle approximation. At this stage, the problem domain is represented by a finite set of particles, which serve as the discrete nodes through which field quantities are estimated. These particles, which may be arbitrarily distributed in space, act as carriers of information: each is associated with physical properties such as mass, density, volume, velocity, energy, or temperature.

Particles can be initially positioned using mesh-free generation techniques or derived from a pre-existing spatial discretisation. Regardless of the method employed for their initial placement, they represent the current state of the physical system under investigation and are used not only for interpolating field quantities, but also to physically represent the material itself.

The infinitesimal volume dx' present in the integral expressions is replaced in the particle approximation by a finite volume associated with each particle. This volume, denoted V_i, represents a portion of the domain centred around particle i, and is not necessarily tied to any specific or regular geometric shape. In the most common formulations, the ratio m_i/ρ_i is used to represent the effective volume of the particle, where m_i and ρ_i denote the mass and density of the particle, respectively (Liu & Zhang, 2019). Once the domain has been described by a finite number of particles, the continuous integral defined by the kernel approximation (Equation 2.4) is discretised into a weighted summation over the neighbours of the particle of interest, as follows:

$$\begin{aligned} f(x) &\cong \sum_{j=1}^{N} f(x_j) W(x - x_j, h)\, \Delta V_j \\ &= \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(x_j) W(x - x_j, h) \end{aligned} \tag{2.9}$$

where N denotes the total number of particles located within the influence domain of the particle at position x, that is, all particles within the support domain defined by a maximum distance equal to the smoothing length h multiplied by a scalar constant κ (Fig. 2.2) (Shen et al., 2023).

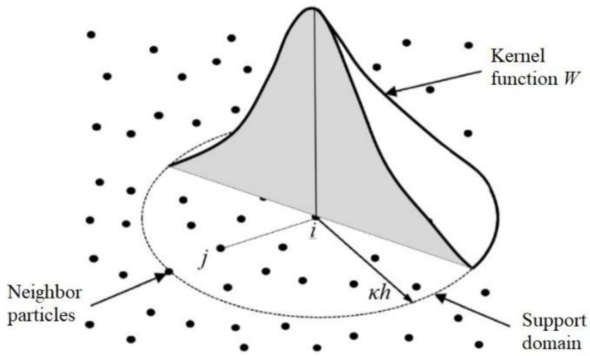

Figure 2.2: Particle approximation. The smoothing function W is employed to approximate the field variables at particle i through a weighted sum of the contributions from particles j located within the support domain, bounded by a maximum distance equal to κh (Shen et al., 2023).

The particle approximation for a function at the i-th particle can therefore be written as:

$$\langle f(x_i) \rangle = \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(x_j) W_{ij} \tag{2.10}$$

The procedure of summing the contributions from neighbouring particles is known as the particle approximation. According to this approach, the value of a function at a given particle is estimated as a weighted average of the function values taken at particles located within its support domain, using the smoothing kernel values as weights (Liu & Liu, 2003).

The same principle applies to the spatial derivatives of physical quantities. In such cases, the derivative values are estimated through a weighted sum, where the weights are given by the gradient of the kernel with respect to the positions of neighbouring particles. This technique enables the conversion of the continuous approximation of a function and its derivatives into a discrete form, expressed through simple summations over particles.

However, in the transition from the continuous approximation, based on regularised integrals, to the discrete approximation, based on sums over a finite number of particles, certain limitations arise due to particle inconsistency. This phenomenon, commonly referred to as particle inconsistency, may introduce systematic errors in the estimation of field quantities, even in apparently regular regions. Theoretically, for a discrete SPH function to exactly reproduce a constant or a first-order polynomial, the particle distribution within the support domain must be both balanced and complete. In realistic scenarios, however, this ideal condition is often not fulfilled (Fraga Filho & Chacaltana, 2016).
A typical example is that of particles located near the computational domain boundary, as shown in Figure 2.3a. In this configuration, the support domain of the kernel function, which should ideally be centred on the particle and include a symmetric neighbourhood of particles, is truncated due to intersection with the physical boundary of the domain. Therefore, the discrete summation loses the symmetry required to satisfy the conditions of normalisation and the reproduction of simple functions, thereby compromising zero-order (constant) and first-order (linear) consistency.
A similar issue arises when particles lie within the interior of the domain but are irregularly distributed, resulting in local inconsistency (Figure 2.3b). Although the kernel function is, by construction, regular and symmetric, it is applied over a set of particles that may not guarantee a uniform or balanced coverage of the support domain. As a result, the summation may fail to return the correct value for a constant or linear function, thereby introducing systematic interpolation errors.

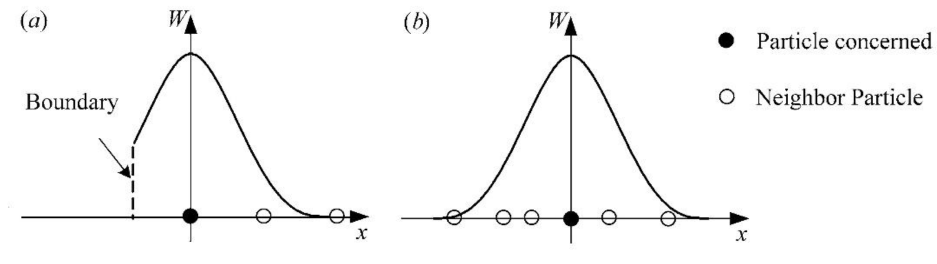

Figure 2.3: SPH particle approximations in one-dimensional configurations. (a) Case of a particle whose support domain is partially truncated due to proximity to the boundary of the computational domain; (b) case of a particle surrounded by an irregular distribution of neighbours within its support domain, which compromises the quality of the approximation (Fraga Filho & Chacaltana, 2016).

It is important to emphasise that these discrete inconsistencies are not negligible: they directly impair the accuracy of the simulation and the method's ability to converge toward the correct solution as the model is refined. To mitigate such effects, various correction techniques have been developed that modify the smoothing function on a per-particle basis, adapting it to the actual distribution of neighbours (Chen et al., 1999). While mathematically effective, these methods can introduce undesired side effects, such as negative kernel values, violations of symmetry, and numerical instabilities, especially in hydrodynamic models.

The particle approximation therefore represents one of the key steps that render the SPH method mesh-free, i.e., independent of an underlying grid for numerical integration. Nevertheless, this very approximation is also one of the main sources of numerical error and instability. In fluid dynamics, however, the particle approximation proves particularly effective, primarily due to the natural inclusion of mass and density, quantities essential for describing flows, directly in the governing equations. This also explains why SPH is widely applied in dynamic fluid flow problems, whereas in solid mechanics it requires more sophisticated treatments, such as the construction of shape functions or the adoption of weak formulations to ensure accurate representation of mechanical behaviour (Brownlee et al., 2007).

This delicate interplay between particle structure, numerical accuracy, and fundamental physical requirements highlights the crucial role of the smoothing function. Its construction is not merely a technical detail, but a determinant step in ensuring consistency, stability, and accuracy within the SPH method.

2.2.1.3 Construction of the Smoothing Function

The construction of the smoothing function is one of the foundational pillars of the SPH method, as it directly determines the method's ability to correctly interpolate physical quantities distributed in space. This function, also known as the kernel, plays a crucial role in computing the weighted average of properties between particles, regulating the relative influence of each neighbouring particle on the central one. From a theoretical perspective, a well-constructed kernel must satisfy several fundamental conditions to ensure the reliability of the simulation: normalisation, to guarantee the conservation of physical quantities; symmetry, to respect the reciprocity of interactions; compact support, which limits influence to a finite neighbourhood in order to contain computational cost; and finally, convergence to the Dirac delta function in the limit of vanishing smoothing length, a condition that ensures the recovery of the original function.

Over the course of SPH development, many different kernels have been proposed, each with specific properties and levels of suitability for physical contexts. The initially adopted kernels, such as the Gaussian function and the cubic spline (Monaghan, 1985; Monaghan & Lattanzio, 1985), display regular and continuous behaviour but suffer from numerical instabilities, especially near boundaries or in the presence of non-uniformly distributed particles. Such issues may lead to systematic errors and local instabilities, undermining both interpolation accuracy and the conservation of physical quantities.

To address these challenges, the need arose to develop more robust and stable kernels. Among them, the Wendland family of kernels (Wendland, 1995) has emerged as one of the most effective solutions, thanks to their excellent numerical properties and their ability to mitigate several major sources of SPH error. Wendland kernels are positive definite, continuously differentiable to a high order, symmetric, and possess compact support, specifically designed for use in mesh-free methods. One of their most important features is the absence of negative values, which prevents the emergence of spurious pressures and the generation of unphysical values (such as negative densities) within the computational domain.

From the standpoint of stability, one of the major strengths of Wendland kernels is their ability to eliminate or significantly reduce pairing instability, a pathological numerical behaviour in which particles tend to clump into close pairs, thereby degrading the interpolation (Macià et al., 2011). This issue is common with more traditional kernels, such as the cubic spline, and can severely affect the regularity of the particle distribution. In contrast, Wendland kernels produce a more effective short-range repulsive force, maintaining a good inter-particle spacing even under highly dynamic conditions.

Furthermore, these kernels are distinguished by their greater robustness near boundaries and in regions where the particle distribution is non-uniform, situations frequently encountered in free-surface flows, multiphase interfaces, or in the presence of discontinuities. Systematic studies, such as that of Dehnen and Aly (2012), have compared various kernel types and shown that Wendland kernels offer an optimal compromise between accuracy and numerical stability. They are particularly well suited to simulations requiring high precision in regions of transition or strong deformation. Their computational robustness thus makes them an ideal choice even for large-scale particle simulations, where small local errors may accumulate and significantly affect the overall result.

Finally, it is essential to note that the choice of kernel, though often considered a minor technical detail, has, in fact, a decisive impact on numerical consistency, the conservation of physical quantities (mass, momentum, energy), and the predictive capacity of the simulation. For this reason, the adoption of Wendland kernels in the simulations considered here is not arbitrary, but the result of a deliberate decision aimed at ensuring numerically regular, stable, and reliable behaviour, even under complex or transient conditions (Battaglia & Fazio, 2019).

2.2.2 Navier-Stokes equations in Lagrangian form

The Navier-Stokes equations constitute the mathematical core of fluid dynamics, as they describe the evolution of fluid motion under the influence of internal and external forces. They are directly derived from the conservation laws of mass, momentum, and energy, and enable the modelling of a wide variety of fluid-dynamic phenomena, both in theoretical and applied contexts. These laws can be formulated through two different descriptive approaches: the Eulerian framework, in which the evolution of physical fields is observed at fixed spatial locations, and the Lagrangian framework, in which the motion of the fluid is tracked by following the trajectories of the constituent particles.

Within the context of the SPH method, which is based on a discrete representation of the domain via moving particles, the Lagrangian formalism arises naturally. This not only allows for the direct tracking of the dynamics of each fluid particle but also enables the fundamental equations to be reformulated as a set of partial differential equations that describe the temporal evolution of physical properties along material trajectories.
The Navier-Stokes equations, when expressed in Lagrangian form, thus constitute the theoretical framework within which the dynamics of the SPH-simulated system unfold (Chung, 2002; Wendt, 2008). For the sake of clarity, the present discussion will focus on the first two fundamental equations: the conservation of mass and the conservation of momentum, which form the core of the SPH model employed in this study. While an equation governing the conservation of energy also exists, it will not be addressed in detail here, as no thermodynamic contribution is considered in the simulations presented. Parameters such as temperature, and more generally the internal energy of the system, do not influence the evolution of the modelled fluid, rendering the inclusion of the energy equation unnecessary for the purposes of the current analysis.

To fully understand how the SPH method reproduces the behaviour of fluids, it is helpful to begin with the first of the fundamental equations: the continuity equation, which expresses the conservation of mass in a fluid system.

2.2.2.1 Continuity equation

The continuity equation, also known as the equation for mass conservation in Lagrangian form, expresses one of the fundamental laws of fluid physics: the conservation of mass. It describes how the density of a fluid evolves over time as the material particles move. In other words, when the fluid is observed from the viewpoint of a particle moving with it, the continuity equation ensures that mass is neither created nor destroyed along its trajectory. This formulation is particularly well suited to the mesh-free SPH approach, in which particles carry mass and density, and their motion through the computational domain corresponds directly to the fluid flow. The SPH implementation of the continuity equation plays a central role in ensuring the correct temporal evolution of the fluid density, an essential element in the determination of pressure forces and, by extension, the entire system dynamics.

In accordance with the above, the SPH discretisation of the continuity equation is given as follows (Monaghan, 2005):

$$\frac{d\rho}{dt} = -\rho\nabla \cdot \vec{v} \tag{2.11}$$

where ρ is the fluid density and $\vec{v}$ is the velocity field. This equation describes how the density of a fluid particle varies over time due to the divergence of the local velocity field.

To employ the continuity equation within an SPH simulation, it is necessary to reformulate the expression defined in equation (2.11) into a discrete form compatible with the particle-based nature of the method. At this stage, both fundamental approximations on which SPH is built come into play: the kernel approximation and the particle approximation. The former allows any physical quantity to be expressed as a weighted average of the values assumed in the vicinity of the particle under consideration, by means of a smoothing function with compact support. Each particle contributes locally to the evolution of the density depending on its properties and its distance from the central particle, according to the weight assigned by the kernel. The second approximation replaces the continuous integral with a discrete summation, in which particles act as mobile sampling points, each endowed with its own mass and density.
In this manner, the temporal variation of density is numerically reconstructed as a summation that reflects the interaction with the surrounding neighbourhood. The resulting discrete form constitutes one of the essential components in the construction of a consistent and stable SPH model.

By applying these approximations, the time derivative of the density for the i-th particle takes the form:

$$\frac{d\rho_i}{dt} = -\rho_i \sum_{j=1}^{N} \frac{m_j}{\rho_j} v_j \nabla_i W_{ij} = \sum_{j=1}^{N} m_j v_{ij} \nabla_i W_{ij} \tag{2.12}$$

where $v_{ij} = v_i - v_j$ represents the relative velocity between particles i and j, m_j is the mass of particle j, and $\nabla_i W_{ij}$ is the gradient of the kernel function with respect to the position of particle i.
This formulation reflects the fact that the density in a region of the fluid increases (or decreases) as fluid particles approach (or recede from) one another.

Having addressed the conservation of mass, it is natural to turn to the second key component of fluid dynamics: the momentum equation, which expresses the force balance and forms the core of the Navier-Stokes formulation within the SPH framework.

2.2.2.2 Momentum equation

The momentum equation, also known as the second Navier-Stokes equation, provides a mathematical formulation of the principle of conservation of momentum. It expresses the balance between the forces acting on a fluid element, specifically, pressure forces, viscous forces, and external forces, and the resulting variation in its velocity. In the Lagrangian formulation of the SPH method, this equation acquires a particularly intuitive form, as each particle represents a material element of the fluid directly subjected to the direct force, which in turn update its dynamical state over time. One key advantage of this approach is that there is no need to explicitly compute the convective transport of physical quantities, since the motion of the particles embedded in the discretisation inherently captures this effect. However, the formulation and discretisation of pressure and viscous forces require particular care to ensure numerical stability and to avoid unphysical effects such as particle interpenetration or the emergence of spurious oscillations. A detailed analysis of the momentum equation thus enables a deeper understanding of the mechanisms by which the SPH method describes the dynamical evolution of the fluid, as well as the strategies employed to correct or mitigate its limitations.

The momentum equation in a Lagrangian reference frame can be written as (Monaghan, 2005):

$$\frac{D\vec{v}(t)}{Dt} = -\frac{\nabla \mathrm{P}(t)}{\rho} + \nabla \cdot \mathbf{T} + g \tag{2.13}$$

where P denotes the absolute pressure and T the viscous stress tensor, g represents the gravitational acceleration, and ρ and $\vec{v}$ retain the meanings already introduced in the context of the continuity equation.
Equation (2.13) represents Newton's second law applied to a fluid, i.e., the balance between the forces acting on a fluid volume element and its resulting acceleration. On the left-hand side appears the material derivative (also called Lagrangian) of the velocity, which describes the acceleration experienced by the fluid particle along its trajectory. On the right-hand side, we find the contributions of the forces responsible for such acceleration:

- the term $-\nabla P/\rho$ accounts for the pressure gradient force, which drives the fluid from regions of high pressure to regions of lower pressure
- the term $\nabla \cdot \mathbf{T}$ represents internal viscous forces, responsible for the transfer of momentum between fluid layers moving at different velocities

To implement these equations within a computational model, it is necessary to convert them into a discrete form compatible with a particle-based representation of the fluid. As in the case of the continuity equation, the transition from the differential description to a discrete formulation, where spatial and temporal derivatives are evaluated through weighted summations over neighbouring particles, requires the use of the kernel and particle approximations, which constitute the conceptual pillars of the SPH method.

The discrete form of the momentum conservation equation is thus expressed as:

$$\frac{dv_i}{dt} = -\sum_{j=1}^{N} m_j \left(\frac{P_j}{{\rho_j}^2} + \frac{P_i}{{\rho_i}^2}\right) \nabla_i W_{ij} + 2\eta \sum_{j=1}^{N} m_j \frac{(v_i - v_j)}{\rho_i \rho_j (x_i - x_j)^2} (x_i - x_j) \nabla_i W_{ij} + g \tag{2.14}$$

where η denotes the dynamic viscosity.
In Equation (2.14), the pressure gradient term, the first term on the right-hand side, was introduced by Monaghan (1992), while the second term, describing the effects of viscosity, was proposed by Morris et al. (1997).

Having introduced the discrete formulation of momentum conservation as expressed in Equation (2.14), it is now appropriate to examine its individual components more closely. This equation encapsulates several physically meaningful contributions, each of which warrants specific discussion to understand its role in the simulated fluid dynamics. This step is essential for grasping how each term influences the system's evolution and for appreciating the delicate balance between numerical accuracy and computational stability that characterises the SPH method.

A particularly critical aspect in the transition from the continuous to the discrete formulation of the Navier-Stokes equations concerns the treatment of viscosity. In Equation (2.14), the parameter η represents the dynamic viscosity, an intrinsic physical property of the fluid that quantifies its resistance to internal flow induced by shear forces. In the continuous formulation, this parameter appears within the viscous stress tensor and contributes to the physical dissipation of mechanical energy in the form of heat.
However, in SPH-based simulations, the explicit inclusion of the viscous tensor can be computationally expensive and potentially unstable, particularly in the presence of strong discontinuities. To overcome these challenges, a commonly adopted strategy is to introduce an artificial viscosity, designed not to faithfully reproduce a physical phenomenon but rather to act as a numerical stabilisation tool. This artificial viscosity is introduced to damp non-physical numerical oscillations, prevent instabilities in regions with strong velocity gradients, and simulate effective dissipation in scenarios where real viscosity would be negligible relative to the adopted discretisation scale.
One of the most widely known formulations of artificial viscosity is that proposed by VonNeumann and Richtmyer (1950), later adapted to the SPH context by Monaghan (1992). It typically comprises two components: a linear term, conceptually reminiscent of dynamic viscosity, and a quadratic term designed to absorb discontinuities in regions of flow convergence, such as those occurring at shock fronts or moving interfaces. In particular, the quadratic term is a function of the divergence of the velocity field, allowing the dissipation to be intensified in areas undergoing rapid compression, thereby improving the numerical behaviour of the system.

It is important to highlight that, although the parameter η is often treated as constant, more advanced simulations allow for its local modulation, depending on the dynamic conditions of the fluid, to strike an optimal balance between physical fidelity and numerical stability.

Within the SPH framework adopted in the simulations employed in this study, the fluid is treated as weakly compressible. This assumption represents a compromise between the ideal physical incompressibility of real liquids and the computational necessity of avoiding the direct integration of the Poisson equation for pressure, which would require a numerically expensive implicit resolution. Methods based on strictly incompressible constraints, such as the Moving Particle Semi-implicit (MPS) method (Koshizuka et al., 1998), enforce constant density through an implicit system, but become complex and less efficient in the presence of large deformations or free surfaces.

In the weakly compressible SPH approach, pressure is not solved as an independent variable through differential constraints but is instead computed directly from the local density of each particle via an equation of state (Monaghan, 1994; Van Liedekerke et al., 2013). This approach, also known as the artificial compressibility technique, makes it possible to simulate flows that are theoretically incompressible by introducing an artificial compressive response of the fluid.

A modified form of the equation of state proposed by Cole (frequently misattributed as the Tait equation) (Cole, 1948) is adopted, which assumes the following form:

$$P = B\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right] = \frac{\rho_0 c^2}{7}\left[\left(\frac{\rho}{\rho_0}\right)^{7} - 1\right] \tag{2.15}$$

where ρ is the local particle density, ρ_0 is the reference density (initial density), c is the speed of sound in the medium, and $B = \rho_0 c^2/\gamma$ represents the bulk modulus of the medium. The exponent $\gamma = 7$ is an empirical value commonly chosen to model weakly compressible liquids such as water (Colagrossi & Landrini, 2003).

The inclusion of the "-1" term is meant to eliminate the static pressure contribution when $\rho = \rho_0$, thereby enhancing numerical stability near free surfaces.

The adoption of a quasi-incompressible equation of state in Equation (2.14) enables the SPH method to efficiently simulate complex liquid flows, maintaining a satisfactory balance between physical accuracy and computational cost. The main advantage lies in its numerical flexibility: pressure is computed locally from particle density, allowing a natural evolution of the fluid configuration and a direct treatment of density discontinuities, such as those occurring in cavitation or jet breakup phenomena. Moreover, since the density remains close to the initial value, the resulting behaviour approximates that of incompressible fluids, yet with significantly reduced computational times compared to implicit integration methods.

To incorporate the effects of surface tension and fluid-solid interactions into the simulation, Equation (2.14) was modified by explicitly introducing particle-

particle interaction terms, in accordance with the formulations proposed by Tartakovsky and Meakin (2005, 2006).

$$\frac{dv_i}{dt} = -\sum_{j=1}^{N} m_j \left(\frac{P_j}{{\rho_j}^2} + \frac{P_i}{{\rho_i}^2}\right) \nabla_i W_{ij} + 2\eta \sum_{j=1}^{N} m_j \frac{(v_i - v_j)}{\rho_i \rho_j (x_i - x_j)^2} (x_i - x_j) \nabla_i W_{ij} + g + \frac{F_i}{m_i} \quad (2.16)$$

The force F_i acting on particle i is defined as the resultant of the interactions with all surrounding particles. In the simulations considered in this work (Battaglia et al., 2021), such a contribution is referred to as a molecular-like force:

$$F_{ij} = \begin{cases} S_{ij} cos\left(\frac{3\pi}{4h}\left|x_j - x_i\right|\right) & \left|x_j - x_i\right| \leq 2h \\ 0 & \left|x_j - x_i\right| > 2h \end{cases} \quad (2.17)$$

this force was modelled by assigning specific values to the interaction strength between each pair of particles i and j, denoted as S_{ij}, and defining $\left|x_j - x_i\right|$ as the distance between the two particles (Tartakovsky & Meakin, 2005).

The overall force resulting from interparticle interactions is obtained as the sum of the contributions from the particles located within the support domain of each particle i:

$$F_i = \sum_j F_{ij} \quad (2.18)$$

Since the force acting between two particles satisfies the antisymmetric condition $F_{ij} = -F_{ji}$, conservation of momentum within the system is ensured. Although the exact form of the interaction function is not critical to the qualitative success of the simulation, it is essential that it exhibit short-range repulsion and long-range attraction, to correctly reproduce the cohesive and exclusion behaviours characteristic of real fluids.

For reasons of computational efficiency, the interaction force was defined to be zero beyond a distance of $2h$, a choice that significantly reduces the number of particle pairs to be considered compared to the original approach of Tartakovsky and Meakin (2005, 2006), who set the interaction radius to h. In this

configuration, the force behaves repulsively for distances less than $2/3\,h$, attractively in the range between $2/3\,h$ and $2h$, and vanishes above that threshold (Battaglia et al., 2021).
It is important to emphasise that, aside from local density and configuration fluctuations, the net contribution of these interactions is negligible within the bulk of the fluid. Their effect becomes significant only near the fluid's free surface and at fluid-fluid and fluid-solid interfaces. Near such interfaces, the molecular-like force acts along the density gradient, generating a net effect that can be interpreted as surface tension.

In the case of interactions between fluid particles and those belonging to solid boundaries, the short-range repulsive component of the molecular-like force plays a crucial role in preventing fluid particles from penetrating the solid domain. This aspect is also described by Monaghan (1994) in the context of Lennard-Jones type interactions. The particles representing the solid material are positioned and kept fixed along a thin band surrounding the surface of the solid body, thus forming a virtual barrier. When a fluid particle approaches this zone, the repulsive force acts to deflect its trajectory, preventing it from crossing the imposed physical boundary. In certain situations, however, it may occur that a fluid particle temporarily surpasses the interaction region (Tartakovsky & Meakin, 2006).
A comprehensive understanding of boundary treatment requires an examination of how boundaries are typically represented in simulations.

2.2.3 Boundary treatment techniques

One of the main challenges in the Smoothed Particle Hydrodynamics method lies in the treatment of boundary conditions, particularly in the vicinity of solid surfaces or fluid-fluid interfaces. As a grid-free Lagrangian method, SPH lacks a natural definition of the domain boundary. The origin of the problem lies in the truncation of the kernel integral due to the absence of particles beyond the physical domain, a condition which compromises the symmetry of the kernel support and reduces the accuracy of the estimation of field variables such as density, pressure, or velocity. Particles located near the edge of the domain, in fact, receive contributions only from the interior, leading to approximation errors and numerical instabilities (Fraga Filho, 2019).

The earliest developments of the SPH method in fluid dynamics largely disregarded this issue, adopting extremely simplified boundaries or, in some cases, no boundary conditions at all. In hydrodynamic models without deviatoric stresses, the boundary was implicitly treated as a zero-pressure region, whereas in solid models with material resistance, all components of the surface stress were nullified. This apparent simplification stemmed from the fact that, in the

kernel summations, particles missing at the boundary were treated as if they exerted no contribution, which, in certain cases, led to approximately correct results. However, such solutions were severely limited considering the actual complexity of the problem, causing significant difficulties in the accurate computation of density, which was often severely underestimated near the boundaries.
The first systematic attempt to address boundary conditions in a more rigorous manner was made by Campbell (1989), who re-examined the integral formulation of the SPH equations, introducing boundary terms through integration by parts. Similarly, Takeda et al. (1994) proposed specific treatments for fluid flows, eventually leading to a generalisation of techniques based on ghost particles. Nonetheless, these solutions remained strongly dependent on the nominal spacing between particles and did not foresee any explicit or systematic handling of complex boundaries.

To address the problem of kernel symmetry loss and boundary errors in a more structured way, most modern SPH implementations have introduced the use of virtual or artificial particles (also known as ghost, mirror, or dummy particles). These particles, placed along or outside the physical boundary, are designed to restore kernel symmetry and, in many cases, to generate artificial repulsive forces inspired by molecular interaction models. For instance, Monaghan (1994) introduced ghost particles that produce a highly repulsive force to prevent the non-physical penetration of fluid into the solid. Randles and Libersky (1996) instead developed an interpolative approach based on assigning constant values to ghost particles to improve the consistency of estimations near boundaries. A significant evolution was proposed by Liu et al. (2002), who distinguished between two types of virtual particles: type I, placed exactly on the boundary and responsible for the repulsive force; and type II, obtained by mirroring internal real particles, with the aim of improving the accuracy of approximations in the boundary region.
However, despite their widespread adoption, these techniques have raised numerous criticisms, as many rely on mechanisms lacking physical justification at the continuum scale. The artificial forces employed, though computationally useful, are often inspired by molecular interactions that cannot be justified within the framework of continuum mechanics. This has led an increasing segment of the scientific community to develop new strategies that are more consistent with physical laws and do not make use of fictitious particles. Among these are the semi-analytical boundary conditions (Ferrand et al., 2012; Leroy et al., 2014) and the integral boundary formulations (Macià et al., 2012).

The treatment of boundaries in SPH has undergone profound evolution over the years: from an initially simplified and neglected approach, it progressed to computationally sophisticated but theoretically questionable techniques,

eventually reaching an intense phase of research focused on developing physically grounded methodologies capable of respecting the principles of continuum mechanics while ensuring numerical accuracy and stability in simulations (Liu & Li, 2016).
Considering the numerous solutions proposed in the literature, often heterogeneous in their theoretical foundations and degree of adherence to the principles of continuum mechanics, it becomes evident that the choice of boundary treatment must be calibrated to the specific objectives of the simulation and the expected behaviour of the modelled physical system.

Having established the theoretical and structural framework of the SPH method, we can now proceed to study the numerical simulations employed in this work (Battaglia et al., 2019).

2.3 SPH application to model observed phenomena

Within the framework of this work, two-dimensional numerical simulations were chosen to assess the robustness and consistency of the implemented SPH model, with particular focus on phenomena such as surface tension and capillary processes (Battaglia et al., 2019).
The simulated configurations were inspired by well-known physical phenomena encountered in experimental contexts and were chosen to allow for a direct comparison between observed dynamics and those reproduced numerically. The primary goal of the selected simulations is twofold: on the one hand, to validate the accuracy of the adopted formulation in replicating real phenomena; on the other, to explore the potential of the SPH method in modelling complex fluid dynamic processes involving boundaries and cohesive/adhesive forces.
Surface tension modelling was treated within the Lagrangian formalism as a volumetric force distributed near the free surface of the fluid, in line with widely adopted approaches in contemporary literature (Zhang, 2010). To ensure a correct representation of physical quantities, the authors carried out a careful preliminary process to defining and calibrating the system's numerical parameters. To this end, each application case was preceded by a series of test simulations aimed at identifying a parameter configuration capable of balancing physical accuracy with computational feasibility.

Among the constitutive elements of the model, the choice of the smoothing function used to interpolate physical quantities plays a central role. In the simulations employed, the authors utilised the Wendland kernel, as it is known for its robustness against tensile instabilities and its ability to generate well-conditioned matrices in boundary regions. These properties make it particularly

suitable for simulations involving surface effects and rigid boundaries, as in our case.
Temporal integration has been managed through a second-order variant of the leapfrog scheme, following the formulation proposed by Monaghan (1992, 2005). This method is widely used in SPH models because it provides a sound compromise between stability, energy conservation, and implementation simplicity. Its symmetric, time-centred structure makes it especially well-suited to systems governed by conservative forces, ensuring a smooth evolution of particle motion even in long-duration simulations.

The first step in configuring the system involves assigning the fundamental geometric parameters: the smoothing length h and the initial particle spacing S_{EP}. In all the simulations reported, the smoothing length h was chosen to be of the order of magnitude of $2 \cdot S_{EP}$. This relationship, however, should not be interpreted as a strict constraint, but rather as a heuristic guideline aimed at ensuring an appropriate balance between the interpolation capability of the kernel and the number of neighbouring particles effectively involved in the kernel summation. Typically, these parameters take values on the order of fractions of a millimetre, allowing for a decent resolution without compromising numerical efficiency. It is important to emphasise that, in the SPH context, particles do not represent isolated point elements but occupy finite volumes with partially overlapping domains of influence. Each particle, in fact, acts as the centre of a support subdomain extending radially up to a distance h. When h exceeds the initial spacing S_{EP}, the subdomains of two or more neighbouring particles intersect over common regions of space, resulting in partial overlap.
This overlap is not a numerical artefact but a structural feature of the SPH method, essential for solving differential equations in integral form. It ensures that each particle contributes to the average properties of the fluid in the surrounding region, thereby reinforcing the continuity and stability of the system. Uniformity in particle size and initial spatial distribution also ensures numerical balance, preventing heterogeneities that could compromise simulation quality (Shibata et al., 2017).
Figure 2.4 illustrates how, starting from the spacing S_{EP} between particle centres, a regular network of overlaps between their respective domains of influence is formed, this network constitutes the operative framework upon which the interpolation kernel acts.

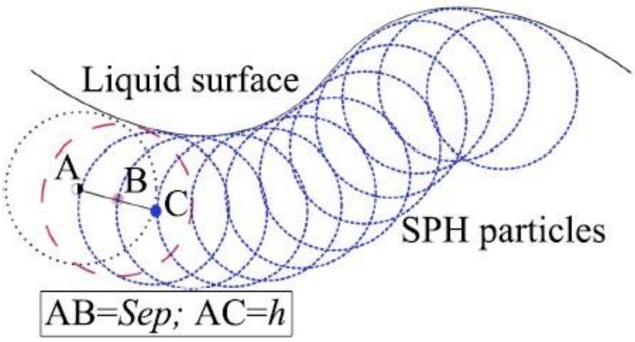

Figure 2.4: Schematic representation of a fluid section modelled using SPH particles. The initial distance between two adjacent particles is denoted by S_{EP}, while h represents the radius of influence associated with each particle (Battaglia et al. 2019).

We now proceed to analyse the main parameters used in our formulation, highlighting their function, the values adopted, and the way in which they interact to construct a fluid-dynamic simulation that is faithful to the macroscopic behaviour of the real liquid, while maintaining an efficient computational structure. The aim is not only to clarify the numerical meaning of each parameter, but also to make explicit its concrete impact on the simulated system's behaviour, showing how each modelling choice influences the quality, efficiency, and physical fidelity of the adopted model.

- Reference density (ρ_0). A reference density value of $\rho_0 = 1000$ (in arbitrary units) was adopted, considering water as the reference fluid. It is important to note that in SPH simulations, the concept of density differs from the traditional physical definition, especially when transitioning from three-dimensional (3D) to two-dimensional (2D) simulations. In 2D, density may be interpreted as mass per unit area rather than per unit volume. To maintain numerical consistency and simplify implementation, arbitrary units are preferred, thus avoiding dimensional discrepancies between 2D and 3D configurations.

- Speed of sound in the medium (c). The choice of the speed of sound in the medium is a crucial parameter for controlling the compressibility of the simulated fluid. A high value of c makes the fluid less compressible, bringing its behaviour closer to that of an incompressible fluid; however, it may introduce numerical instabilities and require smaller time steps to maintain simulation stability. Conversely, a value that is too low increases compressibility, causing the simulated fluid to deviate from real physical behaviour. It is therefore essential to strike a balance that ensures both numerical stability and a physically accurate representation of the fluid.

- Gravitational acceleration (g). Gravitational acceleration is a parameter that can be activated or deactivated depending on the physical phenomenon to be simulated. By setting $g = -9.81\,m/s^2$, terrestrial gravity is simulated, influencing the shape and behaviour of the fluid. In the absence of gravity ($g = 0$), particles are not subject to any gravitational force, allowing the study of phenomena under microgravity conditions.

- Artificial viscosity (α). Artificial viscosity is introduced in SPH simulations to stabilise the system and to manage phenomena such as shocks and discontinuities. Typical values of α range between 0.01 and 1.0, depending on the specific needs of the simulation. A higher value of α increases numerical dissipation, damping oscillations and preventing instabilities, but may also suppress physically relevant features. It is therefore crucial to calibrate α to strike a balance between numerical stability and physical accuracy.

- Interparticle force intensity (S_{ij}). This parameter represents the intensity coefficient that determines the magnitude of the force acting between two particles. Within the model employed in this study, S_{ij} is applied in two distinct contexts: fluid-fluid (liquid-liquid) interactions and fluid-solid (liquid-solid) interactions. The values in the two cases are calibrated differently according to the nature of the interacting particles. An effective coupling between the intensities of liquid-liquid and liquid-solid interactions is crucial to obtain numerically stable and physically realistic results, while also keeping simulation times within reasonable bounds. Poorly balanced parameters may lead to inconsistent fluid behaviour or significantly increased computational costs.

- Dimensions of the simulation domain (X-LENGTH and Y-LENGTH). The parameters X-LENGTH and Y-LENGTH define the physical dimensions of the simulated domain along the horizontal and vertical axes, respectively. These values determine the spatial extent of the system and influence the resolution of the simulation. Selecting appropriate values for X-LENGTH and Y-LENGTH is essential for accurately representing the physical phenomenon under investigation and for optimising computational resources.

- Maximum simulation time (TIMEMAX). The TIMEMAX parameter specifies the total duration of the simulation. Setting an appropriate value for TIMEMAX is fundamental to ensure that the phenomenon of interest is fully captured, possibly reaching a steady state or the desired equilibrium. A value that is too low may interrupt the simulation prematurely, while an excessively high value could result in unnecessary computational expenditure.

- Simulation restart parameter (I_START). The I_START parameter allows for the management of simulation restarts. When this value is set to 0, the simulation begins from the initial state. If set to 1, the simulation resumes from the last saved state, enabling the continuation of a previously interrupted run without restarting it entirely. This functionality is particularly useful for long-duration simulations or for testing different configurations from an intermediate state.

Having defined and discussed the main parameters used to calibrate the SPH model, we can now proceed to analyse in detail the simulations employed (Battaglia et al., 2019).

2.3.1 Simulation of a two-dimensional droplet in microgravity

Numerous studies over the years have attempted to model the behaviour of a two-dimensional droplet in the absence of gravity (Brackbill et al., 1992; Duan et al., 2003; Liu et al., 2005; Zhang et al., 2012), a highly delicate experimental context that can offer valuable insights into fluid dynamics when gravitational forces are absent.
One of the main challenges encountered in various modelling approaches is the difficulty in faithfully reproducing the behaviour of a real system, particularly about the distribution of surface tension along the liquid interface. Under realistic physical conditions, surface tension may not be uniformly distributed (Adami et al., 2010), as it depends on the local properties of the fluid and on boundary conditions. Nevertheless, in the SPH model used in this simulation, a uniform distribution of tension along the droplet profile is assumed, thereby simplifying the physical framework to facilitate analysis and comparison with theoretical expectations.

In this simulation, a droplet of water under microgravity conditions was represented using a two-dimensional SPH model, in which the particles are initially arranged homogeneously in a rectangular, mechanically unbalanced configuration. The primary objective is to observe how the particles evolve over time under the combined influence of pressure forces and interparticle forces, until they reach an equilibrium shape that approximates the physical behaviour of a real droplet.
The simulation was performed by varying the droplet radius while maintaining constant the initial dimensions of the rectangle defining the spatial distribution of the fluid particles. Figure 2.5 shows a snapshot of the system near equilibrium, in which both molecular-like forces per unit mass F_{ij} (red arrows) and pressure forces per unit mass T_{ij} (yellow arrows) are visible. It is evident that particles located at the droplet boundary are subjected to significantly greater forces than

those in the interior, as the net result of interactions does not cancel out, generating a net tension directed inwards toward the centre of the droplet.

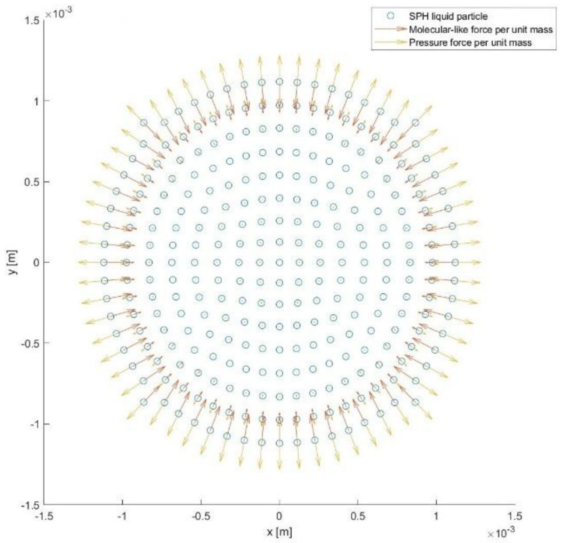

Figure 2.5: Equilibrium configuration of a droplet in microgravity conditions, obtained via SPH simulation starting from a rectangular particle distribution. The final shape is circular, determined by the balance between the pressure force (yellow arrows) and the molecular-like forces (red arrows) acting on the particles (Battaglia et al. 2019).

The total force between two particles is therefore the result of the sum of the pressure force and the interparticle force:

$$R_{ij} = T_{ij} + F_{ij} \tag{2.19}$$

The parameters used for this experiment were selected to maximise stability and adherence to the expected physical behaviour: the interaction strength parameter S_{ij} was set to 3.0, the smoothing length to $0.0002\,m$, the initial distance between particles (S_{EP}) to $0.000125\,m$, and the initial radius of the droplet to $0.0015\,m$. The acceleration due to gravity was set to zero, as the simulation was conducted under microgravity conditions.

From a theoretical perspective, a fundamental reference for the analysis of the internal pressure within the droplet is provided by the Young-Laplace law, which in two-dimensional conditions and in the absence of gravity takes the form:

$$P_i = \frac{\gamma}{R} \tag{2.20}$$

where P_i represents the internal overpressure relative to the surrounding environment, γ is the surface tension, and R the equilibrium radius of the droplet. To obtain a numerical value for the pressure from the microscopic quantities provided by the simulation, one may refer to the virial theorem, which allows the connection of interparticle forces to the average pressure in the system (Battaglia et al., 2023).
It is worth recalling that pressure, being a macroscopic quantity, is not directly defined on a microscopic scale. However, within the SPH framework, the particles represent finite volumes of liquid, and the interactions between them are modelled to permit the deduction of an average pressure across the entire system. It is precisely on the basis of these considerations that the authors were able to obtain, as an outcome of the simulation, a value for the internal pressure of the droplet consistent with theoretical predictions, ultimately enabling an indirect yet effective estimation of the surface tension coefficient γ.

2.3.2 Simulation of a two-dimensional droplet in the presence of gravity

The transition from microgravity to the presence of a gravitational field allows the droplet simulation to more clearly reveal the influence of external forces, gravity in particular, on the interactions between particles. In this case, the static spherical equilibrium observed under microgravity conditions is disrupted by the gravitational force, leading the droplet into a dynamic configuration, lacking radial symmetry, which evolves over time without ever reaching a steady state.

The initial configuration from which the simulation begins consists of a rectangular distribution of SPH particles, representing a suspended liquid volume. The particles in the upper region are fixed and act as a geometric constraint, simulating a wall or solid surface from which the liquid detaches, analogous to the macroscopic case of a droplet forming at the mouth of a tap.

Figure 2.6 shows a snapshot of the droplet just before detachment, with the interaction strength parameter S_{ij} set to 3.0, as in the microgravity case. The spatial distribution of SPH particles was fixed using a smoothing length $h = 0.0002\ m$ and an initial interparticle spacing of $0.000125\ m$. Furthermore, in this case, gravitational acceleration is also included, set to $-9.81\ m/s^2$.

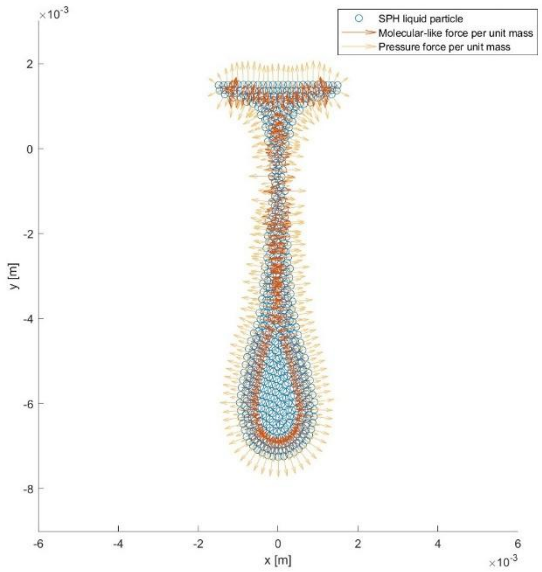

Figure 2.6: Spatial distribution of SPH particles forming a droplet under the effect of gravity, simulated from a rectangular configuration. The fixed particles at the top constrain the liquid, simulating the presence of a solid surface. The red arrows represent the resultant of molecular-like forces per unit mass, while the yellow arrows indicate the pressure force per unit mass. The system evolves towards an unstable and dynamic configuration, where gravity competes with surface tension, preventing the achievement of static equilibrium (Battaglia et al. 2019).

Unlike the previous case, however, the resultant force acting on the particles does not converge to zero, and the droplet does not attain an equilibrium shape. On the contrary, the continuous action of gravity induces a downward particle flow, generating a dynamic evolution that resembles the formation and detachment of real-world droplets.

The yellow arrows represent the resultant of the pressure force T_{ij} per unit mass, whereas the red arrows indicate the resultant of molecular-like forces F_{ij}. The latter are attractive at longer ranges and repulsive at short distances, according to a modified Lennard-Jones potential, as described by Battaglia et al. (2021). The interaction between these forces produces behaviour consistent with the concept of surface tension, observable in the profile of the droplet, which tends to constrict laterally while elongating under the influence of gravity.

The dynamic behaviour of the droplet closely parallels experimental observations and the simulations of Shi et al. (1994), who investigated the breakup of a droplet hanging from a tap as an example of a hydrodynamic singularity. In their study, the simulations display the formation of an unstable "neck" that progressively thins until the droplet detaches. Although the SPH model described here does not explicitly reproduce the development of the instabilities described, it clearly illustrates how gravity, by breaking the symmetry of isotropic interactions, imposes a preferred direction and drives the system towards a configuration far from static equilibrium.

From a pedagogical standpoint, this simulation proves particularly effective in demonstrating to students how molecular forces may either compete with or cooperate with external forces to determine the evolution of a system. The comparison between the droplet under microgravity and that subject to gravity highlights the regulating role of surface tension: in the former, it is sufficient to stabilise the spherical shape, while in the latter, it is gradually overcome by gravitational force, resulting in a continuously evolving dynamic.

2.3.3 Formation of liquid menisci

In SPH simulations, the formation of the meniscus directly depends on the intensity and configuration of the interactions between particles, whether liquid or solid. In the presence of gravity, when the fluid meets a solid surface, the particles near the container walls experience an inhomogeneity in interaction contributions compared to those immersed within the bulk. This imbalance determines the curvature of the liquid's free surface, namely the meniscus. The geometry of the system and the local distribution of particles induce an asymmetry in the attractive and repulsive contributions, producing a visually recognisable effect consistent with the expected macroscopic behaviour.

The formation of the meniscus reflects the balance between cohesive forces (between liquid molecules) and adhesive forces (between the liquid and the container), and determines the configuration with which the fluid settles against the solid, giving rise to a characteristic contact angle.

This dynamic has also been analysed in detail by Akinci et al. (2013), who demonstrate how the combination of fluid-fluid cohesion and fluid-solid adhesion forces can reproduce various wetting conditions and meniscus configurations, by locally modulating the force distribution and ensuring physically plausible behaviour.

In the implementation used, the modelled system consists of a container formed by fixed SPH particles and a fluid represented by mobile particles initially arranged in a non-equilibrium configuration. This setup allows the system to evolve naturally towards a state of mechanical equilibrium. The deformations of the liquid surface are therefore governed by the dynamic balance between intermolecular forces, both attractive and repulsive force, pressure forces, and physical parameters such as gravity. In SPH modelling, these effects are reproduced by assigning different interaction coefficients S_{ij}, both between liquid particles and between liquid and solid particles.

To computationally investigate meniscus formation in two distinct cases, concave and convex, SPH simulations were conducted in the presence of gravity ($g = -9.81\,m/s^2$), keeping the initial configuration unchanged and varying only the relative intensity of the liquid-solid interactions.

In the first case (Figure 2.7a), a concave meniscus was simulated, as occurs with water in a glass container. To obtain this configuration, a value of $S_{ij} = 3.0$ was assigned for liquid-liquid interaction and $S_{ij} = 2.6$ for liquid-solid interaction. In this scenario, adhesion between liquid and solid particles is comparable to the internal cohesion of the liquid. In the visualisations, red arrows represent molecular-like forces per unit mass, while yellow arrows indicate pressure forces. The particles located near the vertical boundaries of the container are subject to a resultant directed towards the solid interface, producing a concave meniscus curvature.

In the second case, a convex meniscus was simulated, reproducing the behaviour of mercury. In this configuration, while maintaining the same liquid-liquid interaction ($S_{ij} = 3.0$), the liquid-solid interaction coefficient was reduced to $S_{ij} = 1.85$. Adhesion to the container is therefore weaker than the cohesion among mercury particles, which thus tend to minimise contact with the walls. As shown in Figure 2.7b, the molecular-like forces are less intense than the corresponding pressure forces. The net force acting on particles near the boundary is directed upwards, generating the typical convex curvature of the meniscus.

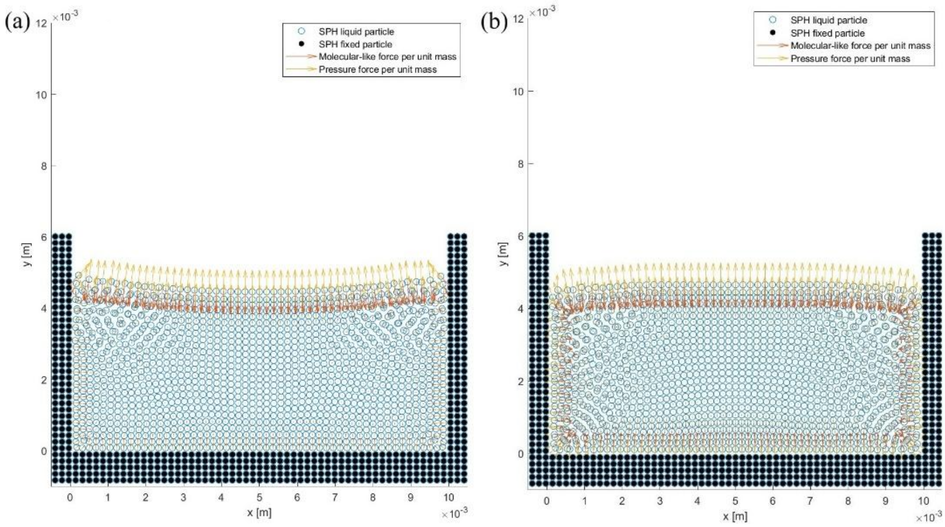

Figure 2.7: Configuration of SPH simulations for meniscus formation in the presence of gravity. (a) Concave meniscus: the interaction between liquid particles is comparable to that between liquid and solid particles, simulating the behaviour of water. (b) Convex meniscus: the liquid-liquid interaction is stronger than the liquid-solid interaction, simulating the behaviour of mercury (Battaglia et al. 2019).

The yellow arrows represent the resultant of the pressure force T_{ij} per unit mass, while the red arrows indicate the resultant of the molecular-like forces F_{ij}. The simulations were conducted with a particle radius of $h = 0.00037\ m$ and an initial inter-particle distance of $S_{EP} = 0.00018\ m$, identical in both cases. The use of subscripts i and j remains valid even when the interacting particles belong to different phases (liquid or solid), since the SPH formulation does not depend on the nature of the material, but on the position and the type of interaction specified.

The visualisation of the acting forces provides a powerful interpretative tool: it not only allows the correlation of the meniscus shape with the balance between pressure and molecular-like forces but also highlights how this shape emerges from a dynamic evolution far from the initial equilibrium. The simulations directly show that the curvature of the meniscus is a macroscopic manifestation of the competition between cohesive and adhesive forces, which operate on a mesoscopic scale and combine in a locally non-uniform manner along the solid-liquid interface.

2.3.4 Interaction between a solid body and a fluid

A seemingly simple phenomenon such as the interaction between a solid body and a liquid surface, for instance, an object floating on water, conceals a considerable degree of complexity when analysed from a modelling and computational perspective (Li et al., 2013). This aspect is particularly relevant in the context of physical modelling using SPH simulations, where each element of the system, whether fluid or solid, is represented as a set of interacting particles.

In this simulation, we examine the equilibrium behaviour of a two-dimensional solid object partially immersed in a fluid, akin to the case of a "floating needle", under the influence of the Earth's gravitational field. The object is composed of solid particles rigidly bonded to one another by a very strong elastic force and has a density 2.5 times greater than that of the surrounding fluid. The fluid, in turn, is modelled using SPH particles, which interact with the solid particles through a force of the same functional form as Equation (2.17), already discussed in previous sections.

Three distinct configurations are explored, each characterised by different intensities of interaction between solid and liquid particles. Meanwhile, the liquid-liquid interaction ($S_{ij} = 3.0$), the particle radius parameter ($h = 0.00035\ m$), and the initial inter-particle distance ($S_{EP} = 0.00018\ m$) remain constant across all three scenarios:

a) Initial configuration ($S_{ij} = 2.5$): This represents the moment just prior to contact between the solid body and the liquid. At this stage, no effective interaction is observed, as the object is still suspended above the surface. The corresponding image (Figure 2.8a) shows the initial state of the simulation, serving as a reference point for understanding the effects of interactions in the subsequent cases.

b) Strong interaction ($S_{ij} = 1.85$): In this configuration (Figure 2.8b), the high intensity of the solid-liquid interaction favours the formation of a "network" of forces among the liquid particles adjacent to the solid, which contributes to supporting the object on the liquid surface. Molecular-like forces dominate over pressure forces, producing a net resultant that effectively counteracts gravity. The object, therefore, is supported on the fluid not only because the fluid exerts an upward pressure force, but also (and more importantly, in terms of simulation) because the cohesive force between the solid and liquid particles is sufficiently strong to produce a net resultant that acts as a "supporting force". This force is directly modelled by the molecular component of the simulation (i.e. the force represented by S_{ij}).

c) Weak interaction ($S_{ij} = 0.1$): The low intensity of the interaction prevents the fluid from exerting sufficient cohesive force to support the solid body, which thus tends to sink almost completely (Figure 2.8c). Hydrostatic pressure is no longer sufficient to balance the gravitational force, and the solid particles penetrate the fluid until reaching a more stable, but more deeply immersed, configuration.

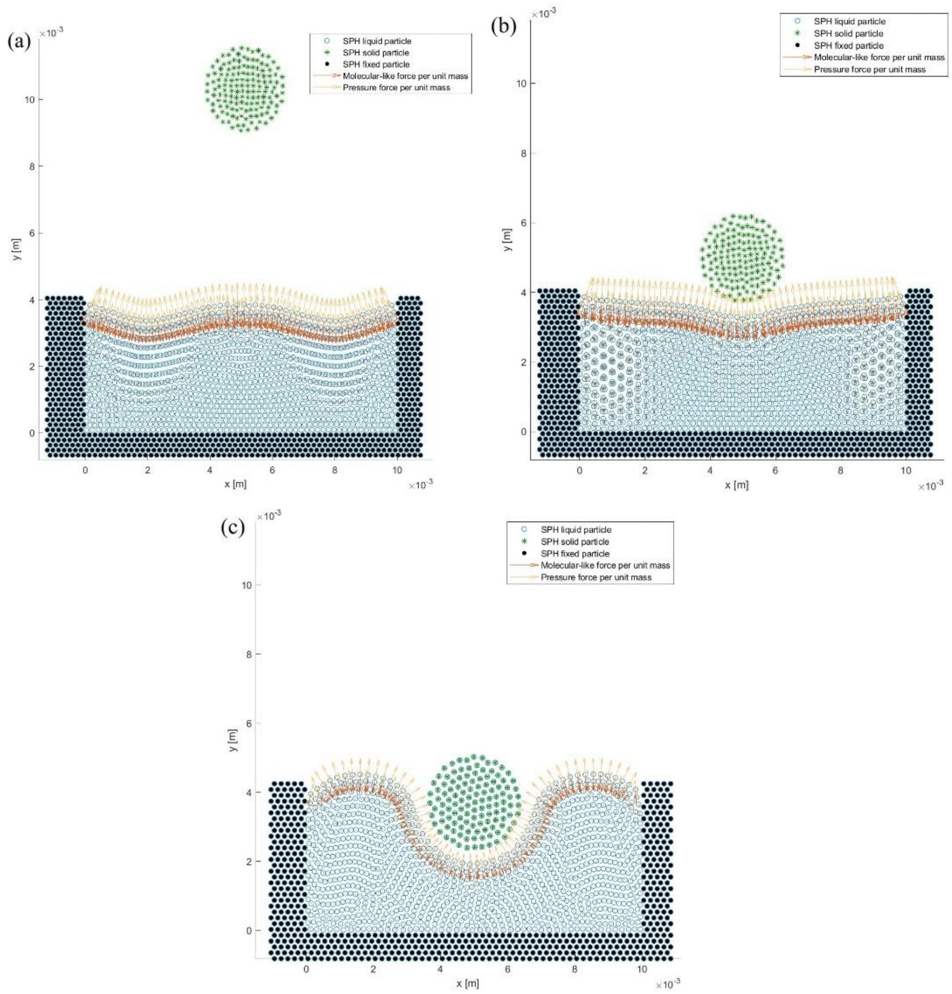

Figure 2.8: Comparison of three simulated configurations of interaction between a solid body and a liquid surface using the SPH method. (a) The body is distant from the fluid: the solid-liquid interaction is negligible. (b) Strong interaction: cohesive forces between liquid and solid particles generate a resultant opposing gravity, allowing the body to remain suspended above the fluid surface. (c) Weak interaction: the object sinks into the fluid; adhesive forces are insufficient to generate a stable configuration (Battaglia et al. 2019).

Yellow arrows represent the pressure forces acting on particles (T_{ij}), red arrows indicate molecular-like forces (F_{ij}), and the green stars enclosed in circles identify the particles that comprise the solid body. These observations are consistent with the findings of Yoo et al. (2022), who investigated how wettability significantly influences the entry dynamics of spherical objects into water, with hydrophobic surfaces tending to penetrate more deeply than hydrophilic ones.

To understand the phenomenon from a mechanical perspective, it is worth noting that the solid-body particles, which are tightly bound to each other, act as a medium through which the liquid particles can interact indirectly. Consider the case of two liquid particles situated too far apart to interact directly (i.e. beyond the interaction range defined by Equation 2.17). If both interact with different solid particles located between them, the solid body can function as a "bridge" that mediates an effective interaction between the two liquid particles. The degree to which the solid transmits this force depends directly on the S_{ij} parameter.

2.3.5 Formation of a sessile droplet with static contact angle

The formation of a sessile droplet, namely, a small volume of liquid resting on a solid surface, represents a paradigmatic case for understanding the balance between molecular-like forces and pressure forces in the presence of gravity. The final shape assumed by the droplet is essentially determined by the competition among three principal groups of forces: cohesive forces between liquid particles, adhesive forces between the liquid and the solid, and gravitational force. This balance defines the static contact angle of the droplet, which is classically described by Young's law (Equation 1.41).
In computational terms, however, the tensions described by Young's law correspond to the resultant effect of molecular-like (attractive or repulsive) and pressure forces acting on the fluid particles. The SPH simulations employed allow these interactions to be explicitly visualised through the continuous calculation of local resultants, thereby making it possible to observe how such forces are spatially distributed and balanced in the equilibrium configuration (Das & Das, 2010; Breinlinger et al., 2013; Yeganehdoust et al., 2016).

The simulation employed here were designed by the authors in two dimensions, starting from a liquid mass resting on a rigid solid surface represented by fixed SPH particles. The initial velocities of the fluid particles were set to zero, allowing the droplet to evolve solely under the influence of the internal forces within the system.
In both simulations, the following parameters were kept constant:

- SPH particle influence radius: $h = 0.0003\ m$
- Initial distance between fluid particles: $S_{EP} = 0.00018\ m$
- Interaction parameter between liquid particles: $S_{ij} = 3.0$

The difference between the two configurations lies exclusively in the value of the S_{ij} parameter between liquid and solid particles, which controls the intensity of the adhesive molecular interaction.

In the first case, a non-wettable surface, the solid-liquid interaction parameter is set to $S_{ij} = 1.85$, resulting in a weak adhesive effect between the droplet and the substrate. In this configuration, cohesion between liquid particles, i.e. liquid-liquid molecular-like forces, dominates, keeping the particles bound within the fluid mass. The particles are therefore more strongly attracted to one another than to the solid surface, preventing significant spreading on the substrate. The pressure force, directed outward due to density distribution, is effectively counterbalanced by cohesive forces, maintaining the droplet in a predominantly hemispherical shape. The result is a configuration with a contact angle greater than 90°, typical of non-wettable (hydrophobic) surfaces.

In the second case, a wettable surface, the solid-liquid interaction is set to $S_{ij} = 2.7$, producing a significantly stronger adhesive force. Molecular-like forces between the solid and liquid now prevail, inducing effective attraction of the liquid particles towards the substrate. The pressure force distribution adapts to the new geometry and helps stabilise the elongated droplet configuration. The solid surface becomes partially wetted, and the droplet spreads horizontally, assuming a flattened shape with a contact angle less than 90°, consistent with the behaviour of partially wettable surfaces.

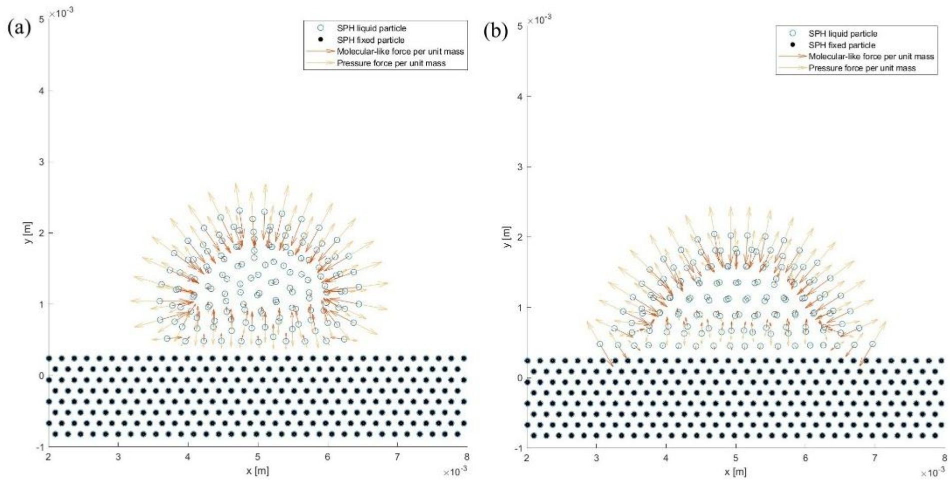

Figure 2.9: SPH simulation of sessile droplet formation on a solid surface in the presence of gravity, for two different values of interaction strength between liquid and solid particles. (a) Non-wetting configuration: cohesive forces between liquid particles prevail over adhesive ones, resulting in a contact angle $\theta > 90°$. (b) Wetting configuration: adhesive forces between the liquid and the substrate become predominant, inducing greater fluid spreading across the surface and a contact angle $\theta < 90°$ (Battaglia et al. 2019).

The reference figures (Fig. 2.9 a-b) clearly illustrate the two steady-state configurations, including a vectorial representation of the resultant per unit mass of molecular-like forces F_{ij} (red arrows) and pressure forces T_{ij} (yellow arrows), demonstrating the local balance that defines the equilibrium state of the droplet.

In both configurations, gravity contributes to shaping the droplet, but as highlighted by Vafaei and Podowski (2005), its influence becomes negligible in the case of microdroplets when compared to molecular-like forces: the contact angle depends almost exclusively on the intrinsic wettability of the surface. This result is consistent with SPH simulations employed here, in which it is observed that the final shape of the droplet is not determined by gravity, but rather by the spatial distribution of molecular-like and pressure forces, which compensate one another to generate a stable configuration.

Chapter 3

The pedagogical theoretical framework

What truly happens when someone learns? Is it a silent shift, a sudden reorientation, or a slow and laborious construction? Is it an adaptation to something external, or an internal movement that transforms the very way one perceives the world?
Behind every cognitive transformation, even the subtlest, lies an invisible web of thoughts, intuitions, resistances, and divergences. Learning is neither a container to be filled nor a mechanism to be activated, but a process that is at once fragile and powerful, in which experiences, words, gestures, doubts, and even hesitations contribute to redrawing the mental landscape of the learner.
And yet, despite its complexity, learning leaves traces. It manifests itself in an unexpected response, in a shift in language, in a gaze that moves from what is apparent to what is intuited. It is within these cracks in routine, these sudden openings, that the act of learning becomes recognisable.
For such transformations to occur, the surrounding environment must be generative: it must provoke without disorienting, invite questions without pre-empting answers, and expose learners to complexity without abandoning care.

Designing such contexts requires more than goodwill or experience: it demands a theoretical outlook capable of grasping the depth and diversity of the forms through which knowledge unfolds. It calls for critical reflection on what truly underpins educational choices, on the images of the student, of knowledge, and of development that these choices presuppose. It requires time, context, cognitive perturbation, but also emotional stability. It demands trust, opportunities, and eyes that recognise latent potential.
One who learns does not merely repeat: he/she transforms. He/she transforms themself, but also the knowledge he/she receives, reworking it, hybridising it, and connecting it with his/her own experiences and pre-existing frameworks. Learning, from this perspective, is a creative act, and often an identity-forming one: it entails redefining one's relationship with what is known and what remains unknown.

This chapter emerges from the need to orient students' educational choices, to motivate them to grow, to see and listen anew. It arises from the necessity to

return to the roots, to understand which visions of learning, often implicit, underpin all didactic design, and how these visions shape our interpretation of students' words, gestures, and silences.
The aim is not to embrace one model while rejecting another, but rather to approach, with attentiveness and critical thought, the ways in which knowledge takes shape, transforms, resists, and opens, within and beyond the classroom. Only through such awareness has it been possible to conceive and construct an educational proposal that does not merely transmit concepts but seeks to engage with the deeper structures of understanding. The reflection that follows moves in this direction.

3.1 Theories of learning

The study of learning processes underwent profound transformation throughout the twentieth century, interweaving with developments in psychology, the philosophy of science, and cognitive science. Interest in how human beings acquire, rework, and apply knowledge is by no means a recent phenomenon: as early as classical antiquity, philosophers such as Plato and Aristotle questioned the nature of knowledge and how understanding of reality is attained. However, it was only with the establishment of psychology as an autonomous scientific discipline, towards the end of the nineteenth century, that a systematic framework of learning theories began to emerge, grounded in empirical and experimental criteria.
The earliest scientific approaches to the study of learning developed within a context heavily influenced by positivism and by the effort to establish psychology on experimental foundations analogous to those of the natural sciences. In particular, the emerging field of American psychology embraced the ideal of objectivity as a guiding principle of research, favouring the systematic observation of external behaviour over the investigation of internal mental processes, which were considered too subjective or inaccessible. This epistemological shift led, in the early twentieth century, to the marginalisation of introspection as a scientific method and to the progressive centrality of the study of observable behaviour, regarded as the only reliable and measurable data. Danziger (1990) highlights that this shift was not merely methodological in nature but reflected a broader transformation in the practices and structures of psychology as a discipline: the interest in subjective experience was replaced by an operational stance focused on the manipulation of experimental variables and the quantification of behavioural responses. From this approach emerged various theoretical currents over the course of the twentieth century, each seeking to address the fundamental question of how human learning occurs. Every paradigm has articulated, either explicitly or implicitly, a specific anthropology, that is, a vision of the human being as a knowing agent: at times a passive

recipient of stimuli, at others an active processor of information, or alternatively, a situated constructor of meaning.
The historical evolution of learning theories thus reflects a gradual redefinition of the very concept of knowledge, transitioning from an objectivist and associative epistemology to one that is more subjective, relational, and dynamic. As Fosnot (2005) observes, every learning theory implies a theory of knowledge and, ultimately, an epistemological stance. Learning, once conceived as a merely adaptive and reactive process, has come to be recognised as a complex activity situated within cultural and social contexts, influenced by cognitive, motivational, and affective factors (Bruner, 1996; Vygotsky, 1978).

These conceptual shifts have also had a significant impact on educational practice, where teaching methods have gradually moved away from the idea of unidirectional knowledge transmission, embracing instead approaches that place the learner's activity at the centre. In this sense, the development of learning theories cannot be separated from the historical and cultural context in which they emerged: each paradigm responds, whether explicitly or implicitly, to the educational, technical, and ideological needs specific to its time (Sfard, 1998).

The following sections present the main theoretical orientations that have shaped thinking about learning during the twentieth century: behaviourism, cognitivism, and constructivism. Each will be introduced with reference to its theoretical foundations, its contexts of application, and its implications for the teaching and learning of science.

3.1.1 Behaviourism: a paradigm of learning as adaptive response

Within the context of the epistemological transformations that, from the late nineteenth century onwards, progressively redefined psychology as an empirical science grounded in the systematic observation of behaviour, behaviourism emerged as the first theory of learning to adopt an explicitly scientific structure in the modern sense. In an era dominated by the need to measure, predict, and control phenomena, behaviourist psychology gained prominence for its capacity to offer rigorous and replicable experimental models, based on the analysis of relationships between observable stimuli and responses. The central tenet of this paradigm is that learning can be entirely described as a stable change in behaviour resulting from experience, without recourse to invisible or unmeasurable mental entities. The mind, from this perspective, is treated as a "black box" (Watson, 1913), whose internal workings, deemed inaccessible to objective measurement, are temporarily excluded from the domain of scientific inquiry.

The official origins of behaviourism are traditionally traced to the publication of John B. Watson's manifesto, *Psychology as the behaviorist views it* (1913), which called for a clear rejection of introspection as a scientific method, replacing it with the systematic observation of animal and human behaviour. Although Watson is regarded as its principal advocate, the roots of behaviourism lie both in the Russian reflexological tradition (Sechenov, 1965; Pavlov, 2010) and in Anglo-American experimentalism (Thorndike, 1898), united by the shared objective of reducing learning to observable and quantifiable associative mechanisms.

Ivan Pavlov's contribution, through his theory of classical conditioning, is emblematic of this approach: learning consists in the formation of an association between a previously neutral stimulus and a biologically determined response, made possible by the regular and systematic pairing of stimuli (Pavlov, 2010). However, it is with Edward Thorndike that the concept of learning begins to include a more nuanced interaction with the environment: in his experiments with animals, behaviour is no longer simply "elicited" by a stimulus but is gradually "shaped" according to the effectiveness of the response in relation to a goal. From this, the idea of trial-and-error learning emerges, alongside the formulation of the Law of Effect (Thorndike, 1927), which states that responses followed by positive consequences tend to be reinforced.

The paradigm reaches its fullest development in the work of B.F. Skinner, who systematised the concept of operant conditioning: learning is the result of behavioural selection through reinforcement, in a continuous process of adaptation to environmental contingencies. Unlike Pavlovian conditioning, in which the response is elicited by a stimulus, operant conditioning involves a response that is spontaneously emitted and subsequently reinforced or weakened depending on the consequences that follow it (Skinner, 1965, 1991). This model functions as a feedback system, in which reinforcement, positive or negative, modifies the probability of a behaviour reoccurring.

In the educational domain, behaviourism had a significant impact, particularly during the first half of the twentieth century, providing a theoretical framework for the development of teaching techniques focused on the management of student behaviour. The teacher is conceived as a shaper of learning, responsible for breaking down complex objectives into simple units, for administering stimuli in a controlled manner, and for providing systematic reinforcement. Instruction is thus structured into gradual and cumulative sequences, which facilitate the stable and repeatable acquisition of desired responses (Slavin, 2018).

A paradigmatic example is represented by systems of structured instruction. So-called "programmed instruction" and, later, models of "Explicit Teaching" are based on didactic sequences articulated in small steps, with clearly defined objectives, frequent checks, and immediate feedback (Rosenshine, 1987). In this view, learning is not a spontaneous or self-organised process, but an intentionally designed outcome, achieved through the manipulation of environmental variables. The teacher assumes a directive role: guiding the student's behaviour towards the desired responses through selective reinforcement and guided practice.

In the context of science education, however, this approach begins to reveal its limitations. The objective is not merely to apply formulas or conduct experiments according to protocol, but to understand concepts, to construct mental models, and to develop intuition. The practice of "sequential transmission" may support the development of mechanical skills but proves less effective in fostering deep conceptual understanding, cognitive flexibility, or the ability to transfer knowledge to novel contexts. The risk is that students learn "how" to solve a problem without understanding "why" it works that way. Nevertheless, it was only from the mid-twentieth century onwards that the first substantial critiques of behaviourism's capacity to explain complex cognitive processes, such as reasoning, comprehension, or creativity, began to emerge. Learning was reduced to a matter of observable performance, disregarding the constructive dimension of meaning and the learner's active role in reworking experience. This reductionism was mirrored in the transmissive approach typical of behaviourist-inspired models, where knowledge is presented as a set of contents to be transmitted and consolidated, rather than negotiated, explored, or problematised. It was in this context that scholars such as Edward C. Tolman and Clark Hull, although initially working within the behaviourist paradigm, highlighted its key limitations and helped broaden the theoretical framework of learning, anticipating several principles of cognitivism.

Tolman rejected the idea that behaviour resulted solely from mechanical associations between stimulus and response. Based on numerous experiments with animals, he proposed the concept of a "cognitive map" to explain how individuals, human and non-human alike, are capable of mentally representing their environment and navigating within it in a flexible and goal-directed manner (Tolman, 1948). In doing so, Tolman introduced a perspective that, while not denying the value of behavioural experimentation, attributed an active role to cognitive processes, thus paving the way for a conception of learning as mental construction. Similarly, Clark Hull attempted to reformulate behaviourism in more nuanced terms by introducing the notion of "intervening variables", quantities not directly observable but logically inferred from the systematic observation of behaviour. Through his hypothetico-deductive model, Hull sought to reconcile the empirical observability of behaviour with the need to explain variations in response as a function of internal factors, such as motivational drive or the organism's physiological state (Hull, 1943). Although

Hull remained committed to a mechanistic conception of learning, his effort to formalise it mathematically introduced theoretical mediation that, in effect, softened the radical stance of Watsonian behaviourism.
These contributions, despite differing in approach and intent, highlighted how learning cannot be reduced to a mere chain of external events, but necessarily involves internal processes, representations, and goals. The ongoing tension between the rigorous observation of behaviour and the necessity of positing unobservable mental structures eventually led to the decline of the behaviourist paradigm in favour of cognitivism, which placed explicit emphasis on such mental constructs as legitimate objects of scientific investigation.

Nonetheless, it is undeniable that behaviourism marked a fundamental methodological turning point in the history of education: it introduced the notion that learning could be intentionally designed, validated through empirical procedures, and assessed in terms of effectiveness. Some tools and strategies derived from this paradigm, such as interactive tutorials, systems of immediate feedback, or formative assessments based on multiple-choice testing, remain effective today, provided they are consciously integrated within a broader and more articulated pedagogical framework that goes beyond mere performance to promote reflection, generalisation, and the personal reconstruction of knowledge (Biggs & Tang, 2011). From this perspective, behaviourism continues to offer valuable resources for teaching, if it is not upheld as the sole model of learning but recognised instead as one of several tools at the service of richer and more intentional educational design.

3.1.2 Cognitivism: active information processing and the transformation of knowledge

With the emergence of cognitivism in the 1950s, a significant epistemological shift occurred within the field of learning theories. Cognitive psychology shares with behaviourism the conviction that the study of learning must be objective and that learning theories must be grounded in experimental evidence. However, unlike behaviourism, cognitivism restores internal mental processes, such as perception, attention, memory, comprehension, and reasoning, to the centre of psychological inquiry. The human being is no longer conceived as a passive recipient of environmental stimuli but as an active processor of information, capable of organising knowledge, constructing meaning, and developing strategies for problem-solving.
The theoretical foundations of cognitivism lie in the so-called “cognitive revolution,” an interdisciplinary movement that encompassed psychology, linguistics, philosophy of mind, and information sciences, particularly computer science. Scholars such as George A. Miller (1956), who laid the groundwork for a theory of human cognitive capacity through his studies on working memory,

played a crucial role in this development. Another key figure was Noam Chomsky (1967), who, in his critique of Skinnerian behaviourism, demonstrated that language acquisition could not be explained solely in terms of conditioning but required the existence of innate cognitive structures. Ulric Neisser (2014) is credited with having coined the term "cognitive psychology," thus inaugurating a systematic approach to the study of mental processes. Within this new theoretical framework, the mind is often likened to an information processor, in accordance with the computational metaphor that dominated the early phase of classical cognitivism.

In the educational context, cognitivism prompted a radical rethinking of the aims and methods of teaching. It is no longer sufficient for teaching merely to transmit facts: what matters is how information is processed, transformed, connected to prior knowledge, and rendered meaningful to the learner. Learning entails the construction of coherent mental representations, the integration of new information with pre-existing knowledge (as in Ausubel's concept of "meaningful learning," 1968), the development of metacognitive strategies, and the ability to transfer knowledge to new contexts. This gives rise to a marked shift of focus from observable behaviour to the structure of knowledge, from immediate outcomes to the processes of encoding, storage, and retrieval of information, and to the motivational and attentional dynamics that underpin long-term learning.

According to this perspective, learning is an active and intentional process: learners must be placed in a position to mentally manipulate information, reflect on their own cognitive strategies, and monitor their progress. Hence the growing interest in self-assessment techniques, self-reflective learning, and metacognitive awareness, now regarded as essential elements in educational design. Instruction is no longer something "done to students", but rather a process that actively involves them, strengthening and stimulating their cognitive abilities. As a result, the educational sciences have begun to concern themselves not only with "what" to teach, but above all with "how" knowledge is constructed, shifting the focus to the mental organisation of information rather than its mere reproduction. Consequently, the importance of teaching activities that promote deep understanding, inferential skills, and cognitive flexibility has been increasingly recognised, in contrast to repetitive drills. The teacher's role is transformed: from a unidirectional transmitter of content to a designer of environments that facilitate knowledge processing and transfer. This requires a pedagogical design attuned to the underlying cognitive mechanisms, such as selective attention, semantic organisation, elaborative rehearsal, and retrieval strategies. Indeed, for information to be effectively learnt, it must pass through a series of cognitive stages, from initial sensory perception to its consolidation in long-term memory. When environmental or methodological conditions fail to support this cognitive flow, or when information is not reinforced through active recall, it tends to fade rapidly, as highlighted by models of the forgetting curve (Ebbinghaus, 1885) and short-term memory.

As early as the 1940s, Kenneth J. W. Craik had intuited the temporal and structured nature of mental processing. In his experiments, Craik (1948) observed that humans are unable to respond to a visual stimulus in less than half a second, and from this empirical finding he formulated one of the earliest hypotheses concerning the existence of an internal system of processing and decision-making, anticipating the notion of the mind as an "information processor". This insight pointed to the need to consider both the temporal interval and the complexity of mental operations in the processing of experience. Equally significant are the contributions of scholars such as Jean Piaget and Jerome Bruner, often positioned at the intersection between cognitivism and constructivism. They demonstrated that learning is not merely a linear accumulation of information, but rather a structural transformation of knowledge, shaped by the learner's cognitive development and their active reorganisation of experience.

Piaget (1952), through his theory of cognitive development, showed that knowledge emerges from the interaction between pre-existing mental structures and environmental stimuli, via the processes of assimilation and accommodation. Assimilation involves integrating new information from the external environment into an already existing behavioural or cognitive schema. Accommodation, on the other hand, entails modifying the cognitive structure or behavioural model to incorporate new information. These two processes alternate in a continual pursuit of equilibrium.

Bruner (1960), by contrast, argued that any disciplinary content can be learnt, provided it is restructured in cognitively accessible terms, a notion embodied in his proposal of a "spiral curriculum". He also championed discovery learning as a privileged method for activating processes of conceptualisation. These authors thus represent a bridge between cognitivism and constructivism, helping to move beyond the computer metaphor of the mind in favour of a more dynamic, social, and situated conception of learning.

3.1.3 Constructivism: learning as the active and situated construction of knowledge

Within the broader cognitive framework, an educational perspective has emerged that has marked a significant paradigm shift in approaches to knowledge: constructivism. Constructivism is one of the most influential and complex learning theories to have arisen in the twentieth century. While it does not constitute a unified theory, but rather a family of approaches sharing a conception of learning as active, situated, and subjective, constructivism has profoundly reshaped pedagogical and didactic reflection. Its historical roots lie in the work of Jean Piaget, a pivotal figure between cognitivism and constructivism, who argued that knowledge is not merely transmitted from the environment but actively constructed by the learner through interactions with the physical and social world (Piaget, 1952). However, it is with Lev S. Vygotsky (1978) that the social dimension of learning assumes a central role: knowledge develops primarily within a cultural context, mediated by language and participation in shared practices. The "zone of proximal development", introduced by Vygotsky, becomes a key conceptual tool for understanding how a learner can progress with the assistance of an adult or more capable peers, thus underpinning the value of tutoring and peer learning. According to this perspective, learning precedes development and acts as its driving force, contrary to Piaget's position, which holds that learning follows the pace of cognitive maturation.

During the 1980s and 1990s, constructivism underwent significant theoretical expansion, assuming a range of nuances. On one side, psychological constructivism (represented by Piaget and Bruner) emphasises the individual construction of meaning through cognitive processes such as assimilation, accommodation, and symbolic representation. On the other side, social or sociocultural constructivism (Vygotsky, 1978; Lave & Wenger, 1991) focuses on interpersonal interaction, cultural mediation, and learning as participation in communities of practice. From this perspective, knowledge is not a static entity to be acquired, but a dynamic process that emerges from joint activity and the negotiation of meaning among peers, guided by experts or cultural tools. A further development is situated constructivism, which holds that learning cannot be separated from the context in which it occurs. Cognition and environment are interdependent, and knowledge acquired in an abstract or decontextualised manner is often fragile and difficult to transfer. This approach, advocated by authors such as Brown et al. (1988), has significantly influenced the design of authentic learning environments, grounded in real-world contexts and oriented towards the resolution of complex problems. Learning, therefore, is not the faithful reproduction of concepts, but the elaboration of personal and situated interpretations within contexts that are meaningful to the learner.

This framework represents a clear discontinuity not only with behaviourism, which conceives of learning as a passive association between stimulus and response, but also with classical cognitivism, which focuses on knowledge as an internal, symbolic representation of reality. Constructivism, by contrast, highlights the generative, active, and situated nature of learning. From this standpoint, each individual constructs meaning through a continuous process of interpreting and reorganising their experiences. Knowledge is not transmitted but co-constructed; it emerges from a dynamic interaction among the learner, the environment, and others engaged in the process (von Glasersfeld, 1995; Bruner, 1990).

From an educational perspective, constructivism entails a profound rethinking of both the role of the teacher and the structure of teaching practice. The learner ceases to be a passive recipient of knowledge and becomes an active agent in their own learning process, driven by curiosity and personal motivation, capable of exploring, questioning, and reworking information. The teacher, consequently, is no longer the sole bearer of knowledge, but rather assumes the role of facilitator, designer of meaningful contexts, and guide in the process of knowledge construction (Jonassen, 1991; Brooks & Brooks, 1999). This vision implies a learning-centred approach, shifting the focus from mere teaching to meaningful learning. Within this framework, the educational activity is not primarily about delivering information, but about creating environments rich in stimuli, capable of fostering deep, exploratory, and reflective cognitive processes. A pedagogy grounded in inquiry, discussion, problem solving, and collaborative work is thus encouraged, where error is no longer regarded as failure, but as an opportunity for cognitive restructuring. Techniques such as modelling, experimental investigation, and simulations become privileged tools, as they allow students to engage with complex, open-ended situations in which the application of knowledge precedes its formalisation. Students construct mental models through exploration, manipulation, and collective discussion of their representations. These are environments that do not transmit pre-defined content but instead stimulate reflection, argumentation, and negotiation of meaning, in accordance with constructivist principles. In this respect, the constructivist approach proves particularly effective in promoting deep, durable, and transferable learning, focussed not only on *what* is learned, but more crucially on *how* and *why* it is learned.

Constructivism, therefore, does not advocate a pedagogy of improvisation or absolute relativism, but rather invites educators to regard knowledge as a process that is always situated, negotiated, and subjective. As Merrill (2002) highlights, this implies a set of key characteristics that should inform pedagogical action: valuing the personal construction of knowledge; promoting Active Learning; recognising the importance of context; embracing the collaborative nature of knowledge; and implementing integrated, formative, and authentic assessment practices that prioritise the learning process over mere outcomes.
Assessment, too, undergoes a transformation: it can no longer be conceived as a moment distinct from the educational process, but must instead be integrated and continuous. Jonassen (1999) emphasises that the fundamental criterion is not the reproduction of content, but rather the learner's ability to apply knowledge effectively to analyse, interpret, and solve real-world problems. In this sense,

one speaks of *authentic assessment*, which values process over product, and individual transformation over standardised performance.

Naturally, the concrete implementation of constructivist principles encounters numerous challenges. Within the field of instructional design, it is not always straightforward to reconcile learners' interpretative autonomy with the necessity of defining shared objectives, tools, and evaluation criteria. Nonetheless, contemporary research is increasingly moving towards a flexible and informed implementation of constructivism, one capable of adapting to the specificities of different educational settings and disciplinary domains (Tam, 2000).

3.2 Common conceptions and conceptual change

The learning theories considered thus far, despite their differences, all highlight a crucial and transversal aspect: knowledge is not merely transmitted, but rather constructed, reworked, and often transformed through experience, interaction, and dialogue.
This learning process entails a transition from forms of spontaneous understanding, intuitive or rooted in common sense and everyday experience, to forms of thought that are more abstract, systematic, and formalised, characteristic of scientific knowledge. It is important to clarify that the term *scientific knowledge* does not refer exclusively to knowledge produced within the academic or specialist scientific community, nor should it be understood as the exclusive domain of formally recognised scientific institutions. Rather, this term designates any form of knowledge that has undergone a process of formalisation, validation, and sharing within a given community of reference, a community which may vary depending on the disciplinary domain, the level of elaboration, or the context of application. Scientific knowledge, therefore, is codified, systematic, and intersubjectively recognised; it is distinguished from personal or intuitive interpretations of phenomena not so much by its object, but by its method, internal coherence, and capacity to be communicated, discussed, and critically examined.

In every discipline, students approach learning with a repertoire of pre-existing ideas. These are not mere gaps to be filled, but rather constitute genuine conceptual structures, often internally coherent and subjectively functional. These initial conceptions, commonly referred to as *naïve ideas* or *spontaneous knowledge*, derive from everyday experience, colloquial language, and intuitive interpretations of phenomena. While they may appear approximate or inaccurate from the standpoint of scientific formalisation, they provide the learner with stable points of reference that guide understanding and interpretation of reality. Disciplinary learning, therefore, cannot be reduced to the mere introduction of new concepts; it must also engage with the more complex and profound task of conceptual restructuring.

The study of this transition, from intuitive explanations to theoretically grounded understandings, has led to the formulation of the concept of *conceptual change*, understood as a transformative process that involves not only the abandonment of prior knowledge, but also the active construction of new structures of meaning. From this perspective, the difficulty of learning lies not only in the intrinsic complexity of content, but also in the cognitive tension generated between the learner's pre-existing conceptual framework and the one proposed by scientific discourse.

The present section aims to examine these two fundamental poles: on the one hand, the nature and pervasiveness of the intuitive knowledge that students activate in their engagement with phenomena; on the other, the necessary conditions for triggering a meaningful conceptual change capable of fostering authentic and enduring learning.

3.2.1 Spontaneous conceptions

In the process of knowledge construction, one of the most significant and, at the same time, most complex elements to address in education is the presence of pre-existing ideas developed by students well before their encounter with formal teaching. These conceptions, commonly referred to as *spontaneous*, are not mere gaps or errors to be corrected, but rather coherent worldviews, deeply rooted in everyday experience and resistant to change. They play a central role in learning processes, both as an initial resource and as a potential obstacle to the construction of scientific knowledge.

As early as the first half of the twentieth century, Gaston Bachelard (1967) emphasised that access to scientific thinking is not a linear evolution from common sense, but rather an *epistemological rupture* requiring the overcoming of what he called *epistemological obstacles*, mental configurations deeply anchored in perception, language, or naive generalisation, which prevent genuine conceptual restructuring. Learning within scientific domains, according to Bachelard, demands a radical shift in perspective, whereby the learner must relinquish a naive view of reality to adopt a new way of thinking that is more abstract, formalised, and counterintuitive.

This framework was further elaborated by Guy Brousseau (1976), who, in the field of mathematics education, proposed a classification of the origins of learning obstacles into three fundamental categories: ontogenetic, related to the cognitive development of the individual; didactic, arising from the educational practices themselves; and epistemological, inherited from the historical development of scientific knowledge. This distinction helps to clarify that students' difficulties cannot simply be attributed to individual shortcomings, but rather emerge at the intersection of learner, knowledge, and educational context.

Spontaneous conceptions thus emerge as functional, yet unformalized responses to the need to interpret the world. They arise from a complex interplay of sensory experience, everyday language, and informal knowledge, and constitute genuine *alternative frameworks* for interpretation (Driver & Easley, 1978). These frameworks privilege immediate perceptual evidence and coherence with common sense over logical or empirical validity according to scientific standards (diSessa, 1993). Rather than being simply *incorrect*, these conceptual structures express meanings attributed to phenomena that are internally consistent within a pre-scientific belief system.

Over time, the literature has employed various terminologies to describe such knowledge: Ausubel (1968) referred to *preconceptions*, highlighting the pre-instructional character of these ideas; Doran (1972) used the term *misconceptions*, underscoring their incompatibility with formal scientific knowledge; while Driver and Easley (1978) proposed *alternative frameworks* or *conceptual frameworks*, acknowledging their internal coherence and interpretative function.

An intriguing phenomenon noted by many scholars is that some of these preliminary student conceptions share similarities with outdated scientific theories. In the field of physics, for example, it is common to encounter students' beliefs such as the idea that a moving object naturally comes to rest unless acted upon by an external force, an Aristotelian view of dynamics that contrasts with Newtonian mechanics, yet appears perfectly compatible with everyday experiences involving friction and air resistance (Clement, 1982). To account for the emergence of such conceptions, it has been hypothesised that there is a form of parallelism between the conceptual development of individuals and the historical development of science. However, this hypothesis has never gained full consensus: it has been criticised as overly simplistic on the one hand, and unfounded on the other, since common conceptions lack the philosophical framework that guided scientists of the past (Besson, 2015).

These ideas do not readily disappear even after formal instruction: they often coexist with school knowledge, emerging in informal contexts or unfamiliar situations (McCloskey, 1983; Viennot, 1979; diSessa, 1993). This cognitive duality highlights how scientific understanding does not simply replace previous knowledge but requires a complex restructuring process that involves uprooting familiar concepts and building new mental schemas. This process, known as conceptual change (Strike & Posner, 1992), is neither immediate nor linear: it demands significant cognitive engagement from the learner and requires learning environments that stimulate reflection, comparison between models, and analysis of one's own mental processes.

3.2.1.1 Mixed models of knowledge

Numerous theoretical contributions have highlighted that students' understanding of scientific phenomena is grounded in the activation of mental models of a composite nature, rather than in unitary and formally coherent conceptual structures (diSessa, 1993; Smith III et al., 1994; Viennot, 2001; Taber, 2009). Explanations produced spontaneously by students indeed display a recurrent coexistence of heterogeneous elements, in which phenomenological descriptions, analogical references, appeals to everyday experience, and partially formalised conceptual fragments coexist within the same explanatory act. Such heterogeneity does not appear accidental or cognitively incoherent; rather, it reflects the ways in which students attempt to make sense of complex phenomena by integrating diverse resources, available at different levels of abstraction.

These explanatory structures are commonly described in the literature as mixed or hybrid knowledge models (Vosniadou et al., 2008). Far from being interpreted in a deficit-oriented manner, as mere misconceptions or errors to be eliminated, such models represent cognitively coherent, albeit partial, attempts to organise experience and to construct meaningful relations among observations, intuitions, and prior knowledge. From this perspective, the "mixed" character of the model does not signal a lack of understanding, but rather an intermediate state in the knowledge-building process, in which different interpretative registers are mobilised simultaneously in order to cope with the complexity of the phenomenon.

The theoretical framework of *knowledge-in-pieces* (diSessa, 1993) provides a particularly effective interpretative lens for understanding this dynamic. According to this perspective, students' knowledge is not organised into global, stable conceptual systems, but rather into dynamic sets of locally consistent conceptual elements, which are activated depending on the context, the cognitive demands, and the affordances of the situation. This implies that the same student may draw upon different conceptual resources, even within a single explanation, some of which may be only partially compatible with one another, without perceiving such coexistence as problematic.

In light of these considerations, scientific learning cannot be conceived as a linear transition from naïve conceptions to formally correct explanations. Instead, it takes the form of a process of progressive conceptual restructuring, in which pre-existing conceptions are reinterpreted, reorganised, and, in some cases, superseded through ongoing processes of integration and differentiation. Mixed knowledge models therefore assume a central role in the dynamics of learning, functioning as transitory cognitive structures that mediate between everyday knowledge and scientific representations, and making visible the gradual, constructive, and non-linear character of conceptual development.

3.2.2 Conceptual change

The emergence and persistence of spontaneous conceptions, as well as their influence on scientific learning processes, compel education to question not only *what* students learn, but especially *how* their systems of thought are transformed. From this perspective, the concept of conceptual change represents a central focus in educational research, as it describes the shift from pre-existing, intuitive but often incoherent cognitive structures to more articulated conceptual systems compatible with the scientific understanding of phenomena. In the context of surface phenomena, such as those discussed in Chapter 1, students' everyday explanations, often grounded in perceptual metaphors or common-sense analogies, provide a particularly fertile ground for analysing processes of conceptual change.

The earliest contributions to the idea of conceptual change are attributed to Thomas Kuhn (2012), who in his seminal work *The structure of scientific revolutions* described the development of scientific knowledge as a series of paradigmatic revolutions, characterised by a conceptual break between old and new ways of interpreting phenomena. Although Kuhn spoke of scientific communities, his view has also influenced reflection on individual learning: just as a scientist abandons a paradigm only when a more adequate one emerges, so too must the student discard their existing conceptual framework in favour of a more powerful one. An illustrative example in this respect is provided by students' frequent interpretation of surface tension through the metaphor of a "elastic membrane", a spontaneous explanatory model that, while experientially plausible, proves insufficient when confronted with a more formal physical account of surface phenomena.

This insight was formalised in the field of education by Posner et al. (1982), who proposed an epistemological model of conceptual change inspired by Popperian scientific falsificationism. According to their model, change occurs only when four fundamental conditions are met:

1. Dissatisfaction with existing conceptions (cognitive dissonance);
2. Comprehensibility of the new conception;
3. Plausibility of the new conception (it must appear coherent with experience);
4. Fruitfulness of the new conception (it must resolve problems that the previous conception could not explain).

Only if all these conditions are fulfilled will the student be willing to replace their pre-existing conceptual scheme with a new one. This process does not merely involve the addition of new information, but a qualitative transformation of the interpretative frameworks through which the individual understands reality. In the case of surface phenomena, dissatisfaction may arise, for instance, when the "elastic membrane" metaphor fails to account for the role of molecular interactions, thereby opening space for alternative explanatory models. The change is neither mechanical nor guaranteed: it occurs slowly, requires time and confrontation, and depends on the establishment of a learning environment that fosters critical reflection and the questioning of one's own assumptions.

Various authors have highlighted psychological and instructional conditions that can facilitate conceptual change. Firstly, it is necessary for the learner to be placed in a state of cognitive conflict, that is, to face phenomena or experiences that cannot be explained with their current interpretative schemes. However, as Hewson (1981) demonstrated, cognitive conflict alone is insufficient: the learner must acknowledge the conflict's existence and be motivated to resolve it; otherwise, defensive mechanisms may be triggered, leading to ignoring or rejecting inconsistent information.

A second condition concerns the mediation of the teacher. The educator cannot merely transmit the correct scientific conception but must activate a process of meaning negotiation, guiding the student through the deconstruction and reconstruction of their worldview, encouraging comparison of ideas, metacognitive reflection, and collaborative knowledge building. Approaches such as *problem situations* (Brousseau, 2002) and *dialogic teaching* (Alexander, 2008) exemplify strategies aimed at creating conditions whereby the student can recognise the limitations of their own conceptions and open to new meanings.

Finally, a key role is played by motivation and readiness to change. According to Pintrich et al. (1993), conceptual change is not solely a cognitive process but also an affective one: the learner must perceive value in the new idea, feel capable of understanding it, and trust their own ability to learn. In this sense, perceived self-efficacy and epistemic identity become crucial variables that can either facilitate or hinder conceptual restructuring.

Not all students are, however, willing to abandon their own ideas even when faced with contradictory evidence. Spontaneous conceptions, as diSessa (1993) has shown, are not monolithic blocks but fragmented sets of situated knowledge that activate in specific contexts. In this sense, conceptual change does not occur through substitution but through the progressive reorganisation of cognitive fragments (called *p-prims*, or phenomenological primitives). This model, known as knowledge-in-pieces, highlights how the stability of naïve ideas stems from their functional coherence with everyday experience and their subjective plausibility.

Another form of resistance is linked to emotional or identity-based attachment to one's ideas. When a conception is tied to one's self-image, changing it can be perceived as a threat. In such cases, the student may engage in post hoc justification strategies or learn the new conception only superficially and decontextualised, without truly integrating it into their cognitive system. This phenomenon has been described by some authors as a "language game" (Scott et al., 1991), meaning students' ability to use scientific language in school contexts while continuing to apply spontaneous conceptions in informal or everyday situations.

Numerous studies (Duit & Treagust, 2003) have demonstrated that change is favoured by meaningful experiences, laboratory activities, modelling, and guided discussions that allow students to problematise their representations and personally discover the inadequacy of their intuitions. In this respect, teaching should create cognitively perturbing situations while simultaneously providing support tools for conceptual restructuring.

Conceptual change is therefore a complex process involving cognitive, affective, and contextual aspects. Far from being a simple correction of errors, it entails a genuine epistemic transformation whereby the student is called to revise their way of explaining, predicting, and attributing meaning to phenomena. More importantly, it represents a tool for the student's cognitive autonomy: guiding them from spontaneous understanding to a more formalised and shared comprehension means enabling them to reason scientifically, exercising a form of critical and aware epistemic citizenship.
Accordingly, understanding how, when, and why such change occurs, and what impedes it, is essential for designing meaningful and inclusive learning experiences capable of truly leading students from naïve knowledge to a scientific understanding of phenomena.

3.3 Pedagogical approaches: a framework for conscious teaching

In the context of contemporary science education, the need to overcome a transmissive view of teaching has led to the development of a plurality of pedagogical approaches or models aimed at promoting meaningful, critical, and participatory learning. By "pedagogical approach/model" is meant a coherent set of theoretical conceptions, educational aims, teaching strategies, and assessment methods that guide teacher practices and define the interaction between teacher, student, and content. Pedagogical approaches do not constitute rigid models but rather epistemological and methodological frameworks capable of inspiring educational design, considering the complexity of learning processes.

Historically, these approaches have developed in response to two fundamental needs. On one hand, the necessity to deepen understanding of how learning occurs, thanks to contributions from cognitive sciences, educational psychology, and instructional research. On the other, the urgency to renew schools as inclusive, equitable, and culturally relevant environments capable of actively engaging students in knowledge construction (National Research Council, 2000; Alexander, 2008).

The transition from teaching focused on simple content delivery to one based on inquiry, interaction, and the learner's cognitive autonomy is rooted in constructivist reflections (Piaget, 1977; Vygotsky, 1978), according to which learning occurs through processes of personal and negotiated construction of knowledge. From this theoretical framework derive approaches that no longer view the student as a container to be filled but as an active subject, endowed with pre-existing conceptions and engaged in a continuous process of conceptual restructuring (Driver et al., 1994; Duit & Treagust, 2003).

Pedagogical models prove particularly effective in contexts where scientific learning requires the re-elaboration of intuitive and common ideas, which often conflict with scientifically accepted concepts. In such cases, it is necessary to create learning environments that stimulate doubt, reflection, discussion, and argumentation, thereby promoting the overcoming of epistemological obstacles and the internalisation of new conceptual structures (diSessa, 2014). From this perspective, these pedagogical models also serve as tools of cultural mediation, enabling the translation of expert knowledge into forms accessible to students without excessively simplifying its epistemic content (Shulman, 1986; Duit et al., 2005).

A further distinguishing feature of contemporary pedagogical approaches is the emphasis on the teacher's role as a facilitator and orchestrator of learning, rather than as a mere transmitter of knowledge. The teacher is called upon to design meaningful educational experiences, observe learning processes as they unfold, adapt strategies to the students' needs, and promote continuous reflection on scientific concepts and methods. In this sense, such approaches offer not only practical tools but also theoretical-practical orientations for a reflective and professionally aware teaching practice (Korthagen, 2004; Loughran, 2010).

Finally, it must not be overlooked that the adoption of a pedagogical approach is never a neutral act: it reflects a specific vision of learning, teaching, and knowledge. For this reason, the choice of a particular method entails epistemological, methodological, and ethical responsibility. In the field of science education, approaches such as Active Learning, Educational Reconstruction, Inquiry-Based Science Education (IBSE), and the Investigative Science Learning Environment (ISLE) represent some of the most effective applications of these principles, offering concrete tools for supporting conceptual change, promoting critical thinking, and fostering a deep understanding of science.

3.3.1 Active Learning

The concept of Active Learning has increasingly gained prominence in contemporary pedagogical discourse, establishing itself as one of the most influential approaches for promoting deep, lasting, and meaningful learning, particularly in the sciences. Although the term entered educational vocabulary more widely from the 1990s onwards, its theoretical roots lie in a broader constructivist tradition, which views learning as an active, situated, and socially mediated process (Piaget, 1977; Vygotsky, 1978).

The idea that students should be actively involved in their own learning process has a long history, originating with Dewey's (1976) progressive educational philosophy, according to which "learning by doing" forms the foundation of any authentic educational experience. In contrast to transmissive teaching, Dewey advocated for educational environments in which students could explore real-world problems, pose questions, reflect critically, and construct meaning within meaningful contexts. These ideas have since been corroborated by research in cognitive science, which has shown that effective learning requires the activation of metacognitive processes, engagement with authentic tasks, and dialogical participation in the construction of knowledge (National Research Council, 2000; Chi, 2009).

The Education Resources Information Center defined Active Learning as a set of strategies in which students do more than simply listen passively: they engage in activities such as reading, writing, discussion, and problem-solving, all of which demand reflective thinking and a high level of participation (Bonwell & Eison, 1991). These practices are based on three key assumptions: learning is more effective when it is active, when it is socially constructed, and when it is oriented towards solving authentic problems (Prince, 2004).

Over the past thirty years, Active Learning has spread increasingly throughout various levels of education, with particular emphasis in university-level STEM (Science, Technology, Engineering and Mathematics) teaching, where student passivity and high dropout rates have been strongly criticised. Large-scale studies have shown that instructional approaches based on Active Learning can significantly reduce failure rates in university-level physics, mathematics, and engineering courses, and can improve conceptual understanding compared to traditional lecture-based teaching (Freeman et al., 2014).

Active Learning practices take on diverse forms depending on the context and educational objectives. Some of the most widely adopted include:

- Peer Instruction (Mazur, 1997), which involves posing conceptual questions to students during lessons, followed by peer discussions and collective feedback with the teacher;
- Problem-Based Learning (PBL) (Barrows & Tamblyn, 1980; Hmelo-Silver, 2004), where learning emerges through the collaborative exploration of complex, ill-structured problems;
- Think-Pair-Share (Lyman, 1981), a simple yet effective technique that stimulates individual reflection, paired discussion, and plenary sharing.

In school contexts, Active Learning is often translated into interdisciplinary pathways, laboratory activities, strategic use of classroom discussion, collaborative exercises, and long-term projects in which students act as co-authors of their own learning experience.
Active Learning is grounded in several key principles:

- Active cognitive engagement: students are required to reflect, make decisions, and elaborate concepts and connections;
- Social interaction: learning occurs through peer comparison, negotiation of meaning, and participation in discursive communities;
- Authentic context: proposed activities are meaningful and related to real or realistic situations;
- Continuous feedback: the teacher acts as a facilitator, guide, and observer, offering stimuli and guidance to support the cognitive process.

The literature shows that the mere adoption of active techniques does not automatically guarantee improved learning outcomes: the quality of instructional design and its integration with clear learning objectives are essential conditions for the success of this approach (Michael, 2006; Lombardi, 2007).

From a practical standpoint, Active Learning is often perceived as demanding in terms of organisation, particularly in school settings characterised by rigid timetables, large class sizes, or heavy curricular loads. Furthermore, some teachers may encounter cultural resistance, stemming from the perception that the lecture remains the dominant and socially legitimised model of "serious" teaching.
Assessment represents another critical challenge, which must be aligned coherently with the active approach. Traditional summative tools, focused on the reproduction of knowledge, are often inadequate for capturing the processes of conceptual construction, metacognition, and transversal competencies that Active Learning aims to develop. For this reason, there is growing interest in

authentic assessment methods such as portfolio, peer assessment, and self-assessment.

Despite these challenges, Active Learning constitutes a transformative educational paradigm, redefining the role of the teacher, valuing students' abilities, and helping to bridge the gap between school and the real world. Its adoption is not merely a methodological matter, but signals a cultural shift in the conception of learning as a participatory, reflective, and relational process. In an era where access to information is increasingly widespread, the added value of schooling no longer lies in the transmission of content, but in the guided construction of meaning, the promotion of critical thinking, and the cultivation of informed, responsible citizenship.

3.3.2 Educational Reconstruction

The Educational Reconstruction (ER) approach emerged in the early 1990s within the field of science education, as a response to the need to bridge advanced scientific research and school practice without reducing the complexity of disciplinary knowledge to decontextualised and simplified notions. It constitutes a theoretical and methodological model that aims to design teaching based on two complementary needs: on the one hand, the didactic reconstruction of scientific knowledge, and on the other, the consideration of students' conceptions and cognitive difficulties.

The concept was initially developed by a German research group led by Ulrich Kattmann (1996) and is firmly situated within the constructivist paradigm, with strong connections to research on conceptual change and evidence-based instructional design.
The model is based on the idea that science teaching cannot simply "transmit" expert knowledge, nor can it replicate in the classroom the same language and abstractions found in academic science. At the same time, however, teaching cannot disregard the epistemic structure and key concepts of the discipline. This structure must therefore be partly reformulated in such a way that it can be understood and embedded in contexts more familiar to students (Duit, 2007). The term "reconstruction" precisely underscores this necessity: the conceptual questions and meaningful links that were often sacrificed in the process of scientific formalisation must be recovered and reworked from an educational perspective, to make the scientific viewpoint accessible and meaningful to learners.
ER thus positions itself as a bridge between disciplinary epistemology and teaching-learning processes, reconciling scientific rigour with cognitive accessibility. This vision is structured around three fundamental pillars:

1. Analysis of the structure of scientific knowledge, aimed at identifying key concepts, theoretical frameworks, models, and disciplinary problems relevant to the content to be taught;

2. Analysis of students' conceptions, which includes the investigation of prior knowledge, conceptual obstacles, and alternative representations commonly held by learners;

3. Design and implementation of didactic strategies that mediate between expert and naïve knowledge using tools, contexts, analogies, simulations, and guided discussions.

This tripartite structure (Figure 3.1) enables an ongoing dialogue between disciplinary research, educational research, and classroom practice, positioning ER as an integrated and highly reflective paradigm (Komorek & Kattmann, 2009). It provides a flexible theoretical framework within which teachers can make informed design choices in line with their educational goals and teaching context.

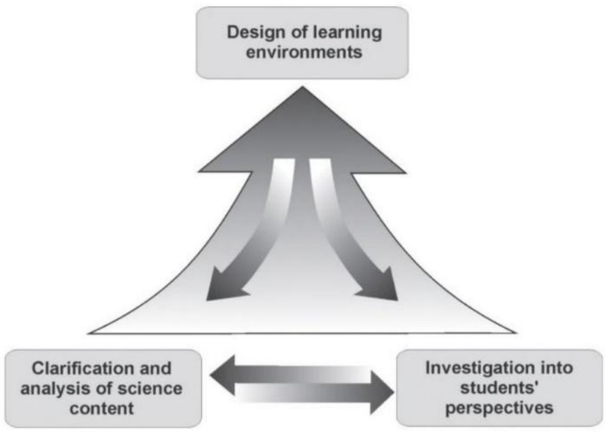

Figure 3.1: The three phases of the Educational Reconstruction model: analysis of the structure of scientific knowledge; analysis of students' conceptions; design of learning environments (Komorek & Kattmann, 2009).

Although the theoretical soundness and proven effectiveness of Educational Reconstruction are evident across various contexts, the approach does present certain practical challenges. Firstly, it requires a high level of disciplinary and pedagogical competence on the part of the teacher, as well as the ability to analyse scientific content from a didactic perspective. Secondly, it entails extended planning times and careful experimentation, which may prove difficult to reconcile with rigid curricular structures or fragmented teacher training. Moreover, translating complex scientific concepts into cognitively accessible forms without oversimplifying them is a delicate process that demands ongoing negotiation between rigour and simplification.

Despite these implementation difficulties, Educational Reconstruction remains a key reference model for those who seek to teach science in an authentic, meaningful, and evidence-informed way. It is, in fact, one of the most mature and systematic approaches to curriculum design in science education. Its strength lies in its capacity to integrate theory and practice, disciplinary and psycho-pedagogical knowledge, as well as attention to both the learner and the content to be learned.

3.3.3 Inquiry-Based Science Education

Inquiry-Based Science Education (IBSE) is one of the leading constructivist approaches to science teaching, grounded in the idea that learning science should occur through investigative processes akin to those employed in actual scientific practice. The historical roots of IBSE can be traced back to reform movements in science education that emerged in the post-war period, particularly in the United States with the Science – A Process Approach (SAPA) and Jerome Bruner's (1960) curricular proposals, which emphasised discovery as a privileged mode of learning. In 1996, the National Research Council formally introduced IBSE as a recommended teaching protocol in the United States (National Research Council, 1996). At the European level, IBSE was formally structured only in the early 2000s, thanks in part to the support of international initiatives such as Pollen, Sinus, Fibonacci, and ESTABLISH. These projects promoted its integration into school curricula and contributed to systematising its methodological framework. According to the definition provided by Rocard et al. (2007) in the well-known European Commission report, IBSE is a pedagogical method that encourages students to explore by posing questions, making observations, conducting experiments, and engaging in discussions to construct a personal understanding of natural phenomena. This implies that knowledge is no longer presented as a set of dogmatic truths, but rather built progressively through authentic questions and meaningful experiences.

IBSE is based on a non-linear vision of science that aims to replicate, within the school context, the authentic modes of scientific inquiry. It guides students through a process of active knowledge construction via the investigation of natural phenomena. The core element of this approach is not the disciplinary content per se, but the experience of doing science: students are encouraged to ask questions, collect data, formulate hypotheses, test them, compare results, and communicate their conclusions, thus retracing, albeit in a simplified form, the full scientific process (Colburn, 2000).

IBSE stands in clear contrast to more traditional models, in which the student is viewed as a passive recipient of pre-defined content. In this approach, by contrast, learning arises from the student's active involvement in an investigative process, which also includes errors, negotiation of meaning, and interaction with peers and the teacher. It is, therefore, a process-oriented model, centred more on open and meaningful questions than on pre-set correct answers (Bybee, 2002).

The literature identifies at least three levels of inquiry (Bell et al., 2005), differentiated by the degree of autonomy granted to students:

- Structured inquiry: the teacher provides both the research question and the experimental method; students carry out the procedure and analyse the data. This is the most basic form, suitable for lower school levels or introductory activities.

- Guided inquiry: the teacher poses the problem, but students determine how to investigate it, which materials to use, which hypotheses to test, and how to organise the data.

- Open inquiry: students independently identify the research question and design the entire investigative process, from formulating hypotheses to analysing and communicating results. This type is closely aligned with authentic scientific research and requires well-developed competences.

The coexistence of different levels of inquiry reflects a logic of gradual progression: IBSE is not conceived as a rigid model but as a set of flexible practices to be adapted according to age, context, and educational objectives. This scalability allows teachers to implement scaffolding strategies, that is, to provide initial support that is gradually withdrawn as students gain autonomy in constructing scientific knowledge.

Among the various operational models developed to give concrete form to IBSE, the most widely adopted and validated is the 5E model, introduced in the 1990s by the Biological Sciences Curriculum Study (BSCS) under the leadership of Roger Bybee (2002). This model has been highly successful due to its flexible yet coherent structure for designing and implementing learning experiences grounded in scientific inquiry.
The five “E” represent the phases of the learning process (Figure 3.2):

1. Engage: students are prompted by a question, a problem, or a concrete situation that stimulates curiosity and activates prior knowledge.

2. Explore: students engage in experimentation, observation, and hands-on manipulation of materials or simulations, actively and collaboratively gathering data.

3. Explain: the collected data are analysed, results are discussed, and relevant scientific concepts are introduced, both through students' elaboration and teacher guidance.

4. Elaborate: students apply what they have learned to new contexts or deepen their understanding of the phenomenon, testing the robustness of their acquired knowledge.

5. Evaluate: both learning processes and outcomes are assessed, through self-evaluation and metacognitive reflection, as well as more traditional forms of assessment.

The structure is commonly represented as cyclical rather than linear, to highlight the recursive nature of the process: the phases are not strictly sequential but interact dynamically and may be revisited considering the students' evolving thinking, their responses, and the reflections that emerge throughout classroom interaction.

Figure 3.2: Representation of the 5E pedagogical model, structured into five sequential phases: Engage, Explore, Explain, Elaborate, and Evaluate. The model reflects a constructivist learning framework designed to foster active inquiry, cognitive engagement, and the progressive construction of meaningful scientific concepts through guided exploratory experiences, moments of formalisation, and application in novel contexts (Continuous Learning Institute, 2025).

The success of the 5E model lies in its adaptability across educational levels, its fidelity to the actual scientific process, and its capacity to integrate inquiry, theoretical reflection, and the development of transversal skills. Empirical studies (Wilson et al., 2009) have shown that systematic adoption of this model leads to significant improvements in conceptual understanding, motivation to learn, and students' argumentative skills.

Despite its recognised benefits, the widespread implementation of IBSE still faces significant barriers. These include cultural resistance to non-transmissive methods, insufficient teacher training in using inquiry as an instructional tool, and the perception that overloaded curricula hinder the planning of complex inquiry-based activities (Blanchard et al., 2010; Crawford, 2014).
The risk of trivialising inquiry, by reducing it to procedural exercises devoid of theoretical reflection, has also been frequently raised in the literature. As Furtak et al. (2012) remind us, for IBSE to be genuinely effective, it requires careful instructional orchestration, capable of balancing student autonomy with guidance, and stimulating not only action but also metacognition and theoretical elaboration.

3.3.4 Investigative Science Learning Environment

The Investigative Science Learning Environment (ISLE) model is an approach to teaching physics and natural sciences developed from the early 2000s by Eugenia Etkina and collaborators (Etkina & Van Heuvelen, 2007) at Rutgers University. Conceived in response to the need to make science learning more authentic, meaningful, and aligned with real scientific practices, ISLE is based on the idea that students should build knowledge through cycles of observation, hypothesis generation, experimentation, reflection, and communication, in a manner that closely mirrors the practices of the scientific community.
The investigative learning environment proposed by ISLE is grounded in the assumption that learning science means learning to think, act, and communicate like a scientist. Far from being passive recipients of pre-formulated content, students are encouraged to develop explanatory models, subject them to empirical testing, and revise them based on the data gathered. This process is not only epistemically active, but also metacognitively aware: students are invited to reflect not only on what they are learning, but also on how they are learning (Etkina & Van Heuvelen, 2007; Brookes et al., 2020).

The methodological core of the ISLE approach revolves around a recursive investigative cycle, in which error, revision, and peer comparison play a central role (Figure 3.3).

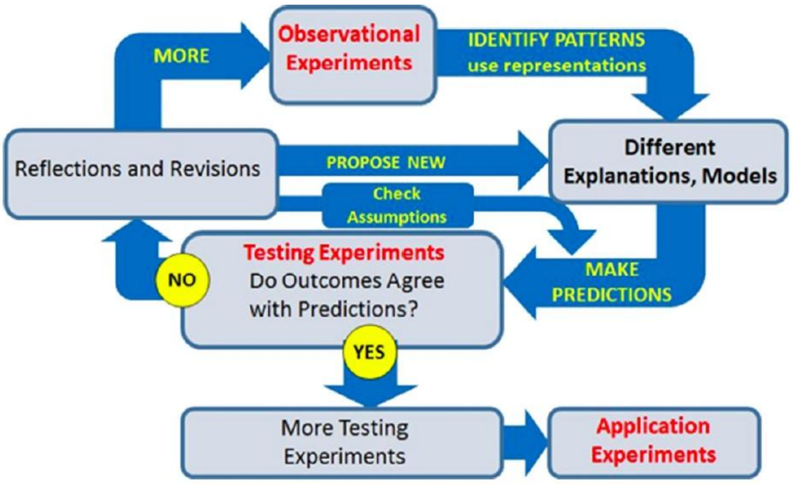

Figure 3.3: Schematic representation of the ISLE (Investigative Science Learning Environment) cycle, illustrating the dynamic and iterative sequence of cognitive and experimental actions carried out by students. The cyclical structure highlights the recursive nature of scientific knowledge, grounded in continuous interaction between theory and evidence (Etkina et al., 2019).

This cyclical structure is consistent with the logic of scientific inquiry, which rarely follows a strictly sequential path (Etkina et al., 2019). The process is articulated into several key stages, which should not be viewed as rigid steps, but as interconnected phases within a reflective dynamic, one that mirrors the actual construction of knowledge in scientific research:

1. Observational experiments: observation of unexpected or counterintuitive phenomena, capable of challenging students' spontaneous intuitions;
2. Explanations/hypotheses/models: generation of explanatory frameworks and interpretative models, provided they are logically coherent and falsifiable;
3. Testing models/explanations: design and implementation of new experiments to test the proposed models;
4. Judgement: critical evaluation and communication of results;
5. Application experiments: application of the constructed ideas and models to new contexts or project-based tasks.

One of the most appreciated aspects of ISLE is its close alignment with authentic scientific practices. Students learn to construct and test models, to recognise the centrality of empirical evidence, to negotiate meaning, and to discuss their ideas within a community of learners. This fosters the development of not only scientific competencies, but also transversal skills such as communication, critical thinking, and collaboration. Moreover, the model is supported by structured teaching materials, adapted laboratory activities, assessment rubrics, and scaffolding tools that facilitate its adoption, particularly in university and upper-secondary settings (Etkina et al., 2019).

Although IBSE and ISLE may at first appear to share a common foundation in promoting active and inquiry-based learning, they differ substantially in their underlying epistemological orientation.
IBSE is primarily conceived as a teaching strategy focused on observation, experimentation, and hypothesis formulation, guiding students through the fundamental steps of the scientific method. However, in many school-based implementations, IBSE tends to emphasise the procedural aspects and practical skills of scientific investigation, often neglecting explicit reflection on the nature of scientific knowledge. In other words, the emphasis is placed on doing science, but not necessarily on thinking about science.
In contrast, ISLE adopts a more explicitly epistemological stance. Students are not only guided to test hypotheses through experimentation, but also to reason critically about what makes a model acceptable, what the limitations of a theory might be, how explanations in physics are constructed, and what validation processes make them convince within the scientific community. The goal is not merely to acquire concepts or investigative skills, but to enhance scientific thinking, understood as the ability to model, argue, and revise. ISLE insists on fostering a critical understanding of the knowledge construction process, emphasising the cyclical, non-linear, and constantly revisable nature of science.

Despite its many strengths, the implementation of ISLE poses several challenges:

- It requires specific teacher training, not only in scientific content, but also in modelling practices, formative assessment, and laboratory management;
- It demands time and resources, both in terms of school schedules and material availability;
- It may cause disorientation among students unaccustomed to playing an active role, especially in the absence of adequate instructional scaffolding;
- It is more readily adoptable in academic or experimental settings, whereas it can be difficult to integrate into rigid or overly content-driven school curricula.

The ISLE model represents a deep and transformative approach to science education. It aims to develop not only disciplinary knowledge, but also epistemic, investigative, and metacognitive abilities. By actively engaging students in scientific practices, it helps them learn to think like scientists and to understand how knowledge is constructed in the real world. In this sense, the ISLE approach constitutes a powerful tool for overcoming transmissive teaching and for promoting deep and meaningful understanding of scientific concepts.

3.4 Teaching Learning Sequences: instructional design within the constructivist framework

Within an educational context increasingly aware of the complexity of scientific learning, the need to rethink the role of subject-specific teaching has led to the development of tools designed to intentionally and coherently guide students' cognitive paths. Teaching Learning Sequences (TLS) have emerged as a response to this need, taking shape as structured design tools aimed at promoting meaningful learning through the intentional and coherent articulation of teaching and learning situations.
The development of TLS has been strongly influenced by the pedagogical approaches discussed in the previous section, which have inspired both their structure and educational goals. Educational Reconstruction, for instance, has provided a fertile context for the design of teaching sequences grounded in active exploration, hypothesis formulation, and argumentative dialogue. Similarly, the ISLE model (Investigative Science Learning Environment) by Etkina et al. (2019) has contributed to the dissemination of teaching practices based on cycles of observation, experimentation, and reflection. What unites these approaches is the idea that scientific learning should be based on experience, interaction, and the active construction of meaning.

The emergence of TLS is closely linked to the spread of the constructivist paradigm in educational research. Unlike transmissive conceptions of knowledge, which viewed teaching as the simple transfer of content from teacher to student, the constructivist approach, particularly in its socio-constructivist articulation (Vygotsky, 1978; Bruner, 1990), conceives knowledge as an active and contextual construction, the result of interaction between the learner, the environment, and the culture. From this perspective, TLS aims to orchestrate teaching sequences capable of stimulating reflection, dialogue, negotiation of meaning, and the overcoming of naive conceptions, thereby fostering conceptual change.
International literature traces the origins of TLS to projects developed in the late 1980s and early 1990s in the Netherlands and France, later widely disseminated and refined across other European contexts (Geminard, 1987; Méheut & Psillos,

2004). Their development is based on the idea that teaching should not proceed through mere exposition of content, but through a carefully designed sequence of activities that stimulate a gradual reorganisation of students' conceptions and the reconstruction of cognitive obstacles, leading towards more sophisticated, shared, and scientifically grounded conceptual frameworks. The organisation of activities within a TLS follows a logic that integrates conceptual, cognitive, and metacognitive dimensions (Duit et al., 2005; Etkina et al., 2019), highlighting the importance of mediating between the epistemic demands of the discipline and students' cognitive representations.

A TLS may be defined as a structured and intentional sequence of educational episodes, designed to promote meaningful learning through a coherent progression of phases, each addressing specific cognitive and pedagogical goals:

Phase 1: structuring the sequence into progressive steps, each with clearly defined objectives;

Phase 2: identifying and engaging with students' prior knowledge;

Phase 3: incorporating activities that foster cognitive conflict and metacognitive reflection;

Phase 4: integrating authentic or simulated teaching materials;

Phase 5: consolidating and formalising the knowledge constructed.

This structure is particularly conducive to conceptual change, meaning the transformation of prior conceptions into frameworks more consistent with accepted scientific knowledge.
The design of a TLS is neither casual nor linear: it requires careful reflection on the scientific content, a sound understanding of students' preconceptions, and a clear vision of the intended learning outcomes. For this reason, TLS are deeply rooted in the constructivist paradigm, where learning is understood as a dynamic and contextualised process of meaning-making, mediated by interaction between the individual, others, and the environment (von Glasersfeld, 1995; Bruner, 1990).

The effectiveness of Teaching Learning Sequences (TLS) has been confirmed by numerous empirical studies (Buty et al., 2004; Leach & Scott, 2002), which attest to their success in promoting conceptual change, metacognitive awareness, and student motivation. TLS have proven to be valuable tools in overcoming the fragmentation of traditional teaching activities, ensuring greater continuity and coherence in learning trajectories, especially in

disciplines such as physics and chemistry, where the transition from naïve conceptions to scientific understanding requires systematic guidance.
In educational practice, the design and implementation of TLS demand an active and reflective role from the teacher, who does not merely select content but instead designs learning environments, anticipates learning difficulties, observes ongoing cognitive dynamics, and intervenes with targeted support strategies. This calls for a renewed vision of teacher professionalism, grounded not only in disciplinary expertise, but also in an understanding of cognitive processes and in the ability to act as an effective mediator in the learning process. Within this framework lies the concept of *Pedagogical Content Knowledge* (PCK), introduced by Shulman (1986), which denotes a specific form of professional knowledge that integrates content knowledge with the knowledge of how to teach that content effectively. PCK enables teachers to transform disciplinary knowledge into forms that are accessible and meaningful to students, considering their misconceptions, learning difficulties, and developmental characteristics. In this sense, TLS represent a bridge between didactics research and classroom practice, promoting evidence-based teaching that is aware of learning processes and geared towards transformation.

It may therefore be argued that Teaching Learning Sequences constitute one of the most mature and structured expressions of the constructivist approach to science education. Their strength lies in their ability to integrate disciplinary content, instructional strategies, and pedagogical reflection into a coherent and intentional framework that places students' cognitive experience at its core.

3.5 Modelling as epistemic practice

The epistemological core of the TLS elaborated in this work lies in the progressive introduction of the concept of the scientific model and the practice of modelling as fundamental tools for thinking about, interpreting, and communicating science. To model means to represent, simplify, interpret, and evaluate portions of reality through theoretical, symbolic, analogical, or computational tools, with the aim of generating explanatory, predictive, and communicable knowledge. It is a cyclical and never fully concluded process, which involves theoretical choices, assumptions, idealisations, and continuous revisions based on data and context.

In scientific research, models are never passive replicas of reality but intentional constructions, guided by explanatory or pragmatic goals, capable of making complex phenomena intelligible and operational. Their value does not lie in their direct correspondence with reality, but in their usefulness for generating questions, hypotheses, experiments, and new representations. As noted by Gilbert and Justi (2016), modelling is the most recognisable and central

form of scientific activity, encompassing not only the construction and use of models, but also their interpretation, validation, communication, and potential revision. In this sense, to model means to participate actively in the process of knowledge construction, not merely in its assimilation.
This view aligns with the perspective that epistemic practices of science, such as modelling, experimental design, control of variables, or evidence-based argumentation, are essential components of authentic science and, as such, should be introduced from an early stage in education (National Research Council, 2007). Modelling is identified in numerous international frameworks (such as the Next Generation Science Standards, NGSS Lead States, 2013) as one of the eight core practices of science and engineering to be developed throughout the school curriculum. Teaching modelling, therefore, does not simply mean transmitting disciplinary content, but educating students to think scientifically, fostering critical thinking, epistemic awareness, and a constructivist view of knowledge (Osborne, 2014).

In classroom practice, models may take various forms: conceptual diagrams, graphical representations, mathematical formulas, analogies, interactive or computer-based simulations. Each of these forms carries a specific epistemic semantics and invites distinct types of reasoning: mathematical models enable quantitative prediction, analogical models foster qualitative understanding, and computational models allow dynamic simulation. Depending on their nature and function, models may be used to describe a system, explain its behaviour, predict its evolution, or guide further investigation (Clement, 2000).
However, the introduction to the conscious use of models in educational contexts, particularly at high schools and in non-specialist settings, is neither immediate nor straightforward. Students without an advanced background in physics, chemistry, or mathematics often tend to view models as faithful reproductions of reality or interpret them in a naïvely instrumental way, focusing solely on their outputs without questioning their meaning or the assumptions underlying them (Grosslight et al., 1991; Treagust et al., 2002). This difficulty is well documented in the literature, especially when models involve unobservable entities, operate on unfamiliar scales (e.g., microscopic), or involve abstract or counterintuitive variable relationships.

To address these challenges, the TLS was designed to guide students through a gradual and reflective process of appropriating the concept of a model, through activities that explicitly problematise the nature and limitations of models themselves. Work was carried out on distinguishing between observable and unobservable, between experimental data and interpretation, between real phenomena and their modelled representations. Emphasis was also placed on the idea that every model is partial, situated, and open to improvement, and that its validity depends on the context and investigative aims. In this way, modelling assumed a metacognitive function, prompting students to reflect on how we come to know what it means to explain, and what the criteria for scientific validity are.

The intention was not only to develop technical competencies, but also a critical disposition towards models, conceived as provisional and contested constructs rather than absolute truths. This approach reflects the widely shared educational view (Schwarz et al., 2009) that involving students in authentic modelling activities can foster deep learning, mastery of scientific practices, and the construction of dynamic, evidence-based, and negotiable knowledge.
When students are placed in a position to construct, compare, test, and discuss alternative models, they do not only learn physics, but they also learn how science works, thereby developing a more robust scientific literacy. This is particularly important in an era in which the ability to interpret models, simulations, and data, even outside the school context, is increasingly essential for engaging critically with a complex and uncertain reality.

The ability to interpret the same physical phenomenon through various levels of representation, each characterised by its own scale, specific conceptual vocabulary, and distinct interactions, constituted a central epistemological and didactic pivot of the TLS, opening the way to deeper meaning-making and the restructuring of naïve conceptions.
The TLS focused students' work on two main scales of modelling: the macroscopic and the mesoscopic, as they are complementary and mutually illuminating. This decision was driven by the intention to articulate the learning pathway across two cognitively accessible levels: on one hand, direct observation of physical phenomena; on the other, their dynamic, computable representation.

The macroscopic scale is the one with which students are most immediately familiar. It falls within the visible domain, i.e., for dimensions greater than approximately 10^{-6} metres (Reif, 1965), that can be explored with the naked eye or, at most, with optical microscopes. This scale corresponds to what can be directly observed and measured in the tangible world. Here, surface phenomena manifest through accessible physical quantities such as force per unit length, capillary rise height, or pressure. The language used is phenomenological, based on empirical relationships, simplified physical laws, and the established conceptual tools of elementary fluid mechanics.
Activities at this scale served a dual function: exploratory introduction and problematisation. As qualitative tasks, they helped stimulate curiosity, gather spontaneous observations, and surface students' prior knowledge, thereby fostering a transition toward more sophisticated ways of representing and explaining phenomena.

The limitation of the macroscopic scale, however, lies in its inability to explain the internal mechanisms underlying observable behaviour. For this reason, scientific and educational approaches often draw on the microscopic model, based on an atomistic-molecular description of matter, in the range of approximately 10^{-10} to 10^{-9} metres or less (Reif, 1965). In the TLS, the microscopic model was referred to only as a transitional tool, helping to bridge students' prior knowledge with more sophisticated representations. However, due to its highly theoretical nature, its role remained auxiliary: it was not the object of active modelling, nor were molecular-scale exercises proposed.

The true conceptual and didactic core of the TLS was situated at the mesoscopic scale, between 10^{-9} and 10^{-6} metres (Battaglia & Fazio, 2019; Besson & Viennot, 2004), an intermediate region between the observable world and the atomic one. It is at this scale that the Smoothed Particle Hydrodynamics (SPH) method, used in the central part of the TLS, is located. In SPH modelling, fluids are represented as a discrete set of idealised particles, each of which does not correspond to a single molecule, but rather to an aggregate of real molecules. Each particle acts as a computational unit with mass, position, and velocity, interacting with others through force laws that mimic physical behaviour (for further details, see Chapter 2).
The fundamental strength of this representation lies in its ability to dynamically visualise interactions that would otherwise remain invisible, in other words, it renders the unimaginable observable. While the microscopic scale remains confined to the realm of theoretical thought, the mesoscopic scale, through simulation, allows one to show what happens "within" the fluid, making the role of interparticle interactions explicit. In this sense, mesoscopic modelling functions as an epistemic and cognitive mediation: it allows movement beyond the phenomenological level of the macroscopic scale, while avoiding the conceptual difficulties and opacity of the molecular scale. This makes it cognitively accessible, even to non-expert students, while retaining strong explanatory and predictive power (Monaghan, 1992; Morris et al., 1997).
Within the educational design, simulation-based experiments (as described in §2.3) enabled students to observe the equilibrium between diverse types of forces within a fluid. The simulations modelled two main types of interactions. The first is a molecular-type force, designed to represent liquid-liquid and liquid-solid interactions. This force includes a short-range repulsive component and a long-range attractive component, thus reproducing cohesive behaviour and exclusion forces typical of real fluids. The second is the pressure force, calculated according to the local density of each particle using an equation of state. The interplay between these forces makes it possible to credibly simulate emergent phenomena such as surface tension and capillarity within a virtual environment consistent with observable physical experience.

The interaction between these two scales of representation, the macroscopic, observed through direct experimentation, and the mesoscopic, mediated by simulation, formed the backbone of the entire project. Students were able to compare the two representations, reflect on their respective strengths and limitations, and understand that no description is "final" or "absolute," but that every model constitutes a partial vision of reality, constructed with a particular cognitive aim. The educational objective was precisely to foster multilayered, reflective thinking, capable of navigating different representational forms and of understanding science as a dynamic process of modelling and conceptual negotiation (Harrison & Treagust, 2000).

Chapter 4

Research design

There are moments, in the path of those who teach or conduct research, when questions can no longer be postponed. They emerge with a quiet, insistent force and transform the way we look at teaching: it is no longer sufficient to apply well-established strategies or replicate familiar methods. One must go beyond. One must question what truly happens when a student learns or fails to learn. What drives them forward? What holds them back? Why do certain experiences lead to deep understanding, while others slip away without leaving a trace?
It is from this sense of urgency that the desire arises to observe with renewed attention, to reconsider one's own certainties. And yet, embarking on educational research is never a simple or linear endeavour: it means entering an exploratory phase where intuitions exist, but the contours remain undefined. Designing a research project, in this sense, is an act that moves between doubt and possibility, between the tension towards a direction and the awareness that the path is still to be charted.
The first step, therefore, is to broaden one's gaze. It requires attentiveness towards learners, towards what happens in classrooms, towards those imperceptible signals that often remain beneath the surface yet reveal much about how knowledge is constructed or shattered. The point of departure is not pre-existing truths, but rather questions that demand to be heard; hypotheses born of intuition, of deep curiosity, of a sense of responsibility towards the educational endeavour. It is a process that combines rigour and openness, method and humanity, as it touches the very core of our work as educators.

The research presented here took shape within this framework. What motivated us was a concrete necessity: to understand how to support science learning more effectively, making it less fragmented, more closely tied to experience, and more capable of restoring to students an active role in meaning-making. Scientific knowledge is too often perceived as a set of formulas and definitions to be memorised, rather than as a tool for navigating the complexity of the real world.
We therefore envisioned a pathway that would place meaning at the centre, enabling the construction of connections and the exploration of relationships between concepts, experiences, and representations. The entire structure was translated into a multi-faceted teaching intervention, adaptable to emerging

needs, shaped through listening and close observation of real learning practices. This was a pathway designed to accompany rather than direct; to welcome the plurality of learning styles; to transform didactic planning into a shared experience. It is within this dynamic and relational space that the work that follows has taken form: an inquiry developed in the field, where ideas meet the faces, voices, hesitations, and intuitions of students.

And it is precisely here that we begin.

4.1 Research hypothesis

The present study is grounded in a specific hypothesis concerning the nature of students' reasoning and its role in the learning process. This hypothesis frames the overall research design and informs both the instructional choices and the analytical perspective adopted in the study.

The central research hypothesis of this work is that students initially interpret physical phenomena through hybrid models, in which elements drawn from everyday experience coexist with fragments of formal scientific reasoning. This hybrid character is not assumed to constitute an obstacle to learning; rather, it is considered a potentially productive starting point, provided that the instructional pathway is designed to engage with these initial forms of reasoning in a structured and purposeful way.

On this basis, learning is conceived not as the straightforward replacement of students' initial models with scientifically accepted ones, but as a process of progressive reorganisation and refinement of their reasoning, fostered through sustained engagement with physical phenomena and carefully designed instructional interventions. The subsequent sections specify how this hypothesis is articulated into research questions and how it is empirically investigated within the proposed teaching-learning sequence.

4.2 Research questions

The design of the present experimental study stems from the intention to explore, within an authentic educational setting, how students construct meaning around a set of complex physical phenomena, namely, those related to surface tension, and how such meanings may evolve over time. To address this challenge, two epistemological and pedagogical perspectives, distinct yet complementary, were integrated: on one hand, a macroscopic approach, centred on the direct observation of matter's behaviour in everyday and laboratory contexts; on the other, a mesoscopic approach, introduced through interactive

computational simulations based on the SPH method, which make it possible to visualise the internal mechanisms and forces acting between liquid particles.
This dual perspective does not merely juxtapose two different representations of the same phenomenon but rather seeks to generate a transformative interaction between the levels of description: direct observation stimulates intuition and connections with lived experience, while the mesoscopic representation encourages a more abstract and coherent conceptual restructuring aligned with the scientific model. The primary interest is not, therefore, in assessing the understanding of static concepts, but in investigating the ways in which educational experiences can trigger a process of change in students' mental models, starting from their initial conceptions.
From this framework, the following research questions were formulated:

> *To what extent do the macroscopic and mesoscopic approaches foster the evolution of the mixed knowledge models initially exhibited by students towards more scientifically grounded models?*

> *To what extent does a mesoscopic approach, based on the use of interactive simulations, promote students' learning?*

These questions focus not only the cognitive effectiveness of the tools employed but, more significantly, the transformative dynamics of learning: how does the transition occur from fragmented, intuitive, or experiential knowledge to a more integrated and formalised understanding? What forms does this transformation take across different learners? Under what educational conditions can it be observed, and to what extent can it be facilitated?

The explicit reference to mixed knowledge models underscores the importance of adopting a non-linear and non-deficit-based perspective regarding students' initial conceptions. In line with numerous studies (diSessa, 1993; Vosniadou, 1994; Taber, 2009), it is acknowledged that learners develop, even prior to formal schooling, personal interpretative frameworks that combine elements from various cognitive domains. The aim of this research is thus to understand how such frameworks can be recognised, valued, and reorganised within educational activities through the introduction of diverse representations and languages that foster explicit comparisons across levels of description and conceptual registers.

However, addressing research questions of this scope necessitates a preliminary clarification of what is meant by learning, and what criteria may be used to recognise, describe, and interpret it. It is not sufficient to assess the correctness of a response or to identify a single accurate idea: learning is a multidimensional process involving cognitive, metacognitive, and affective

aspects. It manifests in varied and distributed forms, often unfolding through intermediate stages that are not immediately evident.
It is precisely the awareness of the complex and stratified nature of learning that made it necessary, from the outset, to adopt a theoretical and methodological framework capable of collecting and interpreting, in an integrated manner, the traces left by the learning process across students' different expressive registers (verbal, written, gestural, metacognitive). Interactions, verbal expressions, proposed solutions, and decisions made during activities could not be interpreted in isolation but had to be situated within a broader interpretative framework, capable of attributing meaning to the diverse signals of learning.
From this need arises the interpretative model articulated around three major dimensions of learning, which will be examined in detail in the following section. These serve as analytical entry points through which the collected data were interpreted, revealing the richness of the conceptual transformation process triggered by the TLS.

4.2.1 Dimensions of learning

Considering the formulated research questions, it became necessary to adopt a theoretical framework capable of making the evolution of students' knowledge models observable, describable, and interpretable throughout the educational experience. Since the aim is not merely to assess the possession of specific concepts or definitions, but rather to understand how meaningful changes occur in students' ways of thinking and representing a physical phenomenon, learning is here conceived as a complex and multidimensional process that manifests through a multiplicity of signals expressed across different layers of educational experience.

In the literature, there exists no single or exhaustive taxonomy of the aspects characterising learning, nor a universally shared framework that organises them in a structured system. Instead, there are scattered contributions, often specific to contexts, which examine isolated aspects of the learning process, such as metacognition, well-being, or social interaction. Rarely, however, are these dimensions integrated into a systemic vision. Within educational research, this represents a significant limitation, as learning is a complex process that cannot be effectively understood or evaluated by reducing it to a single observable variable.

It was therefore necessary to undertake a foundational methodological step: to reconstruct, in a coherent and functional manner, a multi-layered vision of learning.
To this end, a conceptual model was developed that integrates into a unified theoretical structure the many facets of learning that the literature, albeit

fragmentarily, identifies as significant. This model is not intended as a rigid formalisation, but rather as a dynamic conceptual map designed to identify relevant observables for investigating how, with which tools, through which processes, and based on which cognitive, affective, and social resources, the student actively constructs their knowledge. The aim was not to compile a list of isolated elements to be observed separately, but to construct a coherent framework in which each aspect derives meaning from its relationship with the others, thus conveying the idea of learning as a unified yet multidimensional process involving knowledge, strategies, emotions, goals, and values simultaneously.

The structure of this conceptual model draws upon Marzano's proposal (1992). Accordingly, we identified three fundamental dimensions of learning:

1. Acquisition of conceptual knowledge,
2. Intellectual growth,
3. Development of habits of mind suited to learning science.

This tripartition proves especially functional for several reasons. Firstly, it allows us to go beyond the dichotomy between declarative and procedural learning by including aspects related to awareness of one's own cognitive processes and emotional engagement, often overlooked yet essential for meaningful learning. Secondly, these three dimensions are not independent but interact dynamically, offering a multi-layered lens through which to interpret the educational experience. Thirdly, this classification enables the operationalisation of learning processes in terms of *observables*, that is, behaviours, strategies, and communicative and cognitive choices that can be identified and analysed in authentic contexts such as those envisaged by our TLS.

Within each dimension, specific aspects of learning, referred to as observables, were derived from educational and psychological literature, each with its own function and relevance. Although originally described in different contexts, these observables were harmonised and coherently organised within the map. The result is an interpretative framework that not only allows for the observation and coding of learning manifestations during the experimental activities but also provides a broader lens for reflecting on how students learn, what influences the quality of their learning, and which aspects should be further supported from an educational perspective (Figure 4.1).

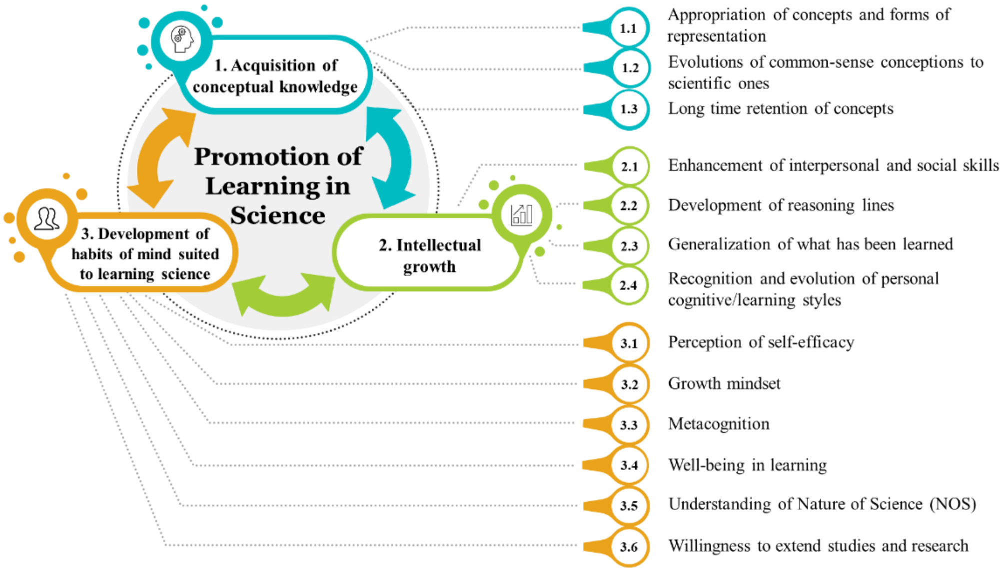

Figure 4.1: Map illustrates the fundamental dimensions involved in fostering scientific learning, highlighting the connections between conceptual knowledge, intellectual growth, and the development of mental dispositions conducive to the study of science.

In this way, the map constitutes a genuine theoretical and methodological scaffold for the research. It does not merely describe learning as a product but enables its analysis as a process in motion, marked by tensions, uncertainties, reformulations, and progress. Moreover, the identified dimensions and aspects serve as heuristic tools to guide both direct observation and the interpretation of the collected data, enabling a structured and grounded reading of the cognitive and affective trajectories of the participating students. It is, however, important to emphasise that these observables do not correspond directly to what students express at any given moment; rather, they serve as interpretative categories through which traces of learning may be read. They are conceptual tools that help infer from what students say, do, write, or represent, which dimensions are active, which processes are underway, and which resources are being mobilised. In practice, this means that data were not coded in a decontextualized way, but rather interpreted thoughtfully, each piece of evidence being examined in search of a meaningful intersection between the original significance of the data and the interpretative framework provided by the observables. In this sense, observables are not merely descriptive indicators, but interpretative horizons: they provide a perspective from which to observe, with the awareness that any given student response may embody several aspects simultaneously, or express an intermediate, incomplete, or even contradictory path.

We are nonetheless aware that the selection of the thirteen proposed observables does not exhaust the richness and variety of possible manifestations of learning. The conceptual map developed here does not claim to be definitive or all-encompassing. Rather, it is offered as an open, revisable, and adaptable proposal, one that may be expanded, redefined, or deepened in response to diverse contexts or emerging research needs. Ultimately, it represents a grounded attempt at systematisation, aiming to reconcile analytical rigour with fidelity to the complexity of educational phenomena.

4.2.1.1 Appropriation of concepts and forms of representation

The observable "appropriation of concepts and forms of representation" lies within a broader educational research framework focused on understanding how students construct disciplinary knowledge in a meaningful and enduring manner. It refers to the student's ability to internalise, master, and flexibly use scientific concepts and the symbolic, graphical, linguistic, or mathematical forms through which such concepts are expressed and conveyed in scientific and educational practice.

The term "appropriation", in its deepest educational sense, is to be understood as a process of active and transformative internalisation, rooted in Vygotsky's thought (1978) and subsequently developed in more nuanced ways within the context of science learning. In this perspective, appropriating knowledge does not merely mean acquiring, repeating, or formally adhering to it: it entails re-signifying it in a personal and situated way, reorganising it within one's own conceptual network, and rendering it an operational and identity-defining tool. As Levrini et al. (2015) highlight, appropriation is a process of hybridisation between elements of scientific culture and the student's own resources, prior knowledge, values, interests, and experiences, which generates new forms of meaning and novel ways of engaging in disciplinary practice. Shared cultural knowledge is thus transformed into personal cognitive tools that the student can mobilise in new contexts and integrate with pre-existing concepts.

This process entails at least two complementary dimensions: on the one hand, a deep conceptual understanding that allows for the recognition of the theoretical structure and epistemic cores of a domain; on the other, mastery of the forms of representation through which these concepts are communicated, explored, and manipulated in scientific and educational practice. Without this dual component, both conceptual and representational, learning remains superficial and fragile, incapable of supporting genuine cognitive operativity.
It becomes evident, then, that this approach conceives of appropriation not as a static event but as a dynamic, iterative, and situated process, developing through interactions between the theoretical structure of science and the personal meanings constructed by the student. These interactions should not be regarded as obstacles, but rather as generative opportunities that activate re-elaborations and interpretative choices which would not otherwise occur. In this context,

appropriation takes the form of an experience of meaning, interweaving cognitive, identity-related, and affective dimensions.
In the field of science education, this appropriative process materialises through the fluid and conscious use of representations, whether graphical, algebraic, symbolic, verbal, or diagrammatic. These are not to be viewed as mere accessories to the concept or visual aids, but rather as its expressive structure, facilitating reasoning, inference, and explanation (diSessa, 2004; Ainsworth, 2006).

Ainsworth's work (1999, 2006) on the notion of multiple external representations (MERs) has demonstrated that effective learning often takes place precisely through the ability to coordinate and compare different representations, which may support one another in clarifying functional or structural relationships among variables. However, this coordination is a skill that must be developed, as students initially tend to treat representations in isolation, failing to grasp their epistemic complementarities. In many learning situations, particularly in the early stages of exposure to new disciplinary content, representations are perceived as discrete objects, each with its own grammar, but rarely articulated within a coherent network of meaning. This fragmented approach hinders deep conceptual understanding and makes it difficult for students to develop a sense of mastery. To foster a durable appropriation of scientific concepts and their associated representational forms, it is therefore necessary to design educational experiences that systematically relate different representations, highlighting the transformations, equivalences, and epistemic differences that connect them. In this sense, the concept of coordinated multiple representations (Ainsworth, 2006) becomes crucial, positing that deep learning arises not only from exposure to multiple representations but also from an explicit process of coordinating among them, a process that involves metacognitive reflection and an awareness of the distinct functional roles each representation may play in constructing meaning.
To enable such a process, it is essential to structure learning environments and activities that foster the following operational domains:

1. Focusing on the epistemic constraints of representations: Students must be placed in a position to explore how each representation highlights certain aspects of a phenomenon while concealing others. Understanding these constraints supports the conscious selection of the most appropriate representation to solve a problem or explain a concept.

2. Translation and transitions between representations: Encouraging students to convert information from one format to another, for instance, from a verbal description to a graph, or from an image to a formula, promotes the construction of connections between different expressive modes. This process is a powerful indicator of appropriation, as it shows

that the student is not merely receiving content passively but is actively reconstructing it according to their own cognitive organisation.

3. Explicit discussion of the meaning of representations: Reasoning about representations themselves is essential for developing integrated understanding. Activities such as comparing alternative representations, engaging in collective discussions about their meanings, or critically evaluating their use in specific contexts contribute to strengthening students' awareness and fostering a sense of epistemic agency.

Through these elements, learning moves beyond episodic understanding or rote memorisation and evolves into a form of conceptual and operational mastery, whereby students can consciously mobilise representations to think, argue, explain, and imagine new situations. It is within this generative, reflective, and meaning-oriented capacity that the deeper value of appropriation emerges, not merely as acquisition, but as the personal re-creation of knowledge. This generative capacity aligns closely with the notion of transformative knowledge proposed by Marton & Tsui (2004).

Recognising the appropriation of concepts and forms of representation as an educational observable thus enables a shift in evaluative focus from fragmented or performative outputs to deeper and more systemic traces of learning. This makes visible those processes that mark the transition from passive knowledge to knowledge that is usable, communicable, and transformable. Within this framework, the student transforms knowledge into a resource for understanding the world and acting upon it, employing scientific concepts in novel contexts. Appropriation therefore constitutes one of the most profound and fertile manifestations of meaningful learning.

4.2.1.2 Evolutions of common-sense conceptions to scientific ones

This observable refers to the progressive and qualitatively significant transformation of students' naïve or common-sense conceptions into forms of knowledge that are more coherent with established scientific models. This is not a mere "correction" of errors, but rather a deep process of conceptual reconstruction, whereby pre-existing ideas are gradually renegotiated, restructured, and partially surpassed through engagement with alternative and epistemologically grounded meaning-making practices.

Common-sense knowledge, also referred to as *naïve theories*, is typically contextual, functional, and experiential, responding to immediate needs. It is often expressed in narrative, descriptive, or implicitly causal forms. It is inherently robust, as it is rooted in the repetition of everyday experience.

Scientific knowledge, by contrast, is model-based, systematic, and explicitly theoretical. It is characterised by abstraction, formalisation, and controlled intersubjectivity. However, as scholars such as Toulmin (1972) and Latour & Woolgar (1986) have pointed out, it remains a human construct, historically situated, with its own rules of validation and representation. Its strength lies not in being "true" in an absolute sense, but in its coherence, productivity, and predictive power within specific theoretical frameworks.

There is no need to oppose naïve and scientific knowledge as if they were absolute or mutually exclusive categories. Both represent forms of world interpretation, constructed through different social, cultural, and historical practices. In the literature, these two epistemic perspectives have been examined under various labels: *conceptual development* (Carey, 1985; Vosniadou, 1994); *science conceptualisation* (Driver et al., 1985); *framework theory perspective* (Vosniadou & Brewer, 1992); and *ontological categories* (Chi, 1992).
These approaches converge on a key insight: students' ideas are not absent or wholly incorrect, but rather structured according to local coherences that are functionally tied to lived experience. The objective is thus not to "convert" students to science, but to offer them tools to broaden their cognitive and representational repertoires. Scientific knowledge thus becomes a powerful cultural resource for engaging with the world in more complex and generative ways.

For such a transformation to occur, it is crucial to identify the factor through which knowledge is initially acquired. Knowledge is never assimilated in pure form; it is always mediated through linguistic forms, signs, narratives, and representations. In this sense, all learning is semiotically mediated. As Vygotsky (1978) noted, language is not merely a communicative tool but the very matrix of consciousness, a mechanism that structures reality and enables the organisation of concepts.
This perspective is central to science education: it is not merely about acquiring "new ideas", but about entering a new symbolic space, composed of specific terminology, representational models, abstract relations, and meanings shared within the scientific community. In this respect, modifying one's linguistic repertoire, by replacing or supplementing everyday terms with scientific ones, is not a peripheral act, but a profound cognitive shift that opens up new ways of interpreting, explaining, and acting upon the world.
As Mortimer and Scott (2003) have argued, access to scientific language allows students to reposition themselves epistemically, adopting a more explanatory, abstract, and systematic stance. It is precisely using language that learners move from phenomenological understanding ("water falls because it is heavy") to conceptual structuring ("water falls due to the action of gravitational force").
From this perspective, the conceptual change required to transition from common-sense to more scientifically formalised knowledge does not primarily

involve replacing content but rather shifting between languages and cultural forms of knowledge.

If we accept that language is the primary medium through which we construct and make sense of experience, then teaching science must involve teaching new languages, not merely vocabulary, but ways of classifying, connecting, abstracting, and representing. Changing language is not an external ornament of thought, but a lever to transform it in depth. As Halliday & Martin (1993) have shown, scientific language exhibits specific features:

- high informational density,
- nominalisation (transforming processes into entities),
- systematic use of metaphors and models,
- explicit causal structures.

These features are neither natural nor immediately accessible to students; rather, they must be cultivated through intentional discursive practices within educational contexts. To this end, it is necessary to design learning environments in which students are guided to explore, negotiate, and appropriate new forms of expression, not only by listening to or reading scientific texts, but by actively participating in conversations where disciplinary vocabulary is introduced, meaningfully employed, and critically reworked. Activities that promote linguistic comparison therefore become central: comparisons between every day and scientific discourse, between intuitive descriptions and model-based explanations, and between concrete experiences and abstract representations. The teacher's mediation is crucial in this process, particularly in deconstructing lexical structures and fostering more conscious usage.
Practices such as guided argumentation or verbalisation of experiments become privileged opportunities in which language is treated not only as a vehicle of knowledge, but also as an object of metacognitive reflection. Through such practices, students learn to use technical terms not as labels to memorise, but as tools to differentiate concepts, articulate relationships, and construct meaning. Approaches such as argumentation-based learning (Osborne et al., 2004) foster environments conducive to conceptual change, as they encourage debate, justification, and mutual critique, thus activating a profound revision of mental models.

Considering the above, the observable "evolutions of common-sense conceptions to scientific ones" should not be understood solely as a cognitive indicator. It constitutes a linguistic-cultural transformation, through which it becomes possible to detect the emergence of cognitive dissonances and, with them, the activation of conceptual restructuring processes. These processes provide significant evidence of students' evolving thinking towards more sophisticated and scientifically coherent forms of understanding.

4.2.1.3 Long-term retention of concepts

One of the most significant indicators of the effectiveness of an educational process is not how much a student learns in the short term, but how much of that knowledge they are able to retain, reuse, and transform over time. The observable "long-term retention of concepts" refers precisely to the ability to maintain conceptually robust knowledge over extended periods, knowledge that does not dissipate after a few weeks but instead becomes stably integrated into the student's cognitive repertoire. Unlike rote knowledge, which tends to deteriorate in the absence of rehearsal, durable retention is a marker of meaningful, rooted, and transferable learning.

A substantial body of research in cognitive psychology has shown that long-term memory is supported by processes involving deep encoding of information. Long-term memory is not a passive repository, but rather a dynamic structure in which new information is processed, reshaped, and reconfigured in relation to prior knowledge. For knowledge to become consolidated over time, it is not sufficient to simply expose students to formal content or to offer them meaningful activities: what is essential is that the acquired knowledge is actively integrated into the learner's existing conceptual network.
Craik and Lockhart's (1972) levels of processing theory demonstrated that retention is more enduring when the material is semantically processed, rather than merely rehearsed. This implies that abstract or disciplinary concepts are fixed in memory not by repetition, but by being understood, connected, re-elaborated, and experienced as cognitively relevant.
In this perspective, learning that leads to long-term retention entails an active conceptual restructuring, as described by Posner et al. (1982) in the theory of conceptual change. New knowledge must not only be intelligible and plausible, but also fruitful for the learner, that is, capable of explaining a wider range of phenomena in a more coherent way than prior conceptions. Only knowledge perceived as meaningful is likely to be retained and reactivated over time. This process of transformative integration is a necessary condition for knowledge to not only endure, but to become usable in new contexts, thereby contributing to the construction of a deeper and more lasting understanding.

At the same time, it is important to recognise that knowledge loss is rarely abrupt. Rather, it is linked to a period of non-use, known as the retention interval. When knowledge is not retrieved, applied, or recalled for extended periods, it tends to fade progressively, especially if it has not found a stable place within the student's conceptual structures. This phenomenon, well-documented by

Arthur et al. (1998), is particularly critical in educational contexts where content is transmitted without being revisited, connected to other learnings, or reactivated through authentic tasks. This suggests that the longevity of learning is influenced not only by the initial depth of understanding, but also by the frequency of reactivation and the learner's willingness to mobilise concepts in diverse settings, whether academic or everyday (Adorno et al., 2018). In this regard, the emotional and motivational context plays a crucial role in sustaining and consolidating learning over time.

Various studies have shown that personal interest, understood as the enduring and autonomously developed engagement with a topic or disciplinary field, is a significant predictor of long-term retention, as it fosters deeper and more voluntary processing of information (Renninger & Hidi, 2015). As emphasised by Ainley (2012) and other scholars of situational interest, emotions experienced during learning are not peripheral to the cognitive process; rather, they are functional components that influence the depth of processing and the likelihood that information will be reused in the future.

Another relevant aspect is the so-called *transfer of learning*: when a concept has been meaningfully learned and retained over time, it is more likely to be applied in contexts different from the one in which it was originally acquired. Transfer is therefore a tangible sign of deep retention, as it implies that the learner has not only retained the concept, but also understands when and how it can be applied in new circumstances (National Research Council, 2000).

Promoting long-term retention thus means enhancing the overall quality of learning, not as an accumulation of static knowledge, but as a dynamic, flexible, and reconfigurable construction, capable of resisting forgetting and being reactivated in varying contexts. Only through an interweaving of meaningful integration and intentional reactivation does acquired knowledge become part of the student's epistemic identity and continue to accompany their learning journey over time, in continuity with future experiences.

4.2.1.4 Enhancement of interpersonal and social skills

In the context of learning, the observable "enhancement of interpersonal and social skills" refers to the progressive development of relational, communicative, and collaborative competencies that enable students to interact effectively, negotiate meaning, assume roles within groups, resolve conflicts, and participate responsibly in collective dynamics. Although not directly linked to the mastery of disciplinary content, these skills constitute an enabling condition for learning itself, particularly in educational settings that promote cooperative work, peer discussion, and shared inquiry. From this perspective, the development of interpersonal competencies should not be regarded as a mere by-product of "working together", but rather as an explicit aim of the educational process, contributing both to the construction of knowledge and to students' personal and social development.

Educational literature widely acknowledges the importance of such skills, often conceptualised within the framework of social and emotional learning (SEL), which regards social and emotional abilities as integral to the formation of conscious, empathetic citizens who can work with others (Collaborative for Academic, Social, and Emotional Learning, 2003). According to DiPerna and Elliott (2000), interpersonal competencies include cooperative behaviours, communicative expressiveness, active listening, and the ability to build positive relationships, all of which are essential components for school adjustment and educational success. In school contexts, these skills are manifested in a willingness to engage with others, respect for speaking turns, the capacity to give and receive feedback, the management of disagreements, and the collaborative construction of meaning.
Studies conducted at university level (Del Barco et al., 2015) also demonstrate that well-designed, sustained group-based activities produce significant improvements in students' social skills, not only in terms of interaction quality, but also in terms of metacognitive awareness of one's own relational style. Once developed, these skills are transferable to contexts beyond the school environment, constituting essential soft skills for students' future professional and civic lives. Furthermore, cohesive and stable groups foster trust and a sense of belonging, which are fundamental for active participation and inclusion.

Of relevance is the enhancement of inclusive processes within peer groups, an aspect that merits further attention. In well-structured collaborative settings, students with diverse personal characteristics, cognitive styles, or levels of participation can find spaces for expression and recognition, feeling legitimised to contribute in ways that align with their own modes of engagement. This strengthens the sense of belonging and reduces exclusionary dynamics, promoting a culture of shared learning in which each participant sees themselves as an active contributor to the process.
Simultaneously, the consolidation of advanced interpersonal competencies within learning groups facilitates the emergence of innovative potential. When interactions are characterised by trust, openness, and mutual respect, students are more likely to share original ideas, explore alternative pathways, and develop novel solutions. Collaboration thus becomes an incubator of cognitive creativity, in which collective intelligence is built through dialogue and the constructive negotiation of meaning. In this sense, this observable does not merely reflect a relational change but also signals the generative and transformative quality of shared learning.

Empirical research confirms the efficacy of such approaches. Educational models based on cooperative learning, such as the one developed by Johnson and Johnson (1998), provide a robust theoretical framework for understanding how intentionally structured cooperation supports the development of these competencies. Elements such as positive interdependence, individual accountability, and mutual support create the conditions not only for content learning, but for learning how to learn together. In these contexts, interaction is not simply a medium for transmitting information, it becomes a subject of learning in itself: students learn to listen, to explain, to seek clarification, to mediate divergent perspectives, and to transform interpersonal relationships into generative spaces of knowledge construction.

From an observational perspective, this dimension of learning can be identified through a series of qualitative indicators: the quality of reciprocal listening, the ability to express dissent in a reasoned manner, the assumption of functional roles within the group (e.g., facilitators, note-takers, synthesisers), the management of conflict dynamics, and the predisposition to value others' contributions. These behaviours do not emerge automatically, but must be cultivated through intentional discursive practices, metacognitive reflection on group functioning, and environments in which participation is genuinely meaningful. In this respect, the development of social competencies is a gradual process that requires time, pedagogical attention, and a climate of trust and mutual respect.

The importance of this observable lies in its ability to highlight a dimension of learning that is often invisible, yet fundamental: the capacity to competently inhabit the social practices of the classroom, to actively contribute to the co-construction of knowledge, and to develop a relational disposition that is open, responsible, and solidaristic. In an era in which learning is increasingly conceived as a distributed and interdependent process, the enhancement of interpersonal and social skills represents a crucial educational challenge, one that intertwines cognitive, emotional, and ethical growth.

4.2.1.5 Development of reasoning lines

The observable "development of reasoning lines" refers to students' ability to construct, articulate, and support coherent argumentative chains based on evidence, principles, and explicit logical connections. This competency does not concern merely the attainment of a correct answer, but rather the way in which such an answer is constructed, justified, and rendered comprehensible to others. In this sense, "reasoning" becomes a learning object, an activity involving cognitive operations such as inference, comparison, generalisation, internal coherence monitoring, and the appropriate use of concepts and representations.

To fully grasp the meaning of a "reasoning line", it must be understood not as a simple sequence of logical steps, but as a dynamic structure of thought that emerges in response to a question, a problem, or a cognitively dissonant event. A reasoning line is constructed as the student seeks to make sense of a phenomenon: selecting relevant concepts, connecting them through causal relationships or structural analogies, anchoring them to observational data or interpretative models, and deriving consequences that feed back into the initial thought. This process is neither linear nor mechanical; it involves internal negotiation, confrontation with prior conceptions, the ability to manage uncertainty, and the exploration of alternative pathways. In other words, a reasoning line is a weave of conceptual and inferential decisions, in which each node contributes to the overall construction of meaning.

A fundamental characteristic of reasoning lines is their revisability: they are not fixed structures, but adaptive systems capable of evolving considering new information, counterexamples, predictive failures, or encounters with alternative viewpoints. The willingness to revise a reasoning line should not be viewed as a weakness, but rather as a sign of epistemological flexibility and metacognitive awareness. This type of revision, whether spontaneous or prompted by the context, is often the clearest indicator that deep learning is taking place: not as mere acquisition of facts, but as an active and reflective reorganisation of thought. According to Lehrer and Schauble (2006), one of the most significant competencies in science learning is the ability to restructure interpretative models based on analysis of one's own lines of reasoning.

From a theoretical perspective, this observable connects to broader reflections on the role of argumentation and logical-scientific reasoning within educational processes. According to Osborne et al. (2004), the capacity for scientific argumentation is a foundational component of contemporary scientific literacy, enabling students to take positions, evaluate claims, distinguish data from inferences, and construct rational explanations. The development of a reasoning line thus implies an internal dialogue among conceptual models, empirical observations, formal rules, and disciplinary languages, materialising in an organised, intentional, and increasingly sophisticated discourse. The student becomes capable of mobilising concepts and representations in sequence, assigning them a functional role in explaining the phenomenon under consideration. As the National Research Council (2007) affirms, promoting scientific reasoning means offering students not merely content to be learned, but thinking practices to be internalised, epistemologically informed ways of proceeding.

Observationally, this competence may manifest through indicators such as: the sequentiality and coherence of logical steps, the pertinent use of key concepts; the capacity to establish causal or functional relationships, reference to experimental evidence or simulations, the formulation of testable hypotheses, and the critical revision of one's own thinking. Reasoning lines often emerge more clearly in contexts of collective discussion or argumentative writing, where students are required to make their inferences explicit, engage with alternative viewpoints, and defend their ideas with supporting reasons.

The educational relevance of this observable lies in its ability to provide access not merely to the "outcome" of learning, but to the cognitive process underlying it, making visible the transformative nature of thinking. In this sense, fostering the development of reasoning lines means creating the conditions for authentic learning, where concepts are not merely acquired but integrated into dynamic and generative cognitive structures, structures capable of supporting understanding, explanation, and problem-solving. As Jiménez-Aleixandre et al. (2000) highlight, what distinguishes advanced reasoning from mechanical response is the awareness of the link between statements and the reasons that justify them, that is, the capacity to transform static knowledge into tools for thought.

It thus becomes evident that the construction of reasoning lines cannot be fostered through transmissive teaching alone. The need to explain, justify, anticipate, or comprehend is activated in specific contexts that pose open-ended questions, present problematic data, or require defending a viewpoint or engaging with contrasting models. As Berland and Reiser (2009) observe, argumentation is not only a communicative practice but a cognitive environment that prompts the student to organise their ideas, test their coherence, and build meaningful connections between concepts and phenomena.

This observable acquires particular significance in teaching contexts that involve the use of models, experiments, simulations, or real-world data. In such environments, developing a coherent argumentative line requires students not only to manipulate information, but to select, prioritise, and connect it based on explicit criteria. It is precisely in navigating complexity that reasoning lines reveal their educational potential, helping students to move among hypotheses, rules, and observations to build explanations that are meaningful, rigorous, and purposeful.

The effects of this process on learning are manifold. On the one hand, reasoning lines act as bridges between isolated bits of knowledge, contributing to the construction of integrated, coherent, and transferable understanding. On the other hand, they become visible traces of evolving thought, tools that allow the student to reflect on their steps, identify critical conceptual junctures, and exercise increasing control over their ways of knowing. Encouraging the development of reasoning lines ultimately means fostering the emergence of a form of reflective, strategic, and sense-oriented thinking, preparing students not only to provide correct answers, but to understand why such answers are valid, and under what conditions they may be so.

4.2.1.6 Generalization of what has been learned

The observable "generalisation of what has been learned" refers to students' ability to extend and transfer acquired concepts, strategies, or models to contexts different from those in which they were originally constructed. It represents a significant indicator that learning has produced not only situated understanding but also a conceptual structure sufficiently abstract, flexible, and internalised to be mobilised in novel situations, whether academic or every day. Generalisation is neither spontaneous nor automatic: it requires the ability to recognise structural analogies between different problems, to abstract operational regularities from specific examples, and to apply already established interpretative schemas to seemingly new phenomena.

The importance of this observable is grounded in a robust theoretical foundation spanning the psychology of learning. Beginning with Piaget (1952), the transition from concrete to formal intelligence is manifested precisely in the ability to internalise logical operations and apply them beyond the immediate context. Bruner (1960), in outlining the spiral nature of learning, emphasised how education must continuously aim at reconstructing concepts at increasingly abstract levels, precisely to foster their generalisability. More recently, research within situated learning and transfer studies (Greeno et al., 1993; National Research Council, 2000) has shown that generalisation occurs effectively only when the student succeeds in discerning the conceptual invariants across contexts, rather than merely repeating an algorithm or procedure.

For this to occur, learning must be deep, connected, and meaningful: what is learned must be integrated within a conceptual network perceived by the student as coherent and functional. Generalisation is not an automatic transposition; it requires a re-framing of the task, that is, the ability to recontextualise what is known in light of a new scenario, often with different constraints or goals. As Gentner et al. (2003) observe, the process of analogical transfer demands a structural mapping between domains, where what matters is not superficial similarity but the correspondence between functional relationships. Consequently, teaching situations that promote generalisation are those that offer systematic opportunities for variation (Marton, 2015), expose students to diverse but structurally analogous contexts, and make explicit the reasons why a particular strategy works. In other words, to foster generalisation, it is not sufficient to "reproduce the same task in different environments"; it is necessary to render visible the abstract dimensions of learning through reflective, metacognitive, and discursive practices.

Students who succeed in this endeavour are often those who, during learning, have had opportunities to vary perspectives, to verbalise their thinking, and to reflect on the principles guiding solutions rather than merely repeating algorithms. In this regard, metacognitive practices (Flavell, 1979) assume a central role: students who develop awareness of how they learn and solve problems are also more likely to recognise common structures in different tasks and thus actively generalise what they have learned.

From an observational standpoint, this competence may be detected in various ways. Students who generalise demonstrate a certain conceptual fluency, that is, the ability to use models learned in new contexts, recognise recurring patterns, draw analogies, propose solutions previously tried in different problems, and adapt concepts to real or interdisciplinary cases. Such behaviours not only attest to the effectiveness of the instructional process but also indicate that learning has reached an operational mental form, ready for use, integrated, and reusable. As Schwartz et al. (2005) highlight, true generalisation does not consist in simply "transferring" something from one context to another but in generating new interpretations and ways of thinking from what has been learned, in a generative and transformative logic.

This observable invites us to move beyond a static idea of learning as content acquisition and instead to promote the construction of dynamic conceptual competencies that enable students to navigate unfamiliar situations, reinterpret familiar problems considering new conditions, and develop transversal mental tools. This is a crucial challenge for science education, where concepts are often learned in a contextualised manner but struggle to be transferred to other domains. Learning that fosters generalisation is learning that leaves stable traces in students' minds, modifies their interpretative repertoires, and enhances their capacity to act, understand, and explain the real world.

Finally, and no less importantly, generalisation is often accompanied by a creative readjustment of knowledge: the learned concept is not merely applied but reinterpreted in the light of the new context, often producing a more robust and conscious reformulation. This dynamic process of transfer and conceptual reconstruction contributes to the student's epistemic transformation (diSessa, 1993), whereby the student ceases to merely possess concepts and instead learns to master them as tools of thought. Thus, the observable "generalization of what has been learned" signals not only durable learning but also a form of cognitive mastery manifested in flexibility, adaptability, and generativity of thought.

4.2.1.7 Recognition and evolution of personal cognitive/learning styles

The observable "recognition and evolution of personal cognitive/learning styles" refers to students' ability to become aware of their own learning modalities, recognising their characteristics, limitations, and potentials, and to modify or adapt them reflectively and intentionally in response to the challenges posed by the learning environment. This observable represents an important indicator of intellectual maturation and educational autonomy. It signals that the student does not merely "receive" knowledge but becomes an active agent in their own cognitive journey, capable of monitoring, directing, and transforming it.

In the pedagogical literature, awareness of one's cognitive preferences and study strategies has long been recognised as a decisive factor for effective and lasting learning (Schraw & Dennison, 1994; Zimmerman, 2002). However, such awareness is not innate: it is constructed through meaningful experiences, targeted feedback, social comparison, and discursive practices that make visible the "way of thinking and learning." The ability to recognise one's cognitive or learning style enables the student to develop more effective self-regulation strategies, thereby enhancing their efficacy in study and problem-solving processes. Various theoretical models have attempted to provide a functional classification of different learning styles. Among the earliest significant contributions is the work of Barbe et al. (1979), who proposed a distinction among three primary learning modes: visual, auditory, and kinaesthetic. According to the authors, everyone tends to favour one of these channels in processing information: some learn better through images, diagrams, graphs, and visual representations; others through listening and the rhythm of speech; and still others through movement, manipulation, and direct bodily action. This tripartite model had a strong impact on pedagogy, as it encouraged the idea that teaching should be multimodal, capable of engaging various sensory registers to address the plurality of cognitive styles present in the classroom.
Building on this framework, Neil Fleming and Colleen Mills (1992) developed the well-known VARK model (Visual, Aural, Read/Write, Kinesthetic), which expands Barbe's classical typology by adding a new category for those who preferentially learn through reading and writing. Although VARK has been subject to debate within the scientific community (Pashler et al., 2008), it has succeeded in raising awareness among educators and students about the diversity of cognitive styles and the necessity of recognising and reflecting upon them. In this perspective, recognising one's learning profile does not imply crystallising it into a fixed type but entails becoming aware of habitual cognitive strategies

and developing the ability to adapt or expand them according to tasks, contexts, and educational goals.

What renders this observable particularly significant is precisely its evolutionary dimension. Learning styles are not rigid or stable traits over time but flexible modalities that can be expanded, enriched, or even transformed through experience, interaction, and self-reflection. In this regard, the role of teaching is not merely to "adapt" to pre-existing styles but to create conditions whereby students can broaden their range of cognitive resources by exploring alternative approaches and learning to select strategies suited to the task and context. As Vermunt and Verloop (1999) emphasise, self-regulation of learning represents one of the highest forms of educational competence, as it integrates cognitive, metacognitive, motivational, and affective aspects. The student not only learns "what" but also "how" they learn and, importantly, "how they can learn differently."

From an observational viewpoint, this competence may emerge in many ways: verbalisation of one's mental processes, the ability to choose different strategies depending on the task type, reflective consideration of what has or has not worked, and willingness to critically restructure study habits. It may also manifest in peer interaction, where the exchange of approaches and perspectives makes different ways of thinking and learning visible, stimulating processes of mutual adaptation.

The educational value of this observable thus lies in its facilitation of autonomous, adaptive, and lifelong learning. Learning becomes transformative, enabling students to become more independent, critical, and resilient in their academic and personal journeys. A student who knows how they learn, and who is capable of questioning and expanding their styles, is one who can face new tasks, manage uncertainty, self-correct errors, and learn beyond formal contexts. Activities that promote the recognition and evolution of cognitive and learning styles do not merely transmit content but nurture reflective individuals capable of consciously navigating their cognitive pathways and building an active, personal, and transformative relationship with knowledge.

4.2.1.8 Perception of self-efficacy

The observable "perception of self-efficacy" refers to the confidence students place in their own abilities to undertake tasks, solve problems, understand complex concepts, and successfully complete learning activities. It is not a mere self-assessment of current competences but an anticipatory and motivational belief that profoundly influences behaviour, engagement, and perseverance when facing cognitive challenges. In this sense, self-efficacy represents a crucial psychological variable for understanding the quality of the educational experience and the actual transformative potential of learning.

The most robust theoretical foundation of this observable lies in the work of Albert Bandura, who defined self-efficacy as the "*belief in one's capabilities to organise and execute the courses of action required to produce given attainments*" (Bandura, 1997, p. 3). According to Bandura, the perception of self-efficacy not only determines the level of motivation but also influences the cognitive strategies employed, tolerance for frustration, persistence in tasks, and the quality of learning. Students with a high sense of self-efficacy tend to select more challenging tasks, demonstrate greater resilience in the face of failure, and engage in deeper elaboration of learned content. Bandura emphasises that those who perceive themselves as efficacious are more inclined to set ambitious goals and persist in achieving them even in the absence of immediate gratification. Within an educational context, this translates into a willingness to sustain cognitive effort even in complex, less structured, and not immediately rewarding activities, such as conceptual modelling, problem posing, or critical review of explanations. Thus, self-efficacy becomes an internal source of regulation that fuels both the motivational and strategic components of learning.

Barry Zimmerman has also made a decisive contribution to the understanding of this variable, situating it within the model of self-regulated learning (Zimmerman, 2000a). In this model, self-efficacy is not an isolated element but interacts with planning, monitoring, and self-evaluation of learning. Zimmerman highlights how confidence in one's abilities directly influences the selection of study strategies, the amount of effort invested, and the capacity for self-regulation in cognitive processes. This implies that working on self-efficacy entails not only motivating students but also educating them to reflect on their cognitive functioning and strengthening their epistemic identity.

This observable is particularly significant within science education, where conceptual complexity, linguistic formalisation, and distance from experiential knowledge can easily generate feelings of inadequacy and negative self-perceptions. Promoting self-efficacy in this context means creating learning environments in which students can encounter progressively challenging situations, receive constructive feedback, experience genuine successes, and reflect on these experiences to reformulate their self-image as capable subjects of understanding and acting upon the scientific world. When students feel able to undertake a task or grasp its implications, they engage more deeply in the cognitive and metacognitive processes that lead to meaning making. Therefore, self-efficacy does not merely facilitate learning: it qualitatively enhances it by orienting students to invest attentive resources, explore alternative pathways,

and reflect on their conceptual choices. It is through such engagement that the educational experience becomes generative rather than purely executive.
The construction of a positive perception of oneself as a learner, however, is not exclusively the outcome of objective success but is nurtured by subjective experiences of competence, social recognition, and cognitive agency. It is precisely when a student perceives themselves as the protagonist of their own comprehension process, rather than as a passive executor, that self-efficacy consolidates. This is especially evident in situations where students actively participate in discussion, explain their ideas, make reasoned decisions, formulate hypotheses, and construct personal solutions, all observable indicators signalling a high perception of self-efficacy.

Another relevant aspect is the relationship between self-efficacy and resilience. As noted by Pajares (1996) and Schunk (2012), students with a strong sense of self-efficacy do not interpret errors as personal failures but as integral parts of the learning process. They exhibit a greater willingness to revise their ideas without undermining their sense of self, to expose themselves to peer evaluation, and to attempt tasks again after encountering difficulties. This attitude is crucial in how errors are experienced: not as identity threats but as opportunities to learn and grow cognitively. Consequently, enhancing self-efficacy directly impacts students' ability to face complex, ambiguous, or novel situations, those that characterise authentic scientific learning.

Finally, the perception of self-efficacy also has significant effects on the construction of students' scientific identity: when a learner begins to see themselves as capable of thinking scientifically, understanding phenomena, modelling, and explaining, profound spaces for identity development open up. In this regard, the observable "Perception of self-efficacy" is not merely a motivational indicator but a signal of epistemological and personal transformation in the relationship between the student and knowledge.

4.2.1.9 Growth mindset

The observable "growth mindset" refers to students' disposition to regard their cognitive abilities and learning potential not as fixed, innate traits, but as dynamic and modifiable qualities shaped through effort, strategy, perseverance, and experience. This mindset, conceptualised and popularised by Carol Dweck (2006), stands in contrast to the so-called fixed mindset, whereby intelligence is viewed as static, and success is attributed more to natural ability than to developmental processes. The distinction between these two conceptions has profound implications for motivation, error management, resilience, and approaches to cognitive challenges.

A growth mindset is not synonymous with general optimism or transient motivation but is rooted in a vision of the self as an evolving entity capable of learning, adapting, and improving through deliberate effort and self-regulation. The pivotal point is not the denial of difficulties, but the recognition of their formative value. The "growth" mind does not evade error or effort: it inhabits, traverses, and uses them as leverage to enhance its competencies.

This implies that the growth mindset is not merely an individual attribute, but a cultural construct grounded in how the educational environment narrates and structures the learning experience. The development of this mindset does not occur spontaneously; it requires a teaching context that values process over product, legitimises error as part of learning, and provides students with opportunities to reflect on their growth trajectories. It is important to emphasise that the growth mindset is not a mere abstract belief but a genuine epistemic framework shaping the interaction with knowledge: it influences the willingness to engage with conceptual models, argue ideas, face ambiguity, and transform initial intuitions into more structured explanations.

Within this framework, the role of pedagogical strategies explicitly supporting the construction of a growth mindset becomes fundamental. These may include the use of rubrics valuing progress over performance, formative feedback aimed at improvement, public discussion of errors as opportunities for collective learning, and guided metacognitive reflection that helps students perceive their developmental trajectory over time. Notably, as Blackwell et al. (2007) highlight, students who internalise an incremental theory of intelligence also tend to adopt mastery goals rather than performance goals, resulting in positive effects on achievement and school satisfaction.

In the scientific domain, the growth mindset manifests as a readiness to confront complex and novel situations without fear of failure, an openness to revising and improving explanations, a seeking of feedback for growth, and a belief that learning is an incremental process. This orientation is intricately linked to how students interpret errors: those with a growth mindset do not experience error as evidence of inadequacy but as an opportunity to explore new strategies and deepen conceptual understanding. As noted by Dweck and Yeager (2019), this perspective supports engagement even under conditions of frustration or failure, contributing to a more resilient and productive educational pathway.

Fostering a growth mindset also entails creating discursive and relational conditions that support metacognitive development, offering frequent opportunities for reflection on progress, encouraging perseverance, and rendering visible learning processes as dynamic and transformable. When students perceive learning as an active, accessible, and improvable practice, a virtuous cycle emerges between motivation, awareness, and mastery: it is precisely in this balance that cognitive growth can take root sustainably.

Literature has also demonstrated that promoting a growth mindset advances educational equity by mitigating the impact of negative self-perceptions and limiting social representations often associated with gender, socioeconomic background, or prior educational experiences (Claro et al., 2016). In this regard, the growth mindset also serves an emancipatory function: it helps construct a student's epistemic identity founded on the possibility of improvement, evolution, and progressive, personal ownership of knowledge. Adopting a growth mindset also means recognising every student's right to change, not to be defined by a single performance, and to rewrite their relationship with knowledge and their epistemic identity. This is particularly relevant for students who have experienced failure, exclusion, or marginalisation. For these individuals, discovering that they can learn "despite everything" represents a form of cognitive and existential redemption, transforming the classroom into a space of emancipation and recognition.

Finally, it should not be overlooked that the growth mindset is not a binary condition (present or absent) but a dynamic horizon, continuously constructed and negotiated. Even students who display it in some areas may show blocks or resistance in others. Therefore, the observation of this variable must be refined, qualitative, and attentive to personal narratives, shifts in argumentative posture ("I understand this better now," "I can learn from this mistake"), and forms of affective engagement. In this sense, the growth mindset becomes not only an indicator of cognitive maturation but also a window into the profound dimension of learning, understood as the self's movement towards knowledge.

4.2.1.10 Metacognition

The observable "metacognition" refers to students' capacity to consciously reflect upon their own cognitive processes, to monitor, regulate, and intentionally control them during learning. It is not merely "thinking about one's thinking," as this observable is often succinctly described, but rather an articulated set of mental operations enabling the student to govern their learning, adapt it to contextual demands, and modify it based on the outcomes of their actions. This form of awareness constitutes a key element in developing autonomous, strategic learning oriented towards meaning making, as it allows students not only to know, but to know that they know, thereby acting with greater autonomy, flexibility, and intentionality in relation to cognitive tasks.

The concept of metacognition was initially formalised by John Flavell (1976), who defined it as the knowledge an individual has of their own mental states and the ability to control them. From this perspective, metacognition comprises two main components: metacognitive knowledge, that is, awareness of one's learning strategies, strengths and weaknesses, and task characteristics; and metacognitive regulation, which includes ongoing monitoring, activity planning, strategy adjustment, and retrospective self-evaluation. Both components are central to self-regulated learning (Zimmerman, 2000b) and contribute to the development of a profile of the learner as conscious, reflective, and intentional. In this light, metacognition is not a secondary process to content acquisition but a fundamental condition of it: it is what enables the student to interrogate how they learn, what is not working, and which alternatives to explore.

In the context of science education, metacognition plays a strategic role. Understanding scientific concepts often requires the deconstruction of intuitive notions, the restructuring of mental schemas, and the adoption of formal languages and models. All these processes, to be effective, entail not only the reception of new knowledge but also the questioning of prior representations, comparison with those of others, evaluation of internal coherence and explanatory adequacy, and the ability to transition between distinct levels of abstraction. In this sense, metacognition is deeply intertwined with discursive and argumentative practices, fostering deeper and transformative learning.

Metacognitively oriented learning is identifiable through observable behaviours: students who verbalise their reasoning, recognise the origin of difficulties, justify the adoption or abandonment of a strategy, reflect on the efficacy of an explanation, or modify their approach following interaction with the teacher or peers. As emphasised by Veenman et al. (2006), metacognitive skill is a more reliable predictor of learning quality than intelligence level alone: cognitive success depends less on what a student knows and more on how they manage what they know.

Educational literature has repeatedly underlined that the development of metacognition is associated not only with improved academic outcomes (Veenman et al., 2006) but also with greater intrinsic motivation, better time management, and increased resilience in the face of failure. Metacognitively aware students can adapt their strategies to different contexts and adopt an active and responsible epistemic stance. From this emerges the understanding that metacognition is neither spontaneous nor uniform; it must be taught, cultivated, and made the object of focused attention and intentional practice. The most effective teaching practices in this regard promote meta-reflective thinking: open-ended questions encouraging justification of choices, self-assessment sheets for one's processes, learning journals documenting changes in thought patterns, and collective discussions focused not only on content but on the "how" of arriving at that content. In this way, metacognition is not only a cognitive function but an epistemic posture: the way the student positions themselves in relation to knowledge, not as an object to be assimilated, but as a field to be engaged with critically.

An additional, often overlooked aspect concerns the relationship between metacognition and the construction of cognitive identity: reflecting on how one learns inevitably leads to questions about the kind of thinker one is. Which strategies work best for me? When do I learn most effectively? What challenges me? These questions do not only pertain to learning organisation but contribute to defining a profile of cognitive subjectivity, which stabilises over time and influences self-efficacy, motivation, and the capacity to tackle complex tasks. Learning to reflect on one's learning processes means progressively defining one's identity as a knowing subject. This awareness contributes not only to performance improvement but also to consolidating a sense of competence and agency, key elements for enduring and meaningful learning.

In conclusion, metacognition is not an ancillary element of learning but its regulatory engine, the principle that enables students to transform cognitive experience into a personal growth journey. Teaching students to think about their thinking does not abstract the educational activity but endows it with depth, intentionality, and awareness. It is through students' ability to reflect, regulate, adapt, and justify their learning that one of the highest forms of knowledge appropriation manifests.

4.2.1.11 Well-being in learning

The observable "well-being in learning" refers to the quality of the subjective experience that the student undergoes within learning contexts. It is not an ancillary or extrinsic dimension of the cognitive process, but rather a constitutive and transformative element of learning itself. In contemporary educational literature, well-being is no longer regarded as a mere psychological correlate but as an enabling condition for cognitive action and epistemic participation (Ritchhart, 2002; OECD, 2019). It encompasses emotional, motivational, social, bodily, identity-related, and even ethical aspects that synergistically influence the extent, manner, and depth with which a student can learn.

Addressing the theme of well-being in learning necessitates adopting an ecological perspective, recognising that learning environments are also emotional spaces where the learner constructs a self-image, experiences relationships, perceives judgments, and processes successes and failures. From this standpoint, well-being is closely intertwined with a sense of belonging, recognition, and the opportunity to express oneself without fear. As Noddings

(2005) emphasises, learning is never a neutral act: it is an encounter between subjects, mediated by emotions, expectations, and bonds. Well-being thus also rests on the quality of the educational relationship: care, trust, active listening, and the possibility of feeling seen.

However, well-being is not limited to the relational sphere; it also has a strong epistemic component. Learning in a climate of well-being means being able to explore, err, and reformulate without fear of judgment, feeling legitimised to ask questions, doubt, and propose hypotheses. This sense of epistemic security, defined by Carolin Kreber (2013), underpins the construction of a critical and autonomous mind, capable of sustaining the complexity and uncertainty of knowledge. In the absence of such security, the learner tends to retreat into defensive, memorisation-based, superficial strategies, thus inhibiting their exploratory potential. Well-being, in this sense, is the opposite of performative anxiety: it is not the absence of effort but the presence of meaning.

Another significant dimension of well-being concerns the integration of body and mind in the learning experience. Numerous studies have highlighted how cognitive activity is intimately connected to bodily, emotional, and physiological states (Immordino-Yang & Damasio, 2007). Learning does not occur solely with the mind but with the whole self. Activities involving the body, expressiveness, manipulation, and movement contribute not only to making learning more meaningful but also more joyful, vital, and enduring. This is especially true in the sciences, where laboratory experience, simulations, and collaborative problem-solving can generate a sense of bodily agency that strengthens motivation and engagement.

Well-being in learning also manifests in the student's capacity to feel that what they are learning is meaningful to themselves, connected to their life, interests, and questions. When learning becomes significant not only cognitively but also existentially, well-being is not merely a condition but a consequence of the process itself. At this point, what Rogers and Freiberg (1994) term actualising goals come into play: an internal force driving the individual towards the realisation of their potential. Well-being is thus not only a positive emotional response but a signal of integrated and authentic growth.

From an observational standpoint, well-being in learning can be detected through a variety of qualitative indicators: active engagement in activities, expression of positive emotions (interest, enthusiasm, surprise), willingness to participate within the group, sustained motivation over time, ability to tolerate error without discouragement, and contribution to the creation of the classroom climate. Nonetheless, it is crucial to avoid a simplistic or naive view of well-being: it is not about making learning "easy" or "pleasant" at all costs but about building conditions that allow the student to face cognitive effort and conceptual conflict in a sustainable, supported, and meaningful manner.

It must be emphasised, however, that well-being is a highly contextual and intersubjective variable. There are no universally valid “strategies for well-being,” but rather educational practices capable of reading the context, valuing differences, and constructing inclusive environments in which everyone can feel authorised to learn. In this sense, well-being is not only an individual condition but a quality of the learning environment, collectively constructed by teachers and students, day by day.

4.2.1.12 Understanding of the Nature of Science (NOS)

Within science education, the understanding of the Nature of Science (NOS) represents a crucial educational objective, although it is often overlooked or misunderstood. This term refers to students’ capacity to grasp how science functions as a cognitive, social, and cultural enterprise. It does not merely entail knowledge of theories, laws, and models, but involves comprehending how such knowledge is constructed, validated, communicated, and transformed over time. NOS is distinct from knowledge of specific disciplinary content or mastery of experimental skills; rather, it concerns a meta-reflective and critical perspective on science, how scientific knowledge is produced, justified, evolves, and communicated.
This constitutes a higher-order form of learning, in which students not only acquire scientific content but also develop a reflective and critical view of science itself, as a distinctive form of human knowledge.

Before further elaboration, it is necessary to clarify the difference between the concept of the Nature of Science (NOS) and the more commonly taught notion of the scientific method. The scientific method consists of a standardised sequence of steps in conducting science, what scientists practically do: observe, hypothesise, experiment, analyse data, and draw conclusions. In contrast, the NOS concerns understanding how science operates in practice: how scientists think, construct theories, validate results, and how culture, society, and imagination influence the process.

According to Lederman (2007), the understanding of NOS encompasses at least seven fundamental aspects:

- Scientific knowledge is provisional, not definitive, and therefore subject to change;
- Scientific knowledge is empirically based, grounded in and/or derived from observations of the natural world;
- Scientific knowledge is subjective, involving personal backgrounds, biases, and/or theoretical frameworks;

- Scientific knowledge entails creative and imaginative elements, including the invention of explanations;
- Scientific knowledge is socially and culturally embedded, meaning it is a human endeavour rooted in the historical and social context in which it operates;
- Scientific knowledge distinguishes between observation and inference, with observations directly accessible to the senses, and inferences accessible and/or measurable only through their manifestations or effects;
- Scientific knowledge differentiates between scientific laws and theories, with laws describing relationships among observable phenomena, and theories providing inferred explanations of observable phenomena.

These elements emphasise that science is not a closed and infallible system of absolute truths, but rather a dynamic, negotiated process open to error and revision. In this sense, NOS is linked to broader scientific literacy, oriented less towards "knowing science" and more towards "knowing how science works".

From an educational standpoint, however, NOS is notoriously challenging to teach and learn. It requires overcoming the naive and positivist image of science as a linear accumulation of impersonal, aseptic truths, which still dominates common sense and many teaching practices. Students often maintain an "absolutist" view of scientific knowledge, believing every theory to be true until disproven, or an extreme "relativist" stance that questions all criteria of objectivity. Both positions, if not critically examined, hinder the development of an authentic understanding of science as a rigorous but fallible cognitive activity, argumentative yet evidence-based, collective but non-arbitrary.

For NOS to be genuinely learned, explicit teaching practices must be introduced to promote metascientific reflection and critical analysis of knowledge construction processes. Established studies (Abd-El-Khalick & Lederman, 2000; Khishfe & Abd-El-Khalick, 2002) show that implicit teaching of NOS, that is, relying on the assumption that students will grasp it simply through "doing science", is ineffective. Instead, intentional, and dialogic instruction is required, where explicit questions are raised about how theories are constructed, how evidence is evaluated, the role of error, and how scientific ideas evolve over time.

The use of historical controversies and case studies in the history of science can be a very powerful strategy. Examining cases such as Galileo or Lavoisier reveals the dynamic, contentious, and human character of scientific knowledge, demonstrating how knowledge emerges from complex cultural practices, theoretical conflicts, and debates within communities. Similarly, the use of computational simulations or interpretative models can be a formidable tool to convey the modelling, constructive, and never definitive nature of scientific knowledge.

From an observational perspective, this variable can be detected during collective discussions, in written verbalisation of critical reflections, in arguments about real or simulated cases, and in the correct use of epistemic terms such as "hypothesis," "theory," "model," "evidence," and "explanation." Moreover, it may manifest in students' willingness to question the certainty of acquired knowledge, manage complexity, and tolerate uncertainty, conditions essential for authentic scientific education.

Understanding NOS has not only epistemological implications but also profound educational and civic significance. As Osborne et al. (2003) emphasise, in a society increasingly shaped by science and technology, developing a critical stance towards science is essential to avoid becoming passive subjects of scientific-media discourse. Students must be enabled to recognise the value and limitations of scientific knowledge, to distinguish between opinion and evidence, between established knowledge and contested hypotheses, and between scientific communication and pseudoscientific rhetoric.

Promoting an understanding of NOS thus means educating for scientific thinking as a form of critical and argumentative rationality, rather than as a dogmatic set of truths. It involves introducing students not merely to science, but into science, understood as a living, open, dialogic cultural practice. In this regard, this observable represents one of the deepest and most transformative aspects of the entire educational process and can be considered a necessary condition for the full exercise of scientific citizenship in the contemporary world.

4.2.1.13 Willingness to extend studies and research

The observable "willingness to extend studies and research" refers to students' readiness and desire to independently deepen the topics addressed in the classroom, exploring new directions of study and initiating personal research processes. It captures a fundamental dimension of the relationship with knowledge: not merely what is learnt within the boundaries of formal educational experience, but what the student chooses to prolong, expand, or rework beyond the school context, driven by curiosity, interest, or a sense of meaningfulness. This variable is directly connected to epistemic motivation and, more profoundly, to what Dewey (1976) defined as the "continuity of experience": the capacity of learning to generate new pathways of meaning and action.

This disposition reflects an attitude that transcends mere compliance with assigned tasks: it implies a willingness to pose new questions, seek additional sources, and connect school knowledge to personal or interdisciplinary domains. In education, such an attitude is regarded as a significant indicator of deep learning (Marton & Säljö, 1976), signalling that the student is not simply acquiring facts but is employing knowledge as a tool to guide their thinking, curiosity, and practices.
Numerous studies have demonstrated that the willingness to pursue autonomous study and research is influenced by several interconnected factors. First, it is shaped by intrinsic motivation, that is, the perception that study is interesting, stimulating, and valuable (Deci & Ryan, 1985). When school activities provide room for choice, invite exploration, encourage open-ended questions, and foster active construction of meaning, students tend to feel more engaged and inclined to continue exploration beyond formal teaching boundaries. A second determining factor is the perception of epistemic agency: students must feel authorised to think independently, to ask questions, and to investigate without constant reliance on external instructions. As Engle & Conant (2002) show, epistemic engagement requires environments that legitimise active participation in knowledge development, positioning students in a dialogic and reflective role rather than a merely receptive one.
Moreover, the desire to deepen studied topics is intricately linked to the construction of personal connections with knowledge: what is perceived as relevant to oneself tends to generate further questions. According to the theory of interest proposed by Hidi & Renninger (2006), individual interest develops gradually through experiences that activate positive emotions, cognitive gratification, and a sense of control. Educational activities that elicit such interest foster, over time, attitudes oriented towards autonomous inquiry.

This observable may manifest in various forms: consulting additional materials, personal initiative in proposing activities, participation in extracurricular projects, independent reworking of learned content, formulation of new hypotheses or research questions. In active learning contexts, this variable can be observed through personal narratives, spontaneous classroom interactions, written work incorporating unsolicited yet pertinent elements, or sustained participation in participatory science experiences or self-managed laboratories.

From an educational perspective, fostering this willingness to extend research entails creating contexts that stimulate curiosity, value non-canonical questions, support autonomy, and convey scientific knowledge as an open, accessible, and evolving space. Learning does not conclude with the instructional unit but branches into personal trajectories that, if nurtured, promote a lasting scientific attitude.

This observable therefore represents a privileged window into recognising the moment when learning emancipates itself from its scholastic form and becomes a desire for knowledge, authentic inquiry, and autonomous construction of meaning. It indicates that what has been learned is not merely understood but has activated a cognitive and existential tension that drives one beyond, towards exploration.

4.3 Development of the TLS

The Teaching-Learning Sequence (TLS) on surface phenomena developed in this study was designed to respond to a dual aim: on the one hand, to enhance the educational value of content that rarely finds space in standard curricula, despite its scientific and applicative relevance; on the other, to create cognitive contexts capable of activating modelling processes and explanatory reasoning in students. Surface tension, droplet shape, capillarity, and other related phenomena are easily accessible experiences within everyday environments, yet they conceal a theoretical complexity that is not immediately visible. This gap between what is observed and what is understood makes surface phenomena particularly suitable for stimulating epistemological inquiry.

The teaching intervention was carried out as part of a PCTO project (Percorsi per le Competenze Trasversali e per l'Orientamento – Pathways for Transversal Skills and Orientation) targeting students from the "G. D'Alessandro" Scientific High School, a state secondary school specialising in scientific studies located in Bagheria, Sicily, Italy. The TLS took place outside the regular curriculum and was developed for 40 hours, distributed across multiple sessions hosted within university facilities.
The PCTO framework provided an institutional setting that allowed for a learning experience free from the constraints of the formal school curriculum, enabling active, collaborative, and inquiry-based learning. In Italy, PCTO pathways are mandatory for upper secondary school students in their final three years and aim to develop transversal and career-oriented competences through laboratory or project-based activities that bridge school knowledge and practical contexts (MIUR, 2019). In this case, the PCTO represented a flexible and fertile space for proposing a TLS focused on non-standard scientific topics and authentic scientific practices.

A total of thirty-six fourth-year students (aged between 16 and 18) participated in the intervention. They were selected based on voluntary enrolment and a demonstrated interest in science subjects such as physics and chemistry. The students came from seven different classes within the same school.

The fact that the participants did not belong to the same classroom group helped reduce the influence of pre-established social relationships and implicit hierarchies, instead fostering the emergence of new relational modes more oriented towards collaboration and personal exploration. Each student was placed in a new social context, engaging with others not based on pre-existing school roles, but through their own competences, curiosity, and willingness to listen. This condition proved conducive to the activation of social and metacognitive learning dynamics (Bandura, 1985), promoting an exploratory and participatory environment in which each student could contribute their own perspective, negotiate meaning, and engage with different viewpoints.
In terms of content knowledge, the students shared a broadly homogeneous background: basic knowledge of atomic structure, ionic and covalent bonding, and a familiarity with classical mechanics. However, none had received specific instruction in fluid dynamics or computational modelling, nor had they previously engaged with computer simulations in scientific contexts. The TLS was therefore designed to gradually build these competences, starting from guided qualitative observations and progressing towards the formalisation of interpretative models.

One notable aspect concerns the gender distribution among participants: of the thirty-six students involved, twenty-nine were male and only seven females. This imbalance, which emerged despite the voluntary and open nature of participation, suggests the persistence of implicit stereotypes and gender biases within the field of science and technology. The project did not include any selection based on specific competences and was open to all interested students. Moreover, it did not involve any form of evaluation that could affect school performance. In this light, the marked male predominance may be interpreted as an indicator of a socially conditioned perception: despite decades of interventions and educational policies aimed at promoting female participation in STEM, many girls still do not fully identify with scientific pathways, especially when these are presented in the form of experimental, technological, or modelling-based activities.

Another crucial element of the experimentation was the learning environment: the project was hosted in the Physics Education Laboratory of the Department of Physics and Chemistry at the University of Palermo, Italy, a space profoundly different from traditional school classrooms. This change of setting played not only a logistical role, but also a cognitive, symbolic, and affective one. Moving away from the conventional classroom allowed students to reposition themselves cognitively, freeing themselves from established scholastic roles, implicit evaluative logics, and consolidated performance expectations. The university laboratory, with its scientific equipment, available materials, and exploratory atmosphere, conveyed a different image of "doing science": more mature, concrete, and participatory.

This type of environment is intended to foster in students a sense of belonging to a broader scientific community, stimulating attitudes of curiosity, responsibility, and collaboration. Recent studies confirm that innovative and well-designed learning environments, particularly those that deviate from traditional teacher-centred classroom models and promote spatial reorganisation, active manipulation, and peer interaction, can positively influence student engagement, wellbeing, and learning effectiveness (Byers et al., 2018; Fisher, 2005).

In science education, the choice of space assumes an even more central role: flexible, stimulating environments designed for exploration can contribute to constructing an image of science not as a set of transmitted notions, but as a practice of inquiry and collective knowledge construction (Beichner, 2008; Dillon, 2008). In this case, the university laboratory functioned as a "productive discontinuity": an unusual context that activated new dynamics and opened previously unexplored learning possibilities. In line with the findings reported by Barrett et al. (2015), the quality of physical space, in terms of flexibility, openness, and sensory stimulation, can have a significant impact on students perceived self-efficacy and cognitive activation.

The students involved in the TLS came from a school context still largely characterised by a transmissive approach to teaching, based on frontal lessons, a sequential and prescriptive exposition of content, and an evaluation system focused on the mnemonic reproduction of knowledge. This type of approach, although deeply rooted in the Italian educational tradition, is grounded in a conception of teaching as the linear transmission of information from teacher to pupil, with the student assuming a receptive role (Freire, 1987). Numerous educational studies have highlighted the limited effectiveness of transmissive teaching, especially in scientific disciplines. It tends to produce superficial and decontextualised knowledge, which often does not translate into genuine interpretative or argumentative competencies (National Research Council, 2000).

The TLS proposed here stands in clear discontinuity with this paradigm, adopting a methodological framework oriented towards active, investigative, and reflective learning. Students are not viewed as recipients of knowledge, but as cognitive agents involved in a process of cooperative knowledge construction.

The design and implementation of the sequence were based on the integration of the Educational Reconstruction theoretical framework and the Investigative Science Learning Environment (ISLE) pedagogical approach.

The Educational Reconstruction framework guided the instructional design through three interconnected phases: the analysis of the relevant scientific knowledge (in this case, the theoretical description of surface tension and intermolecular interactions); the analysis of students' spontaneous conceptions and epistemological difficulties relating to surface phenomena (identified in the preliminary phase through questionnaires and discussions); and finally, the design and implementation of teaching strategies that took into account both the structure of scientific knowledge and the conceptual difficulties that had emerged. This approach enabled the development of activities capable of mediating between expert knowledge and student understanding, thus facilitating genuine conceptual restructuring.

Simultaneously, the TLS was structured in accordance with the principles of ISLE (Etkina & Van Heuvelen, 2007), which promotes a learning environment inspired by the authentic practices of scientific research. Students were engaged in activities that emphasised learning through cycles of observation, hypothesis formulation, experimental design, data analysis, and the comparison of explanatory models. Scientific activity was thus presented not as a collection of consolidated results, but as a process of modelling, experimenting, revisioning, and validating, in which students were required to perform authentic operations and confront uncertainty and complexity. Naturally, the complexity of the ISLE investigative cycle was adapted to the school context, but its essential structure was retained, supporting an active, critical, and reflective approach.

The constructive interaction between Educational Reconstruction and ISLE enabled the construction of a pathway in which students were not mere recipients of content, but cognitive agents called upon to explore, discuss, model, and construct meaning. Computer simulations based on the SPH (Smoothed Particle Hydrodynamics) approach were used not as illustrative supports, but as investigative tools: by directly manipulating the parameters of particle interaction, students were able to observe complex effects and establish relationships between micro and macro levels, developing a dynamic and model-based understanding of the phenomena.

This theoretical and methodological framework formed the foundation upon which the entire instructional design was built. The experience gained during a previous pilot implementation served as a valuable opportunity for critical reflection, enabling the identification of limitations, difficulties, and areas for improvement, both in terms of educational effectiveness and epistemological accessibility. These findings and their comprehensive revision will be discussed in detail in the following section.

4.3.1 Evolution of the TLS design: critical review and educational innovation

The design of the TLS described in this study is the result of a reflective and iterative planning process, which originated from an initial pilot implementation conducted in a comparable context (Termini, 2023). This preliminary experience, involving students of a similar age, academic pathway, and disciplinary background, played a crucial role both in validating the diagnostic tools employed (such as questionnaires and operative worksheets) and in identifying certain criticalities in the structure and management of the sequence. It allowed us to gather valuable insights and to intervene strategically to enhance the educational effectiveness of the TLS.

A particularly significant issue that emerged during the pilot study concerned the students' engagement with the simulations based on the mesoscopic model, which constitute one of the most conceptually innovative components of the sequence. Although initial interest was evident, many students tended to approach these activities in a passive and procedural manner, limiting themselves to following instructions without actively experimenting, exploring, modifying parameters, or reflecting on the meaning of the outcomes. The simulation environment, complex by its very nature, was often perceived more as a task to be completed than as a tool for active scientific inquiry.
This behaviour was interpreted, at least in part, because of the students' limited familiarity with interactive modelling tools and a certain degree of insecurity in engaging with non-standard experimental settings, where no single correct answer exists, but rather a range of interpretative possibilities to be explored. The absence of structured guidance in the use of the simulations exacerbated this sense of disorientation, making it more difficult for some students to adopt an exploratory or hypothetico-deductive stance.
Taking these factors into account, the simulation module was restructured to include a progressive and gradual sequence: prior to engaging with the actual simulation, students worked through guided examples, introductory videos, and walkthroughs that illustrated step-by-step the meaning of computational parameters and their relationship to physical concepts. In parallel, a new preparatory module was introduced at the beginning of the mesoscopic sequence, explicitly presenting the conceptual foundations necessary to comprehend the model's behaviour, such as algorithmic reasoning, the use of force diagrams, and the fundamental principles of mathematical modelling. Elements previously assumed as given were made explicit, to ensure greater conceptual accessibility and broader student participation. As suggested by the research of Redish & Smith (2008) and Sherin (2001), providing students with appropriate interpretive tools prior to using complex computational

environments significantly enhances their ability to draw accurate inferences, formulate reasoned hypotheses, and reflect on the causal relationships underlying the phenomena.

A second critical aspect that emerged from the pilot study concerned the absence of a structured modelling phase during the simulations, essential for supporting adequate reflection, comparison between different cases, and the development of causal explanations grounded in the particulate behaviour of fluids. Students explicitly reported a lack of sufficient time to evaluate hypotheses independently, in other words, to "truly understand" how to construct a given model. This difficulty is well documented in the international literature, which highlights how the effectiveness of exploratory environments relies on extended timescales, opportunities for revisiting concepts, collective discussions, and progressive feedback (Linn & Eylon, 2011).
In response, the revised design centred the experimental activities on modelling, distributing the simulation tasks throughout the timeline and, at times, integrating them with parallel qualitative experimental activities and small-group discussions to facilitate interpretation. In this way, simulations were neither isolated nor relegated to the end of the sequence but integrated throughout, in a continuous dialogue between phenomenological observation and model-based representation.

Another foundational element introduced in the TLS was the intentional reproduction of the dynamic's characteristic of real scientific work, thereby creating a learning environment in which students could perceive themselves as active members of an emerging epistemic community. The main inspiration came from the concept of a *community of practice* as defined by Wenger (1998), understood as a group of individuals who share an interest in a specific domain and who, through active participation, engage in mutual learning and the collective construction of meaning. This theoretical framework, widely adopted in the field of education (Lave & Wenger, 1991; Wenger et al., 2002), was deemed particularly suitable for supporting a design centred on scientific modelling, as it positions learning not as the acquisition of content but as progressive participation in shared cultural and cognitive practices.
Within the TLS, this approach materialised in a sequence of activities designed to replicate, on a didactic scale, the constituent phases of authentic scientific inquiry: the observation of phenomena (both real and simulated), the formulation of explanatory hypotheses, their experimental verification, critical discussion within one's working group, and the public re-elaboration of results. Students, organised into stable small groups, were guided to operate as micro-research teams, each with shared responsibilities and common goals, mirroring the collaborative dynamics of scientific teams. This structure fostered the cognitive distribution of expertise (Hutchins, 1995) and the negotiation of meaning (Driver

et al., 1994), placing the collective construction of knowledge at the heart of the experience.
The collaborative dynamics activated proved crucial in fostering metacognitive skills and argumentative competence. Through discussion, productive disagreement, and the comparison of alternative explanations, students were encouraged to reflect critically not only on content, but also on the explanatory power of the models they constructed, the assumptions involved, and the relationship between data and theory. This process nurtured a climate of co-construction of knowledge, in which peer dialogue functioned as both a cognitive and motivational lever (Mercer, 2000; Ford, 2008).
The extended debriefing sessions, structured towards the end of the activities as plenary discussions, were conceived to simulate the communicative and validation practices of the scientific community. During these sessions, each group presented its observations and interpretations to the class, which functioned both as a peer audience and a critical community. In these contexts, students were required to support their ideas with coherent arguments, respond to questions raised by peers, and consider critical observations that could lead to a revision of their model or proposed explanation. This dynamic had a strong formative impact, as it made the entire process of knowledge construction visible and shareable, including its moments of uncertainty, redefinition, and consolidation.
Within this framework, the role of teacher-researchers was not to transmit already established knowledge, but rather to facilitate learning and guide epistemological reflection. Like moderators at scientific conferences, they intervened by posing key questions, proposing conceptual connections, raising methodological issues, or suggesting alternative interpretative pathways. This facilitative role, essential in inquiry-based learning contexts (Hmelo-Silver et al., 2007), contributed to making the "rules of the scientific game" explicit and to supporting students in developing a mature and flexible modelling mindset.
The TLS designed here thus aimed to render the practice of science visible and accessible, promoting not only content learning but also the learning of scientific practices, languages, cognitive postures, and relational dynamics typical of the scientific community. In doing so, students experienced science not as a body of knowledge to be absorbed, but as a collective process of exploration and meaning making, governed by its own rules, shared tools, and an inherently public and dialogic dimension.

4.3.2 Activity planning

The planning of activities represented a crucial stage in the design process, during which the entire theoretical and methodological framework of the TLS (Etkina et al., 2019) was translated into a concrete sequence, distributed over

time, and adapted to the needs of the participating students. The pathway was structured into five main phases, each characterised by specific aims and operational strategies consistent with the overarching objectives of the intervention. The temporal and didactic organisation of the activities followed a progressive logic, aimed at developing increasingly sophisticated competences in interpreting surface phenomena and in understanding modelling as a scientific practice.
The sections that follow describe the different phases of the learning pathway, comprising a total of 40 hours, outlining their objectives, content, and operational choices.

Table 4.1: Temporal Structure of the TLS. The table outlines the distribution of activities planned within the TLS on surface phenomena, organised into five main phases. For each phase, the table details the activities undertaken, the educational objectives, and the ISLE methodological framework employed. The time schedule was designed to foster a progressive construction of meaning, from the exploratory phase to the metacognitive one, integrating work at both macroscopic and mesoscopic scales.

Phase	Main Activities	Description and Objectives	Didactic-Methodological Framework
1. Initial engagement and activation of prior knowledge	Course and instructor presentation; group division; administration of questionnaires Q.1 and Q.2 (pre-test).	To activate students' prior conceptions and foster motivation. To begin problematising surface phenomena from a phenomenological perspective.	Initial phase of the ISLE cycle, focused on the observation of phenomena and the emergence of authentic questions.
2. Qualitative empirical exploration	Qualitative experiments 1–4 + Activities 1–4 (observation, comparison, discussion).	To promote direct observation of phenomena and encourage the formulation of hypotheses. To strengthen qualitative understanding through collective comparison and discussion.	This phase occurs within the central cycles of the ISLE, during which the formulation of hypotheses, their empirical testing, and the comparison of alternative explanations based on experimental evidence are required.

3. Introduction and transition to modelling	Guided lecture; introduction to macroscopic, microscopic and mesoscopic models; re-administration of Q.1 and Q.2 (intermediate test).	To support the transition from qualitative descriptions to model-based reasoning, providing a theoretical, symbolic, and experiential framework.	Phase of the ISLE, concerned with evaluating the consistency between experimental results and theoretical expectations, with the aim of determining the extent to which the hypothesis requires revision of the model.
4. Guided and independent mesoscopic simulation	Preparatory module; SPH simulations 1–5 (liquid–liquid and liquid–solid interaction, gravity, contact angle, menisci).	To introduce SPH parameters and the computational foundations of the model. To explore the emergent properties of fluids at the mesoscopic scale. To build connections between micro-interactions and observable behaviours. To promote modelling as an explanatory tool.	Phase of the ISLE dedicated to the deliberate use of graphical and reasoning tools to construct, apply, and test the investigated physical concept.
5. Reflection, assessment and metacognition	Final plenary discussion; review of models; evaluation of individual and group pathways. Post-test Q.1 and Q.2; satisfaction questionnaire Q.3.	To foster epistemic awareness, critical reflection on models, and consolidate learning through authentic practices of scientific communication.	Concluding phase of the ISLE cycle, devoted to comparing the outcomes obtained through different representations, interpreting any discrepancies as opportunities to assess the coherence, limitations, and conditions of validity of the models.

Phase 1. Initial engagement and activation of prior knowledge (4 hours)

The initial phase of the TLS was designed with the explicit intention of creating, from the outset, a stimulating and meaningful learning context, one capable of activating students' prior knowledge and motivating them towards the pathway they were about to embark upon. One of the main objectives of this first phase was to foster genuine engagement, building a bridge between students' intuitive knowledge, often derived from everyday experiences, and the scientific formalisation that would gradually emerge throughout the activities. The course, its educational objectives, the overall structure of the activities, and the expected working methods were presented. The researchers involved in the design and implementation of the TLS outlined their role as facilitators of the learning process, clarifying the collaborative and dialogic nature of the entire pathway.

Following this introductory presentation, the topic at the heart of the intervention, surface phenomena, was introduced through references to familiar, tangible situations capable of arousing interest and wonder. Among the examples discussed were the "wine tears" that form along the inner walls of a glass (a phenomenon known as the Marangoni effect), the ability of certain insects to walk on water, and the behaviour of water droplets on different surfaces. These cases, selected for their accessibility and evocative potential, served to problematise simple phenomena, revealing their underlying physical complexity and prompting a first level of scientific inquiry among students. The use of real-world scenarios aligns with established findings in science education literature, which emphasises the educational value of *situated activation* (Driver et al., 1994; Mortimer & Scott, 2003), that is, the use of familiar contexts to facilitate access to new and abstract content.

At the conclusion of this introductory phase, students were randomly assigned to heterogeneous small groups, each of which functioned throughout the TLS as a true "research unit". The choice to avoid pre-existing class groups and instead promote a mix of students from different sections proved strategic: it helped to diminish the influence of established relational dynamics, potentially disruptive to processes of inquiry and discussion, while encouraging the adoption of new roles and fostering a greater sense of individual responsibility within the group.

To immediately prompt reflection on the TLS's key concepts, two diagnostic questionnaires (Q.1 and Q.2 – see Appendices A and B) were administered. These were constructed based on existing literature and had previously been validated during the pilot phase. The questionnaires were conceived not solely as assessment tools, but also as pedagogical instruments, capable of stimulating an initial metacognitive reflection on what students already knew, what they believed they knew, and which questions naturally arose. In this respect, the initial phase fulfilled a dual function: it made explicit the students' cognitive and epistemological starting points, while also opening up the space for a knowledge reconstruction process aimed at the deep understanding of phenomena through observation, comparison, experimentation, and modelling.

Phase 2. Qualitative empirical exploration (10 hours)

The second phase placed students at the centre of a series of laboratory-based experiences focused on the direct observation of macroscopic phenomena related to liquid-liquid and liquid-solid interactions. The university setting, together with simple yet carefully selected materials, helped to make the activities both accessible and intellectually stimulating. Each experiment was designed according to a cyclical structure: individual prediction, discussion in small groups, experimental observation, collective re-elaboration, and plenary discussion. This framework enabled the activation of metacognitive processes and facilitated the transition from naive conceptions to more structured and shared forms of understanding. Students were encouraged to formulate hypotheses, test them experimentally, engage in peer discussion, and thus emulate, in a simplified way, the authentic practices of scientific research.
Below is a detailed breakdown of the qualitative activities, with reference to the worksheets included in Appendix C.

- Activity 1: Objects on the water surface

  Description: Students were provided with small and lightweight objects, such as paperclips of varying sizes and thin needles. They were asked to observe and explain which objects were able to float without sinking, despite being denser than water.

  Purpose and objectives

  1. To introduce the concept of surface tension qualitatively.
  2. To distinguish between buoyancy due to Archimedes' principle and suspension due to surface tension.
  3. To elicit students' spontaneous conceptions concerning density, object shape, and the balance of forces.

  Didactic considerations: This experience highlighted that the behaviour of a liquid surface cannot be solely attributed to the object's mass or density; rather, it involves cohesive forces between water molecules, capable of supporting light objects provided the surface film is not disrupted.

- Activity 2: Soap films on metal frames

  Description: Two types of custom-made frames were used: one rigid frame composed of three fixed metal sides and one sliding metal side, and one flexible frame composed of two metal sides and two inextensible cotton thread sides. After being dipped into a soap solution, the frames were removed and manipulated to observe the shapes assumed by the soap film and the forces acting on the movable sides.

Purpose and objectives

1. To visualise how surface tension minimises the area of the soap film, producing minimal energy configurations.
2. To introduce the concepts of mechanical work and force distributed along a boundary.
3. To reflect on the relationship between shape, geometric constraints, and the distribution of forces.

Didactic considerations: This activity supported a crucial conceptual shift, from mere observation of the phenomenon to inquiry into its underlying mechanism, introducing key notions that will later be revisited in the mesoscopic modelling phase.

- Activity 3: Capillarity

  - Activity 3a: Capillary rise with absorbent paper

    Description: Two glasses were connected by a strip of absorbent paper partially immersed in one of them. The spontaneous transfer of water from one glass to the other was observed.

    Purpose

    1. To introduce the concept of capillary action within a familiar, everyday context.
    2. To explore how the difference in liquid levels influences the rate of capillary rise.

  - Activity 3b: Capillary rise in tubes

    Description: Using glass tubes with different internal rays, students observed the height reached by a column of water rising through capillarity, depending on the diameter of the tube.

    Purpose

    1. To recognise the dependence of capillary rise on the radius of the glass tubes.
    2. To discuss the interplay between cohesive and adhesive forces across different geometries.

Common objectives of both activities

1. To understand that the behaviour of a liquid depends on interactions with the solid surface (adhesion) as well as on internal interactions within the fluid (cohesion).

2. To establish a direct link between empirical observation and physical parameters, thereby introducing the need for interpretative models.

Didactic considerations common to both activities: These activities supported the understanding of cohesive and adhesive forces through the direct observation of capillary phenomena. The comparison between the two experiments encouraged reflection on the relationship between geometry and liquid behaviour.

- Activity 4: The effect of soap on surface tension

Description: After sprinkling the surface of water with light, hydrophobic substances (such as pepper, turmeric, or talcum powder), students added a drop of soap. The powder quickly moved away from the point of contact.

Purpose and objectives

1. To demonstrate how the addition of a surfactant locally alters surface tension.
2. To introduce the notion of a surface tension gradient as the driver of movement.
3. To prompt inquiry into molecular interactions and their macroscopic implications.

Didactic considerations: This activity introduced a dynamic and more complex element compared to the previous ones, demonstrating how surface tension can be modified by external agents such as surfactants. The immediate response of light substances, rapidly dispersing from the point of contact with the soap, enabled students to visualise concretely an otherwise abstract phenomenon: the local variation in surface tension.

Phase 3. Introduction and transition to modelling (6 hours)

This phase represented a critical turning point in the sequence, serving as a bridge between the qualitative observations of macroscopic phenomena and the more formalised approach of computational modelling. Its principal aim was to progressively guide students toward an understanding of scientific models and the practice of modelling, considered central to scientific thinking and activity (Gilbert & Justi, 2016; Schwarz et al., 2009).
The introduction was implemented gradually, beginning with representations already familiar to students, such as macroscopic force diagrams or basic symbolic models. Selective reference was then made to the microscopic model, which students had previously encountered within the domain of chemistry.

While not central to the educational design, this representation provided a useful anchor to facilitate the conceptual transition to the mesoscopic scale, which remained unfamiliar. References to atomic structure, interatomic bonds, and molecular interactions allowed for the activation of prior knowledge, thereby establishing a common foundation on which to build the conceptual shift toward SPH modelling.

Through guided discussions, collaborative reflection activities, and whole-class dialogues, an explicit focus was placed on the epistemological nature of models: it was clarified that models are not copies of reality, but idealised representations constructed for specific interpretative, predictive, or exploratory purposes. The underlying assumptions of each modelling approach, their limits of applicability, and the distinction between descriptive and explanatory models were also analysed. Throughout, the discussion was grounded in examples from prior activities, to maintain continuity between theory and practice and to foster progressive abstraction.

A particularly significant aspect of this phase was the development of metacognitive awareness: students were encouraged to reflect on the processes of representation themselves, and to question how observable reality might be translated into theoretical or computational models. This formed the conceptual basis for understanding mesoscopic modelling as an epistemological tool situated between the macroscopic (visible) and microscopic (invisible) scales, allowing for the simulation of dynamics that are not directly observable but are scientifically grounded.

At the end of the phase, to monitor the evolution of students' conceptions, diagnostic questionnaires Q.1 and Q.2 were administered once again. This intermediate assessment enabled the identification of any changes in their understanding of surface phenomena and in their implicit representations of models, thus providing valuable data for the calibration of the subsequent stages, focused on simulation. This methodological choice reflects the iterative and reflective approach that guided the entire design of the TLS.

Phase 4. Guided and independent mesoscopic simulation (14 hours)

Before initiating the activities based on interactive simulations, a preparatory module was introduced to provide students with the conceptual and operational skills necessary to engage meaningfully with the computational modelling environment. This module served a dual purpose: firstly, to familiarise students with the simulation interface and the interpretation of the involved parameters; and secondly, to explicitly introduce the logical, computational, and mathematical foundations underpinning the functioning of the model. As noted in Chapter 2, the students employed FORTRAN code for

the SPH simulations; however, they interacted with it solely through input files, since a language of such technical complexity would have posed an excessive challenge for high school students.
Students initially worked on guided examples, supported by short introductory videos and annotated walkthroughs. These materials were designed to illustrate the meaning of the main computational parameters (e.g., interaction force intensity between particles, density, initial particle spacing) and to relate them to familiar physical concepts such as pressure, cohesion, droplet shape, and force distribution.

Alongside this technical orientation, a conceptual component was incorporated to reinforce students' understanding of the simulated model's underlying mechanisms. Students were guided through key concepts in computational thinking, including algorithmic reasoning (the ability to deconstruct a process into an ordered sequence of instructions), force diagram representation, and the fundamental principles of mathematical modelling, understood as tools for formally describing the evolution of a physical system. This phase played a vital role in avoiding a merely instrumental use of simulation and instead promoted an active and reflective engagement with the model.
Thanks to this preparatory module, it was possible to render transparent some of the model's underlying assumptions (such as equations of state, particle behaviour, and the definition of attractive and repulsive interactions), and to foster greater student autonomy in analysing the behaviour of the simulated system.

These introductory modules laid the groundwork for a deeper and more critical engagement with the simulations, which constitute the conceptual core of the TLS. Through the mesoscopic SPH modelling environment, students were able to explore the studied phenomena via simulations designed to reveal the emergence of macroscopic behaviours (e.g., surface tension, meniscus formation, wettability) resulting from localised particle interactions. Students observed the dynamic balance between molecular-type forces (comprising short-range repulsion and long-range attraction) and pressure forces, which were calculated based on local density via the equation of state. The simulation interface was supplemented with guiding questions, predictive exercises, parameter comparisons, and collective discussions, as detailed in Appendix D.

- Simulation-based activity No. 1: Simulation of a two-dimensional droplet in microgravity

  Description: At the start of the simulation, students created a square-shaped distribution of particles. Upon running the simulation, they observed the spontaneous evolution of this structure into a circular droplet. If, in the microgravity simulation, molecular-type forces, that is, interparticle interactions, were removed, the initial square configuration would remain unchanged, as no force would act to alter it. Only the presence of these attractive and repulsive interparticle forces gradually smooths the square's corners, promoting the transition toward a spherical shape. Once these forces begin to act, the pressure force comes into play, contributing to the droplet's structural stability.

Purpose and objectives

1. To introduce the mesoscopic scale as an intermediate level between microscopic representation and macroscopic observation.
2. To demonstrate how interparticle forces, in the absence of gravity, spontaneously lead to the spherical configuration of a fluid.
3. To visualise a phenomenon that is not directly observable in everyday experience but nonetheless obeys physical laws consistent with fluid dynamics.

Didactic considerations: The simulation allowed students to visualise the equilibrium between internal forces within the liquid and the emergence of the spherical shape as a minimum-energy configuration. The microgravity context eliminated external perturbations, thus highlighting the cohesive interactions fundamental to understanding surface phenomena.

- Simulation-based activity No. 2: Simulation of a two-dimensional droplet under gravity

Description: Students replicated the formation of a droplet from a fixed base of particles, under the influence of gravity. In this way, they observed the dynamic balance between interparticle forces, pressure forces, and gravitational force.

Purpose and objectives:

1. To analyse the role of gravity in the evolution of a droplet.
2. To understand how droplet shape results from the competition between internal and external forces.
3. To reinforce the concept of state transitions in the system (from stationary to unstable configurations).

Didactic considerations: This activity represented an important moment of conceptual integration between the mesoscopic and macroscopic scales: the simulated phenomenon is common and observable, but the simulation made its invisible mechanisms, those involving interparticle interactions, explicit. The importance of modelling in explaining the origin of observable phenomena became clearly apparent.

- Simulation-based activity No. 3: Formation of liquid menisci

  Description: The simulation displayed the formation of two curved liquid surfaces (menisci) within solid containers. Both water and mercury were simulated. Students observed how the liquid–solid interactions for the two different fluids influenced the curvature of the meniscus.

Purpose and objectives

1. To visualise how adhesive and cohesive forces determine the shape adopted by a fluid in proximity to a solid surface.
2. To dynamically introduce the behaviour of liquids within constrained geometries.

Didactic considerations: This activity made explicit the link between the microscopic properties of interactions, the macroscopic geometry of the liquid, and the mesoscopic modelling of particles.

- Simulation-based activity No. 4: Interaction between a solid body and a fluid

  Description: The simulation represented a solid object placed on the surface of a fluid across three distinct scenarios: in the first, the object remained at a distance from the liquid; in the second, it was suspended on the liquid surface due to surface tension; and in the third, it sank. Whether the object floated or sank depended on the value assigned to the interparticle interaction coefficient.

  Purpose and objectives

  1. To explore the equilibrium condition between gravitational force and surface tension.
  2. To deepen previously explored concepts through experimental observation using real objects (e.g., paper clips, needles), now within a simulated environment.

  Didactic considerations: The activity enabled a direct comparison between empirical experience and simulation, offering a formal explanation of previously observed phenomena. It consolidated the use of simulation as a tool for verification, prediction, and discovery.

- Simulation-based activity No. 5: Formation of a sessile droplet with static contact angle

Description: In the final simulation, a droplet was modelled resting on two different solid surfaces. Students observed the formation of two types of contact angles, either $\theta > 90°$ or $\theta < 90°$, depending on the balance between internal cohesive forces and adhesive interactions with the solid.

Purpose and objectives

1. To understand the concept of static contact angle and its relation to the chemical-physical nature of the solid surface.
2. To reinforce the idea that droplet shape results from complex particle interactions.
3. To introduce the notion of wettability as a measurable and modellable property.

Didactic considerations: This final activity provided an effective synthesis of the entire learning pathway. Starting from visible and intuitive phenomena, students were guided towards a more refined and quantitative interpretation of fluid behaviour. The simulation effectively represented the modelling process, in which all forces at play were analysed in relation to one another.

Phase 5. Reflection, assessment, and metacognition (6 hours)

The concluding phase of the TLS was designed as a moment for collective synthesis and reinterpretation of the concepts addressed throughout the learning pathway, with a dual aim: on the one hand, to assess the actual learning outcomes achieved by students; and on the other, to promote a metacognitive reflection on the scientific practices experienced and on the value of modelling as a cognitive tool.
Through plenary discussions and feedback activities, students were invited to revisit their representations of surface phenomena considering the various modelling scales explored (macroscopic and mesoscopic), comparing their initial interpretations with the new knowledge acquired. This conceptual revision held strong epistemological significance, as it made explicit the dynamic, constructed, and modelled nature of scientific knowledge, moving beyond naïve or rigidly realist views of models.
During the whole-class debriefings, the interactions resembled the dynamics of a genuine scientific community, reaffirming this approach as a powerful educational strategy. Considerable space was also devoted to self-assessment and personal reflection.

The final administration of questionnaires Q.1 and Q.2 allowed for monitoring the extent to which the pathway, particularly the work on mesoscopic

modelling, had contributed to a significant conceptual restructuring, both in terms of content and epistemological awareness.
Finally, students were also invited to evaluate the effectiveness of the learning pathway compared to traditional methods of instruction to which they were accustomed, highlighting difficulties, novel elements, and strengths of the TLS. This was conducted through the satisfaction questionnaire Q.3 (Appendix E), which collected both qualitative and quantitative feedback regarding the pathway, the quality of the activities, the clarity of content, and the perceived level of engagement. The results of these evaluations provided valuable insights not only for estimating the educational impact of the TLS, but also for informing potential future improvements to the project.

Chapter 5

Data collection and analysis methods

Every educational inquiry begins with voices. These are the voices of students, interwoven in written words, in observed gestures, in silences that reveal as much as spoken answers. Listening to these voices means collecting fragments of reality and transforming them into knowledge: a delicate process in which raw data become traces, and traces turn into evidence.
The collection and analysis of data are therefore not merely technical or ancillary tasks; they represent the very heartbeat of scientific inquiry, the point at which theory and practice meet, recognise one another, and begin to engage in dialogue. It is in this phase that the design of the research takes shape, moving from the abstraction of theoretical models to the concreteness of empirical information.
In the field of education, this challenge assumes particular significance: students are not simply "research subjects" or "case studies", but protagonists who bring with them experiences, conceptions, and personal histories that research must value and interpret. To collect data systematically thus means to construct sensitive instruments, capable of grasping the complexity of cognitive and affective dynamics, without reducing them to mere numbers or isolated narratives. True methodological strength lies in balancing these two dimensions: on the one hand, the quantitative approach, which ensures comparability, rigour, and the possibility of generalisation; on the other, the qualitative approach, which conveys depth and meaning.

This chapter therefore opens a perspective on this dual movement: from collecting to shaping, from describing to interpreting, from listening to comparing. Questionnaires, worksheets, interviews, reflective journals, feedback, each of these instruments is not neutral but carries with it a specific perspective on the phenomenon. Similarly, the tools of analysis, both qualitative and quantitative, will be examined in detail, as they enable the organisation of the material collected and its interpretation considering the research objectives. The aim is not merely to present procedures, but to clarify the deeper meaning of the methodological choices adopted: how and why certain techniques were considered suitable for addressing the research questions, and in what ways they contributed to capturing the complexity of the phenomena under investigation.

From this perspective, collecting and analysing data does not only mean describing learning: it means restoring its dignity, understanding it in its full complexity, and transforming it into a resource capable of guiding and improving educational practices. It is a process of listening and construction, a journey that leads from the multiplicity of signs towards a broader and more shared understanding of educational reality.

5.1 Theoretical foundations of data collection

Data collection represents a central and indispensable phase within any empirical research design, as it provides the evidence necessary to describe, interpret, and understand the phenomena under study. It is neither a merely technical nor an accessory step, but rather one of the foundational operations in the production of scientific knowledge. In educational research, the process of data collection assumes a decisive role, as it enables the researcher to access the complexity of the school context and of teaching-learning processes in all their cognitive, affective, relational, and cultural dimensions (Cohen et al., 2018; Wellington, 2015).

Such instruments are never neutral or universally valid; they must be designed, selected, and employed according to the nature of the research problem, the objectives of the study, the context in which it is conducted, and the epistemological framework adopted (Johnson & Christensen, 2019). A conscious choice of instrument requires reflection on the type of data to be collected (quantitative, qualitative, or mixed), on the modes of administration to participants, and on the nature of the inferences to be drawn. In this respect, the validity and reliability of research largely depend on the adequacy of the instruments employed (Lincoln & Guba, 1985; Bryman, 2016).
Data collection instruments thus become an interface between theory and practice, between the pursuit of knowledge and the concrete context. As Denzin and Lincoln (2018) argue, the researcher does not simply "discover" data already present but constructs them through a situated relationship with the field and with the participants involved. In this sense, data collection reflects both an epistemological stance and a methodological choice. For instance, a positivist approach will tend to privilege standardised, replicable, and quantitative instruments, aimed at isolating variables and measuring their effect on a large scale. Conversely, an interpretative or constructivist paradigm will favour qualitative or open-ended tools, seeking to understand participants' subjective perspectives in depth and to grasp the meanings attributed to educational experiences (Schwandt, 2000). This distinction is not merely technical but represents a true ontological and epistemological divergence: what do we

consider data? What can be observed, and how? Which criteria of validity guide our interpretation?
In any case, regardless of the paradigm adopted, data collection instruments fulfil the essential function of translating educational phenomena into information accessible for analysis.

Unlike other disciplines that are more easily standardised, educational research is a field strongly characterised by variability and unpredictability and is populated by individuals who bring with them intentionality, experiences, and unique personal histories. In this context, data collection cannot be reduced to the mere recording of "facts"; rather, it must account for the plurality of meanings that emerge from the interaction between individuals, practices, and environments. Data collection instruments therefore become mediating devices, granting access to this complex reality and rendering it observable, describable, and, to some extent, measurable, while maintaining awareness of the epistemological limitations inherent in the partiality of any observation (Erickson, 1986). It is thus necessary to balance methodological rigour with practical considerations, such as organisational constraints, the time available, and the comprehensibility of the instruments for students with diverse backgrounds.

Recent literature (Maxwell, 2013; Biesta, 2020) invites us to consider data collection not only as an instrumental process, aimed at testing hypotheses or validating theoretical models, but also as an intrinsically dialogical, reflective, and transformative moment within the research pathway. From this perspective, data collection is not a passive act of recording reality; it is an intentional practice capable of generating awareness, change, and learning, both for researchers and for participants (Fals-Borda & Rahman, 1991; Kemmis et al., 2014). Indeed, the interaction established between researchers and participants can become an opportunity to co-construct meanings, to question implicit assumptions, and to foster agency among those involved.
This perspective is rooted in participatory and transformative approaches to educational research, such as action research, formative research, and narrative inquiry, which emphasise the centrality of participants' experiences and subjectivities. Within these models, data collection instruments (e.g., interviews, reflective journals, participatory observations, written productions) are not simply tools for gathering information, but discursive and reflective spaces in which metacognitive and critical learning processes can be activated (Carr & Kemmis, 1986; Mezirow, 1991). Data collection thus also becomes an educational device, capable of attributing pedagogical value to the entire research process, at both the individual and collective level.
Such a view carries profound epistemological implications: it presupposes an understanding of knowledge as socially constructed, situated, and dynamic

(Vygotsky, 1978; Lave & Wenger, 1991), and positions the researcher not as a detached observer but as an integral part of the field of inquiry, engaged in a symmetrical and responsible relationship with the participants (Freire, 1987). Within this framework, data collection can serve to enhance and legitimise the voices and perspectives of both students and teacher-researchers.

Our research is explicitly situated within this theoretical orientation. Specifically, we conceived the instruments of data collection not only as devices for measurement, but also as opportunities for students' cognitive and educational activation. Our methodological design, inspired by the principles of active learning, sought to engage students not as mere respondents to questions but as co-constructors of meaning, capable of reflecting on observed phenomena, on their own explanatory models, and on the conceptual transformations underway. In this sense, data collection also functioned as a metareflective moment, consistent with the objectives of the teaching-learning sequence proposed and with the constructivist approach to knowledge on which it is grounded.

This orientation resonates with Loughran's (2002) argument that authentic inquiry processes in education should support the development of pedagogical awareness and foster reflective professionalism. Moreover, our methodological framework draws upon Mortari and Ghirotto's (2019) contention that every phase of research, including data collection, ought to be conceived as an ethical and formative experience, one that promotes care, listening, and responsibility towards others.

To speak of data collection instruments, then, is to reflect upon the architecture of the entire research design. Each methodological choice directly shapes the quality and depth of the knowledge produced. As Shulman (1986) has emphasised, in educational research the way we collect data is an integral part of the way we construct theory. Consequently, a rigorous discussion of instruments cannot be reduced to a technical description; it must instead be situated within an epistemological framework that gives meaning to the entire investigative process.

Considering these considerations, it becomes evident that the choice and design of data collection instruments constitute a pivotal moment within the research pathway. Precisely for this reason, in the following sections we present and discuss in detail the data collection instruments employed during the experimentation, highlighting their structural features, modes of administration, epistemic aims, and their role within the overall investigative process.

5.1.1 Questionnaires

Questionnaires are among the most widely used instruments in educational research to collect information on students' knowledge, opinions, attitudes, beliefs, and practices. Their diffusion can be attributed to multiple factors: they are relatively easy to administer even to large groups, they offer a certain flexibility in data processing, and they can be employed in both quantitative and qualitative studies, depending on the nature of the questions and the analytical techniques adopted (Cohen et al., 2018; Johnson & Christensen, 2019).
A fundamental distinction concerns the structure of the questions: questionnaires may include closed questions, offering predefined responses, or open-ended questions, inviting participants to formulate their own answers freely. While closed questions allow for easier and more immediate statistical analysis, open-ended questions provide the opportunity to explore in depth students' conceptions, patterns of reasoning, and modes of thinking, particularly in contexts where the aim is to understand how they construct meaning (Oppenheim, 1992).

In educational research, open-ended questions are particularly valued when the objective is to collect rich and qualitatively significant data, especially concerning complex phenomena such as conceptual learning, scientific argumentation, or epistemological reflection. They enable students' voices to emerge, highlight the diversity of their mental representations, and reveal possible changes in the structure and coherence of their discourses (Chi, 1997). However, the use of open-ended questions entails greater complexity in the analysis phase, requiring the development of coding frameworks, rigorous interpretative processes, and, at times, triangulation among multiple analysts to ensure the reliability of the categories employed (Miles et al., 2014).
Another advantage of open-ended questionnaires lies in their formative and reflective potential: the act of formulating a personal, reasoned, and coherent response may stimulate implicit metacognition, encouraging students to become more aware of their ideas, uncertainties, and possible conceptual alternatives. As Mortimer and Scott (2003) observe, the written verbalisation of one's conceptions constitutes an important moment in the process of constructing and revising meanings in science education. Nonetheless, to yield meaningful data, open-ended questions must be formulated with clarity, be appropriate to the participants' cognitive level, and be accompanied by explicit instructions. Furthermore, their administration should take place in a non-judgemental environment, where students feel free to express their perspectives without fear of making mistakes.

Within the present TLS, questionnaires represented a privileged instrument to investigate students' initial conceptions, conceptual transformations, and

explanatory strategies concerning surface phenomena. In line with the qualitative and constructivist approach that guided the entire process, two of the three questionnaires were designed with open-ended questions, aimed at eliciting articulated and personal responses not constrained by predefined options.
The structure of the questionnaires was conceived to progressively sharpen the focus on concepts relevant to our inquiry, without, however, suggesting answers or conditioning students' reasoning. The questions sought to explore prior ideas, phenomenological intuitions, modelling capacities, and potential conceptual reformulations emerging from the teaching activities and simulations.

The construction of these instruments was informed by a careful review of national and international literature, particularly studies addressing students' conceptions of complex physical phenomena, the role of modelling in science learning, and the dynamics of conceptual change (Treagust, 2006; diSessa, 1993; Duit & Treagust, 2003). Building on these theoretical references, a first version of the questionnaires was developed and subsequently subjected to a validation phase through a pilot study with students of the same age group and school track as the final participants (Termini, 2023).
This preliminary phase made it possible to test the linguistic and conceptual adequacy of the questions, their comprehensibility, and their ability to elicit meaningful responses consistent with the research objectives. The responses obtained during the pilot phase were analysed by the research team through a process that led to a critical and targeted revision of the questionnaires, aimed at improving their clarity, relevance, and sensitivity to students' explanatory models. This revision was conducted in accordance with the criteria of construct and content validity (Messick, 1995), ensuring that the questions were consistent with the theoretical constructs under investigation and capable of exploring them in an authentic and non-directive manner.
We shall now examine in detail the structure of the different questionnaires administered during the TLS.

- Questionnaires Q.1 and Q.2

  Within the TLS, the first two data collection instruments consisted of two diagnostic questionnaires (Appendices A–B), designed to explore students' pre-instructional conceptions of surface phenomena. These questionnaires were intended not only as tools for elicitation, but also as opportunities for cognitive activation, capable of stimulating students' spontaneous reasoning in both familiar and theoretical contexts. Both instruments were designed in line with established science education literature (Viennot, 2001; diSessa, 1993; Driver et al., 1994), which emphasises the importance of probing students' spontaneous conceptions through open prompts grounded in everyday situations or common experiences that can generate misconceptions. For this reason, the selected phenomena, such as water absorption by a sponge, capillary rise, or insects walking on water, were chosen for their accessibility and, at the same time, their conceptual complexity, making them capable of activating implicit reflections on cohesion, adhesion, wettability, and surface tension.

From a structural standpoint, Q.1 and Q.2 consisted predominantly of open-ended questions, formulated to elicit personal explanations and arguments based on experience and intuition. Q.1 primarily presented generic situations drawn from everyday life, with the aim of detecting how students spontaneously interpret phenomena involving interactions between liquids and surfaces. Q.2, by contrast, progressively introduced more explicit conceptual elements and questions requiring the activation of theoretical knowledge, particularly concerning cohesive and adhesive forces, capillary action, and surface tension. This choice reflected the intention to observe how students, starting from an intuitive level, engage with greater conceptual formalisation, thereby highlighting possible transitions between spontaneous and scientific models.

In the overall research process, Q.1 and Q.2 played a fundamental role, enabling not only the identification of students' initial conceptions but also the subsequent design of the teaching intervention. The responses provided constituted both an epistemological and pedagogical foundation for structuring the TLS activities, guiding the selection of conceptual content as well as the choice of teaching strategies to be employed during discussion, modelling, and reflection. In this sense, the questionnaires were not merely diagnostic but contributed significantly to the co-construction of the learning pathway.

Both questionnaires were administered individually and in e-learning format, within the university laboratory context in which the TLS was conducted. Students were given a maximum of 50 minutes to complete each questionnaire.

These instruments were re-administered at two further key moments during the intervention: approximately halfway through the teaching sequence and at the end of the educational experience. This choice served not only to verify the effectiveness of the sequence but also as a methodological device to monitor changes in students' conceptions and possible transformations in their explanatory models over time. In particular, the re-administration allowed the detection of both the emergence of new ideas, stemming from engagement with experiments and simulations, and the persistence of alternative conceptions, thus providing a robust basis for qualitative analysis. This recursive approach to data collection, consistent with the reflective cycle characteristic of educational research (Schön, 1992; Elliott, 1991), enabled the tracking of the evolution of students' responses not as isolated events but as cognitive trajectories in transformation, thereby making the very process of learning visible.

- Satisfaction questionnaire Q.3

The third questionnaire (Appendix E) was designed to capture students' perspectives on the entire teaching sequence, addressing subjective dimensions often neglected in more traditional evaluation protocols. The instrument was structured into seven sections: the first six consisted of closed-ended questions organised according to a five-point Likert scale, a widely adopted method in educational research to measure attitudes, perceptions, and levels of agreement or disagreement with specific statements (Likert, 1932; Boone & Boone, 2012). The Likert scale allows for the systematic quantification of subjective responses, while preserving the nuance of individual opinions, and represents a valuable tool for both descriptive and comparative analyses.

The six thematic sections, expectations and prior knowledge, organisation, self-assessment and impact on curricular learning, evaluation of teaching strategies, relational climate and motivation, and overall satisfaction, were designed to encompass, in an integrated and balanced manner, the main factors influencing the perceived effectiveness of an educational intervention. These dimensions are relevant not only to understanding how students experienced the teaching sequence but also to identifying which aspects supported (or hindered) learning, active participation, and emotional engagement. Although not directly linked to disciplinary knowledge assessment, such dimensions are essential for a broader and systemic reading of educational processes and contribute to providing a comprehensive picture of the intervention's impact.

The final section of the questionnaire consisted of an open space for free feedback. This segment, deliberately unconstrained by grids or scales, was conceived to provide students with an opportunity for more personal and reflective expression. Responses to this section were analysed separately through a qualitative approach, to capture possible emerging elements not anticipated by the structured questions and to give authentic value to the participants' voices.

5.1.2 Worksheets

From a theoretical perspective, the worksheets (or activity sheets) are situated within a framework inspired by Inquiry-Based Science Education (IBSE), with a specific adherence to the guided inquiry model (White & Frederiksen, 1998; Chin & Brown, 2000). In this approach, the teacher does not assume the traditional role of content transmitter but rather acts as a facilitator and provider of cognitive scaffolding, offering temporary supports to students' reasoning in the form of guiding questions, prompts, and structured frameworks. The questions contained in the worksheets thus perform a maieutic and orienting function in a process that mirrors the stages of scientific practice: they invite students to observe, formulate hypotheses, compare predictions and outcomes, justify choices, revise their ideas, and attribute meaning to the experiences conducted. The transition from informal learning, often intuitive and fragmented, to scientifically grounded understanding is thus mediated through constant interaction between concrete experience, reasoned discussion, and written elaboration.

The worksheets constitute a didactic and methodological instrument profoundly different from questionnaires, both in structure and in purpose. Whereas the open-ended questions in questionnaires are aimed at assessing prior or acquired knowledge, worksheets are designed to stimulate autonomous exploration, the articulation of thought, argumentation, and peer-to-peer comparison. In this sense, worksheets emphasise not only the final product of learning but above all the process of knowledge construction, highlighting the cognitive strategies adopted by students' step by step, the difficulties encountered, and the conceptual transformations taking place. This makes them particularly suited to investigating transversal competences such as problem-solving, critical thinking, scientific communication, and collaboration.
In practice, worksheets are embedded at the heart of the learning process, with the aim of accompanying, supporting, and documenting students' reasoning during the activities. They are not, therefore, assessment tools in the strict sense, but formative devices, capable of promoting active engagement and critical reflection on what is observed, discussed, or experimented with.

Within the TLS, the worksheets for macroscopic experimentation (Appendix C) were structured in two distinct yet complementary sections, each designed to stimulate specific cognitive and interactive processes.
The first section focused on the exploration of a phenomenon through the viewing of a video, serving as an initial stimulus, followed by individual and group elaboration. Students were invited to observe, propose hypotheses, and compare their interpretations within their small group. This stage served to activate prior knowledge and create a discursive space in which ideas could be

negotiated, developed, or challenged. The process concluded with a plenary discussion, inspired by the community of practice model (Wenger, 1998), which enabled the emergence and sharing of interpretations developed within the groups, bringing different perspectives into dialogue and fostering a collective construction of knowledge.

The second section of the worksheets was dedicated to the experimental activity proper, centred on the observation and analysis of macroscopic phenomena. In this phase, students were required to plan and conduct the experiment, describe their observations, compare the evidence with initial hypotheses, and seek coherent explanations. This stage represented an opportunity to consolidate and restructure their representations, testing previous intuitions against the experimental results. The written responses, comments, and peer comparisons recorded in the worksheets constituted a rich corpus of qualitative data, allowing the research team to closely follow the evolution of students' mental models, identifying critical junctures, conceptual turning points, and the ways in which collaboration and argumentation developed within the groups.

The worksheets designed for mesoscale simulation activities (Appendix D) shared the same educational and methodological framework as those employed for macroscopic experimental activities. In this case as well, the structure of the worksheets fosters a deliberate alternation between individual observation, small-group discussion, and plenary debate, thereby valuing the plurality of perspectives and the negotiation of meaning as fundamental strategies in the construction of scientific knowledge. However, the operational context of the simulations introduced distinctive elements that enriched their educational potential and made cooperative work not only desirable but necessary.

Unlike the previous activities, where each student could independently observe the phenomenon and gather information individually, in the simulation activities each small group was provided with a single measuring device. This choice was not dictated by logistical contingencies, but rather represented a deliberate design element, aimed at fostering coordination, task sharing, and the co-construction of the simulation experiences. Although the first part of the worksheets still required individual responses, intended to gather personal predictions, expectations, or hypotheses, the simulation phase necessarily entailed continuous interaction among group members. Students were required to read the instructions carefully, distribute roles (software management, modification of simulation parameters, recording of observations), discuss strategies to be adopted, and reflect on the outcomes obtained.

To ensure methodological clarity and transparency, and to facilitate readers' understanding of the simulations employed, screenshots corresponding to each configuration required of the students were reproduced in the appendix. These images, however, were not accessible to the participants during the activities: for

this reason, the simulation constituted a discovery process, constructed directly by the groups based on textual instructions. This choice was intended to foster an active and investigative attitude, moving the simulation work away from the logic of mere execution and orienting it towards a dynamic modelling process, in which the cause-effect relationships between parameters and resulting configurations could be understood.
In this respect, the simulation worksheets served a dual function: on the one hand, that of epistemic guidance, providing a structured framework for action and reflection; on the other, that of documentary trace of the modelling process, useful for the subsequent analysis of the learning pathways undertaken by students.

The worksheets, presented in full in the appendix, therefore represent the concrete scaffolding of the TLS, within which the entire design architecture takes shape. Through them, students' experiences are grounded in active, cooperative, and reflective teaching, capable of integrating the conceptual and experiential dimensions and constructing a learning space in which science is learnt by doing science.

5.1.3 Clinical interviews

Clinical interviews represent a qualitative data collection technique that has become well established in both psychology and education for exploring in depth students' cognitive processes, mental representations, and modes of reasoning.
The expression "clinical" was originally introduced by Jean Piaget and his collaborators (Piaget, 1959, 1971) to designate a semi-structured, dialogical, and flexible form of interview, designed to capture the internal logic of thought and the developmental mechanisms of knowledge.
Unlike standardised interviews, in which the questions are fixed in advance and the answers are often codified into predetermined categories, the clinical interview is characterised by an exploratory and adaptive attitude: the interviewer begins with a core set of guiding questions, but allows the interviewee's responses to orient the conversation, reformulating questions, prompting clarifications or elaborations, or abandoning lines of inquiry that prove irrelevant or repetitive.

The choice to conduct clinical interviews is justified by the need to go beyond surface-level responses, probing the underlying reasoning, mental representations, implicit conceptions, and the ways in which the interviewee constructs explanations or solves problems. For this reason, clinical interviews are widely employed in investigations of students' spontaneous conceptions in science education (Driver, 1983; Duit & Treagust, 2003), where written answers may not be sufficiently explicative of the reasoning behind them. The clinical interview makes it possible to detect, in real time, potential inconsistencies in students' thinking, encouraging them to reflect on what they have said, to justify, to reformulate, to question, or to elaborate further. The decision by the interviewer to pursue a given line of questioning is crucial: it may follow from detecting ambiguity, hesitation, or partial justification, or simply from the intuition that behind a statement lies an idea not yet fully articulated or developed. Conversely, when the reasoning is expressed with clarity and coherence, or when the exploration has reached a satisfactory depth, it may be appropriate to conclude that line of inquiry and move on to other themes.

In our TLS, clinical interviews were systematically conducted at the end of the completion of each worksheet, serving as a complementary tool to written documentation. Each worksheet, as already discussed, was structured around an observational or experimental activity, followed by a phase of reflection and discussion, both in small groups and in plenary. The initial questions of the clinical interview drew directly upon the conclusions reached collectively, asking the student whether they considered them consistent with their own observations and beliefs. This initial approach proved particularly effective in placing the student in a condition of relative cognitive security, as it started from content already discussed and shared within the group. In this way, the interviewee did not perceive themselves as being tested, but rather as being accompanied in a process of personal elaboration, supported by the familiarity with the topic and by the possibility of expressing themselves based on a shared foundation of meaning.
The dialogue then proceeded to explore how the phenomenon under study had been understood and reconstructed, examining conceptual connections, difficulties encountered, and the motivations underlying certain interpretative choices. In some cases, counterexamples were proposed or some of the student's statements were deliberately reformulated to prompt deeper reflection, confronting the interviewee with conceptual alternatives or with potential inconsistencies. If carefully calibrated, this type of stimulus does not aim to refute but to broaden the horizon of thought, helping the interviewee to revise their mental models or to strengthen them with greater awareness.

The integration of clinical interviews within our pathway not only provided an opportunity to capture more closely the evolution of students' conceptions but also constituted a metacognitive learning moment. The opportunity to verbalise, to argue, and to engage in dialogue with an attentive interlocutor fostered processes of self-reflection that are difficult to activate in other contexts. This type of interaction is fully embedded within a constructivist and dialogical pedagogy, in which formative assessment intertwines with the construction of meaning, and inquiry becomes itself a tool for learning.

5.1.4 Researchers' logbooks

The researchers' logbook represents a valuable qualitative tool in the context of educational research, despite not being directly produced by students. Its main function is the systematic and reflective recording of observations made *in itinere* by researchers or teachers involved in the study. This instrument makes it possible to capture nuances, impressions, unexpected events, and relational dynamics that would hardly emerge through more structured tools such as questionnaires or worksheets. Indeed, the logbook enables the exploration of the processual dimension of teaching and learning, offering a privileged perspective on the implicit modes of interaction among students, between students and content, and between students and teachers.

A wide body of international literature recognises its potential to support reflective practices and stimulate a deeper understanding of teaching and learning processes. For example, Zeichner and Liston (2013) highlight how systematic reflection on teaching practice fosters continuous improvement in education. Similarly, Bolger et al. (2003) emphasise the capacity of the logbook to provide rich, contextualised, and time-sensitive data, which lend themselves particularly well to qualitative analysis. This tool has also been valued within naturalistic and interpretative approaches to educational research, as it allows the identification of significant micro-events (Lincoln & Guba, 1985), which, though not immediately quantifiable, can serve as crucial indicators for understanding students' conceptual transformations and epistemological stances.
Moreover, the logbook can contribute to triangulating data from different sources, thereby strengthening the internal validity of qualitative analysis (Patton, 1999). Notes allow not only the documentation of surface-level observations, but also the recording of metacognitive reflections and evaluations by researchers, thus fostering a dynamic and contextual understanding of the educational process.

In our specific case, the logbook was adopted as a complementary tool within the TLS for the analysis of educational dynamics that emerged during the experimentation. Three researchers separately kept their own logbook, recording at the end of each day the observations, reflections, and significant events that had occurred during the sessions with the students. This daily work made it possible to maintain a vivid and coherent memory of the progression of the pathway, offering interpretative insights that later proved invaluable in the final phase of analysis.
Once the experimentation was concluded, the collected notes were reread, selected, and reorganised, resulting in a rich and multifaceted account of the dynamics that had unfolded throughout the teaching intervention. This

retrospective analysis enabled us to identify moments of cognitive intensity, recurring obstacles, unexpected reactions, signals of motivation or disorientation, as well as latent elements that had deeply influenced students' knowledge construction. In this way, the logbook emerged as both an interpretative and documentary tool, capable of providing an overview of the experimentation that integrated and enriched the findings from other data collection instruments.

5.2 Data analysis

Data analysis represents a crucial and indispensable phase of any research process, as it enables the transformation of raw material, observations, responses, recordings, into knowledge endowed with meaning and relevance. It is not merely a technical operation of information processing, but a complex process through which data acquire form, coherence, and interpretative value within an epistemological framework. In general terms, analysis can be understood as the set of procedures, reasoning, and tools by which the researcher organises, interprets, and attributes meaning to the collected data (Miles et al., 2014).

The primary purpose of this process is not simply to describe or summarise the data, but rather to identify regularities, connections, differences, and meanings that would otherwise remain implicit or invisible. It is at this stage that research transcends mere empirical collection and becomes a process of knowledge construction. Consequently, analysis cannot be reduced to a simple technical "post-processing" or to a purely executive phase; rather, it should be conceived as an argumentative and reflective activity that connects research questions, methodological design, and the interpretation of results (Maxwell, 2013).

From this perspective, data analysis assumes a dual role: on the one hand, it renders visible the regularities, patterns, and differences that remain implicit or fragmented in raw data; on the other, it allows theoretical constructs to be tested, refined, and sometimes reformulated, thereby providing explanations that are useful not only for interpreting what has occurred, but also for informing future teaching practices, educational interventions, or further research (Patton, 2015). Analysis is therefore not a "neutral" phase, but an active moment of meaning-making, in which the researcher takes decisions that are epistemological, conceptual, and interpretative.

A distinctive feature of analysis, particularly in the social and educational sciences, is its iterative character. It is not a linear procedure progressing mechanically from collection to conclusion, but rather a cyclical movement involving constant interplay between data, emerging categories, and theoretical frameworks. This cyclical nature allows for a progressive refinement of understanding, enriching and revising initial hypotheses in the light of new evidence (Charmaz, 2006; Braun & Clarke, 2006). Analysis thus becomes a dynamic process, open to revisions and reformulations, in which interpretations are never definitive, but continuously negotiated and refined *in itinere*.

Alongside its iterative character, another central aspect is the transparency and traceability of analytical procedures. The credibility of a study does not depend solely on the intrinsic quality of the collected data, but also on the rigour with which the researcher makes explicit the decisions undertaken throughout the analytical process. Documenting coding criteria, intermediate steps, decisions of inclusion or exclusion, and interpretative developments not only strengthens the validity of the study, but also renders it open to critical evaluation by the scientific community (Lincoln & Guba, 1985). In this sense, analysis becomes an exercise in methodological rigour and critical reflexivity, where the role and position of the researcher are not concealed, but acknowledged as integral components of the process of knowledge construction (Schön, 1992; Elliott, 1991).

It is also important to stress that there is no single, universal model of analysis: the way in which data are treated depends strictly on the theoretical and methodological framework of the research. Quantitative approaches aim at the generalisation of results and the identification of statistically significant relationships between variables; qualitative approaches, by contrast, focus on the deep understanding of meanings, processes, and situated practices, valuing the richness and complexity of participants lived experiences. Between these two poles, mixed or hybrid methodologies seek to integrate the strengths of both traditions, thereby offering a more comprehensive and articulated reading of phenomena (Johnson & Onwuegbuzie, 2004; Tashakkori & Teddlie, 2010).
Beyond these differences, what all forms of analysis share is their constitutive role in the production of knowledge: without rigorous analytical processes, data remain a fragmented and mute collection; it is only through analysis that they acquire meaning, are organised into a coherent discourse, and become instruments for generating understanding, transformation, and, ultimately, educational value.
In the following paragraphs, the principal categories of analysis (quantitative and qualitative) will be examined, with a discussion of their specific features and their application to the present study.

5.2.1 Qualitative analysis

Qualitative analysis represents a fundamental approach in educational and social research aimed at achieving a deep understanding of phenomena. Its goal is to capture the meaning, complexity, and nuances of participants' experiences, thereby providing a rich and contextualised representation of the realities under investigation (Denzin & Lincoln, 2018). In other words, qualitative analysis seeks to address not so much how much a phenomenon occurs, but rather how and why it manifests, exploring processes, perceptions, beliefs, and practices in ways that highlight their subjective and situated dimensions (Patton, 2015).

Sources of qualitative data may be diverse: interviews, focus groups, participant observations, logbooks, or textual productions. The common feature is their capacity to reveal meanings that would escape purely numerical measurement, offering the researcher an interpretative lens through which to understand how individuals experience and make sense of phenomena (Maxwell, 2013; Charmaz, 2006). In education, this approach is particularly effective as it allows for the study of learning processes and social dynamics in real contexts, capturing not only what students do, but also how they think, reason, and interact within communities of practice.

A distinctive feature of qualitative analysis is the interpretative construction of data, which requires the researcher to engage in a critical and reflective reading, connecting observations with the theoretical framework of reference. This process involves coding data, categorising, and synthesising content, with constant reference to contextual meanings and participants' experiences (Braun & Clarke, 2006; Saldaña, 2015). Through this operation, conceptual categories, recurring patterns, and theoretical hypotheses may emerge, forming the basis for further investigation or the implementation of targeted educational interventions.

Qualitative analysis, however, is not without challenges. The broader interpretative freedom may introduce risks of subjectivity and interpretative bias; for this reason, methodological transparency and detailed documentation of analytical choices are fundamental to ensuring the credibility and validity of the study (Lincoln & Guba, 1985; Creswell & Poth, 2018). Data triangulation, researcher cross-checking, and the adoption of systematic coding procedures are essential tools for reducing arbitrariness and strengthening reliability (Miles et al., 2014). These strategies, however, do more than mitigate the risks of subjective interpretation: they also enrich understanding by highlighting aspects that might escape a single perspective, thereby ensuring a more complete and articulated view of the collected data.

Qualitative analysis thus emerges as a privileged tool for exploring complex and situated phenomena, allowing researchers to capture not only what occurs, but the meaning experiences assume for those who live them. It does not simply record data, but interprets them and connects them to broader constructs, thereby facilitating the generation of new knowledge, the construction of conceptual categories, and the definition of subsequent research directions. Its effectiveness depends on the researcher's ability to balance methodological rigour with interpretative sensitivity, ensuring conceptual coherence and transparency throughout the analytical process.

In the context of the present study, both phenomenographic analysis and a variant of thematic analysis were employed, chosen for their capacity to explore in depth students' conceptions and cognitive processes. Phenomenographic analysis enables the identification of the different ways in which participants understand and represent a phenomenon, highlighting variations in perception and in the meanings attributed to experiences (Marton & Booth, 1997). Thematic analysis (Braun & Clarke, 2006), in the adopted variant, allows for the identification of recurring patterns in the data and the organisation of information into thematic categories, while preserving the richness of participants expressed content. The combination of these two approaches provided the opportunity to investigate in a structured manner both the conceptual and experiential dimensions of the observed phenomena, maintaining a balance between methodological rigour, interpretative sensitivity, and analytical transparency.

5.2.1.1 Phenomenographic analysis

Phenomenographic analysis is a qualitative approach that emerged within the context of Swedish educational research in the 1970s, particularly through the pioneering work of Ference Marton and the Gothenburg group (Marton, 1981; Marton & Booth, 1997). Unlike other qualitative methodologies, phenomenography does not focus directly on the phenomenon itself, but rather on the different ways in which individuals experience, conceive of, or understand a given phenomenon. In this sense, it is situated within a constructivist epistemological perspective, as it assumes that educational and cognitive reality is not fixed once and for all, but is constructed through the experiences, interpretations, and descriptions provided by individuals.
At the core of phenomenographic analysis lies the identification of variations in students' conceptions of a learning object or experience. These variations are organised into categories, each of which represents a qualitatively distinct way of perceiving or interpreting the phenomenon in question. Taken together, these categories constitute the outcome space: a structured representation that accounts for both the diversity and the hierarchical or logical relationships among the conceptions that emerge (Åkerlind, 2005).

Phenomenography distinguishes itself from ethnography or grounded theory through its specific focus on variation. It does not aim to generate general theories or to provide an in-depth description of a sociocultural context, but rather to systematically map the different subjective experiences of a group of individuals in relation to a particular object. This perspective has proven especially fruitful in educational research, as it enables access not only to what

students know, but above all to how they structure and attribute meaning to their knowledge (Prosser & Trigwell, 1999; Bowden & Walsh, 2000).
A central aspect of phenomenographic analysis concerns the role of language. Students' conceptions manifest primarily through discourse, explanations, and descriptions, which implies that the interpretation of data is deeply rooted in language. As Marton and Booth (1997) emphasise, language is not simply a vehicle for pre-existing thoughts, but the very space in which meanings are articulated, negotiated, and made accessible to research. This reliance on language inevitably introduces an element of interpretative subjectivity on the part of the researcher, which can never be eliminated.
For this reason, phenomenography, like other forms of qualitative analysis, employs methodological strategies designed to reduce the risk of arbitrariness and to ensure rigour. Over recent decades, phenomenography has been applied to a wide range of educational contexts: from conceptual understanding in physics and mathematics, to students' conceptions of learning itself, to investigations of professional training across different fields (Entwistle, 1997; Åkerlind, 2008). In all these applications, what emerges strongly is the capacity of the phenomenographic approach to make visible the complexity and diversity of students' cognitive and affective experiences, while at the same time providing valuable tools for instructional design and pedagogical reflection.

5.2.1.2 Thematic analysis

Thematic analysis is a qualitative methodology designed to identify, analyse, and interpret significant patterns, so-called themes, within textual or multimedia data. Its strength lies in the ability to transform heterogeneous narratives into coherent structures of meaning, thereby revealing not only which issues appear in the data, but also how they are articulated and interconnected (Braun & Clarke, 2006; Guest et al., 2012). In educational contexts, thematic analysis is particularly effective because it combines interpretative depth with descriptive clarity: on the one hand, it highlights the recurring conceptual cores in students' explanations; on the other, it allows these cores to be compared with teaching objectives and theoretical frameworks.
Thematic analysis is inherently flexible: it may be conducted at a semantic level (focusing on the manifest meaning of participants' words) or at a latent level (exploring underlying meanings, cultural assumptions, and implicit cognitive structures) (Braun & Clarke, 2006). This choice, semantic versus latent, is epistemologically significant and must be declared and justified within the research protocol, as it determines the degree of interpretation applied to the data.

One of the most relevant analytical decisions concerns the relationship between data and theory: thematic analysis may follow an inductive (data-driven), deductive (theory-driven), or hybrid approach.

- Inductive approach (data-driven). Here, themes emerge “from the ground up,” that is, from the data themselves without predetermined conceptual constraints. Initial codes arise directly from participants’ formulations, and themes are constructed by aggregating related codes. This inductive route is especially suitable when exploring an under-researched field, when the aim is to give voice to participants without imposing external categories, or when the goal is to discover unexpected patterns (Braun & Clarke, 2006; Guest et al., 2012). Its advantages lie in sensitivity to the data and a reduced (apparent) theoretical imposition; its limits concern the need for strong interpretative transparency (to avoid “emergent” themes being mere constructions of the researcher) and the difficulty of immediately positioning the results within a broader theoretical framework.

- Deductive approach (theory-driven). In the deductive approach, themes are derived from a pre-existing conceptual framework: coding is conducted with reference to theoretical categories that the research seeks to test or explore (for example, mental models or dimensions of motivation). This approach is valuable when the aim is to test or extend specific theoretical constructs, or to compare responses against established categories (Boyatzis, 1998). The advantage lies in its coherence with the theoretical framework and the possibility of producing results that are directly interpretable within the relevant academic discourse; the risk is partiality if data are forced into categories that do not adequately fit them.

- Hybrid approach (inductive → deductive or vice versa). Many studies adopt a strategy that integrates the two poles: beginning with inductive coding to identify themes genuinely present in the data and subsequently comparing or integrating these themes with theoretical categories (Fereday & Muir-Cochrane, 2006). This hybrid pathway is recommended when both exploratory openness and theoretical anchoring are desired; it requires, however, strong methodological rigour and detailed documentation of how and why certain theoretical categories are adopted or adapted.

At a practical level, thematic analysis unfolds through iterative phases, ranging from familiarisation with the data to the generation of codes, the identification and refinement of themes, and their final definition and representation (Braun & Clarke, 2006). Key stages include:

1. Familiarisation: repeated readings, marginal notes, and initial ideas. At this stage, memos are generated to accompany the interpretative process (Miles et al., 2014).
2. Initial coding: segmentation of the data into units of meaning and the assignment of synthetic labels (codes). Coding may be concrete (in vivo) or conceptual; Saldaña (2015) provides a wide range of coding techniques useful in different contexts.
3. Construction and refinement of themes: related codes are aggregated into broader categories; here, the semantic or latent level of analysis is determined. Tools such as thematic networks (Attride-Stirling, 2001) may be used to visualise the relationships between codes and themes.
4. Definition and naming of themes: each theme must be clearly defined, with criteria of inclusion and exclusion.
5. Reporting: the final output is not merely a list of themes, but an argument that links them with one another and with the theoretical framework, illustrated by significant textual extracts.

The credibility of thematic analysis rests on practices of trustworthiness (Lincoln & Guba, 1985), which ensure the robustness and transparency of the interpretative process. Beyond criteria such as credibility, transferability, dependability, and confirmability, qualitative research employs specific procedures to reinforce the internal and external validity of the analysis. Among these, triangulation plays a central role, understood as the comparison of different data sources or analytical perspectives to reduce risks of bias. Another key strategy is peer debriefing, which allows the researcher to submit interpretative categories to external colleagues for critical feedback and reflexivity. Finally, cross-checks among multiple researchers (inter-coder reliability) allow for a comparison of coding choices, the clarification of possible ambiguities, and the strengthening of the coherence of the emerging themes (Nowell et al., 2017; Braun & Clarke, 2021). In this way, thematic analysis does not appear as an idiosyncratic process, but as an intersubjective construction grounded in shared methodological rules that enhance its scientific robustness.

5.2.1.3 Analysis applied to the experiment: methodological choice and operational procedure

The research questions that guide the investigation:

"*To what extent do the macroscopic and mesoscopic approaches foster the evolution of the mixed knowledge models initially exhibited by students towards more scientifically grounded models?*"

"To what extent does a mesoscopic approach, based on the use of interactive simulations, promote students' learning?"

require the deployment of two complementary analytical perspectives.
On the one hand, it is necessary to adopt a phenomenographic plane of analysis, aimed at highlighting the variety of students' conceptions by observing how they interpret, describe and experience the phenomena. On the other hand, it is appropriate to integrate a thematic plane of analysis, which makes it possible to grasp the underlying conceptual models (implicit assumptions, metaphors, meaning structures) that orient those conceptions and which, even when not explicitly articulated, influence the quality and direction of learning.
In this way the two orders of analysis are closely interconnected: while the phenomenographic analysis documents the forms in which students' thinking is manifested, the thematic analysis seeks to interpret those manifestations in the light of a grid of observables, useful not only to decode the evidence collected during the experiment but also to reflect on how students learn, which factors affect the quality of their learning, and which aspects should be reinforced from an educational perspective.

Phenomenographic analysis was adopted as the methodological approach for examining students' responses to questionnaires Q.1 and Q.2, with the aim of reconstructing the different ways in which they conceptualised surface phenomena. The analysis followed a classificatory logic: responses were interpreted and organised into descriptive categories that reflect the variety of ways of understanding the object of study.
To ensure theoretical solidity and coherence with the literature, the construction of the categories rested on two main pillars: firstly, established contributions on students' reasoning in physics, in particular the studies by Greca and Moreira (2002), which highlighted the role of mental, physical and mathematical models in physics learning and teaching; secondly, the work of Sperandeo-Mineo et al. (2006), which illustrated how it is possible to identify descriptive categories through which to interpret and model physical phenomena.
This allowed the analysis to be situated within a conceptual framework in which students' responses were not treated merely as individual productions or classified according to a correctness criterion, but as expressions of broader conceptions, linked both to entrenched cognitive structures and to the educational context in which they took shape.
Three distinct epistemological profiles were therefore identified, reflecting different ways of conceiving and interpreting surface phenomena. These categories, positioned along a continuum of increasing complexity, were elaborated with reference to domain-specific knowledge concerning surface interactions. In this framework, classification is not intended as mere labelling of responses but as an interpretative tool useful for revealing the variety of

perspectives and reconstructing the ways in which students attribute meaning to phenomena.

1. Everyday profile: this category gathers responses grounded predominantly in common-sense reasoning, analogies or immediate intuitions, without explicit reference to scientific concepts. Such explanations draw on images derived from everyday experience, often laden with folk reasoning, which students employ as spontaneous interpretative resources. Although distant from the formal models of physics, these responses are indicative of prior conceptions and constitute a fundamental starting point for any teaching-learning process.

2. Descriptive profile: this second profile encompasses responses in which students identify salient elements of the phenomenon, variables, observable quantities or regularities, but do not make explicit the underlying mechanism. Responses in this category tend to remain at an observational and representational level: they describe "what happens" rather than "why it happens". This form of reasoning, even if not yet causal, represents an important intermediate step because it indicates an initial orientation towards the pertinent selection of factors and relations.

3. Explicative profile: the third category comprises responses in which students invoke causal models, cause-effect relations and theoretical concepts to explain the observed phenomena. From this perspective, understanding is structured through reference to explicit mechanisms, such as the balance of forces at a microscopic level or the action of intermolecular interactions. Explanations of this type of approach the scientific standpoint, showing a more advanced level of conceptual elaboration and command of disciplinary models.

This tripartite scheme enabled a systematic structuring of the analysis while maintaining a strong link with established theoretical frameworks. Moreover, the distinction among the three profiles facilitated identification of cognitive progress and of persistent limitations in students' conceptions, thereby allowing for a more nuanced discussion of the results.

Thematic analysis was applied to the data collected via the operational sheets, the clinical interviews, the field journals kept by the three researchers during each activity and the students' feedback provided in questionnaire Q.3. This choice was deliberate: these instruments supply a rich, situated account of the experiences, since they document not only students' explicit answers but also argumentative processes, encountered difficulties and researchers' observations. They therefore permit access to a level of detail that the end-of-module questionnaires alone could not provide.

The analysis was conducted at both semantic and latent levels, following the approach proposed by Braun and Clarke (2006). The dual perspective proved essential: the semantic level allowed the identification of recurring linguistic patterns and lexical shifts, guaranteeing empirical traceability and monitoring the evolution of students' formulations; the latent level made it possible to uncover implicit meanings and underlying cognitive structures, namely the modelling modes through which students progressively interpreted the phenomena. Limiting the analysis to only one of these levels would have produced a partial picture: the semantic without the latent would reduce the analysis to a descriptive inventory, whereas the latent without the semantic would risk losing the concrete reference to the expressions used by students (Braun & Clarke, 2006). Their integration therefore ensured both empirical robustness and interpretative depth.
Methodologically, a hybrid approach combining deductive and inductive dimensions was adopted. The deductive component referred to the theoretical observables discussed in Chapter 4, regarded as guiding themes capable of steering the analysis towards aspects relevant to the research question. The inductive component, conversely, enabled the construction of emergent codes drawn from the data themselves, often expressed in students' in-vivo language, thereby preserving the richness and spontaneity of their expressions. This dual movement, from empirical data to theoretical framework and back again, allowed the analysis to remain anchored both to students' voices and to a robust conceptual apparatus (Fereday & Muir-Cochrane, 2006).
Under these conditions, the observables did not function as a rigid, all-encompassing grid but as a dynamic interpretative instrument, capable of guiding the analysis without stifling the complexity of the data. The observables thus provided the theoretical anchor, while the emergent codes gave voice to the variety of students' experiences; their integration, supported by a process of triangulation and negotiation among the three researchers participating to the study, made it possible to render a multifaceted and credible account of the mechanisms that influence the evolution of knowledge models.

Below we set out the step-by-step operational procedure adopted to perform the thematic analysis of the students' responses:

1. Preparation and familiarisation: careful transcription of the responses provided by students during the clinical interview phase. Repeated readings and analytical notes (memos) of the operational sheets, interview transcripts, the researchers' field journals, and students' feedback recorded in questionnaire Q.3. This phase allows an initial mapping of the material and the generation of preliminary ideas concerning potential codes and themes.

2. Initial coding (inductive phase) and construction of provisional codebooks: segmentation of the texts into units of meaning and assignment of descriptive codes (often in-vivo). Based on these initial codes, three provisional codebooks were drafted, one for each researcher, containing labels and operational definitions (Appendix F). This document served as the basis for negotiation among the researchers.

3. Triangulation and negotiation among researchers: through structured peer debriefing sessions, the researchers thoroughly analysed divergences and identified correspondences among related codes. The tables presented in Appendix G show the outcome of this comparison, that is, the shared synthesis that led to the merging of initially distinct codes considered equivalent. This procedure enabled a more robust definition of the codes, ensuring conceptual coherence, operational reliability, and interpretative enrichment arising from the integration of different perspectives.

4. Finalisation of codes: following the process of negotiation and convergence among researchers, the definitive codebook was established, serving as the reference instrument for thematic analysis. Each code was accompanied by a clear operational definition, making explicit the modes of application and reducing the risk of interpretative ambiguity (Appendix H).

5. Comparison with observables and mapping of codes (deductive phase): in parallel with the inductive coding, a systematic verification was conducted of the correspondence between emergent codes and the observables defined in Chapter 4. During this phase, a selection was made, narrowing the set of observables from thirteen to eight. This delimitation does not constitute a reductive simplification; rather, it reflects a design choice intended to maintain analytical focus in alignment with the objectives of the study. This decision does not, however, exhaust the analytical potential of the overall observational framework: an extension of the set of observables is explicitly envisaged in a subsequent phase of the research, as discussed in Section 8.3.1, where an expanded methodological design will allow additional dimensions of learning to be incorporated.

The final codes were therefore mapped against the selected observables, in both tabular and descriptive formats, indicating the criteria used to link each code to one or more observables (Appendix I). This mapping constitutes a crucial step in connecting the qualitative data to the interpretative grid, highlighting the relationships between the concrete manifestations of learning observed and the theoretical dimensions considered central for understanding the evolution of students' cognitive models.

6. Validation and quality control: the mapping of codes against observables underwent careful cross-checking among the researchers involved in the experiment, following established peer debriefing and critical comparison procedures. This step aimed to reinforce the plausibility and coherence of the assignments, reducing the risk of arbitrary interpretations or distortions arising from individual perspectives.

At the end of the operational procedure, a complementary descriptive quantitative–qualitative analysis was conducted. In this phase, code-observable assignments were quantified through the calculation of frequencies and co-occurrences, organised into descriptive tables that immediately highlighted which observables were most frequently activated by specific activities and how these patterns evolved over time.

The integration of qualitative evidence, derived from code determination and their association with observables, with descriptive quantitative evidence allowed for the formulation of plausible and well-founded inferences, both conceptually and in terms of prevalence. In this way, it was possible to more precisely identify elements of the educational context capable of influencing students' learning, such as the effectiveness of mesoscopic activities in fostering the transition from descriptive to explicative responses regarding phenomena like surface tension.

This methodological approach adheres to the rigour criteria typical of both qualitative analysis, through data triangulation, researcher comparison, and memos, and quantitative analysis, ensuring transparency in counts and clarity in units of analysis. Furthermore, it aligns with the literature on sequential qualitative → quantitative designs and on the "transformation" processes from coding to data quantification (Creswell & Plano Clark, 2017; Fetters et al., 2013), providing an integrated framework to robustly interpret the learning dynamics that emerged during the experiment.

It should finally be emphasised that the entire procedure remains influenced by interpretative choices. Thematic analysis depends both on the operational definitions assigned to codes and observables and on the negotiation and comparison among researchers. To ensure transparency and reliability, all methodological decisions were meticulously documented and justified. The results obtained must therefore be regarded as reasoned and verifiable interpretations, rather than as univocal statements or absolute truths.

5.2.2 Quantitative analysis

Quantitative analysis represents one of the central methodologies in educational and social research, as it allows the measurement, description, and interpretation of complex phenomena using numerical data. It is founded on the assumption that educational, cognitive, and social variables can be observed, defined, and investigated using systematic and standardised measurement instruments. The primary aim is to identify regularities, explore relationships between distributions, test hypotheses, and draw generalisable inferences, while ensuring replicability, transparency, and methodological rigour (Cohen et al., 2018; Punch & Oancea, 2014).

From an epistemological standpoint, the core of quantitative analysis lies in the capacity to translate observed phenomena into measurable variables, that is, attributes that can be described numerically. This process requires careful operationalisation, entailing the rigorous definition of theoretical constructs and their translation into empirical indicators. At this critical stage, conceptual clarity is essential: poorly defined constructs inevitably compromise the validity of subsequent analyses.

Quantitative analysis can take various forms depending on the research objectives: from statistical description of observed phenomena to the exploration of relationships between variables, and up to the experimental testing of causal hypotheses.
A central aspect concerns data quality. The validity and reliability of measurement instruments are indispensable criteria to ensure that they accurately capture what is intended and produce consistent results across time and contexts (Messick, 1995). Transparency in the processes of data collection, coding, and treatment is also necessary to allow study replication and independent verification of results, thereby strengthening the credibility of the research.

In the educational context, the potential of quantitative analysis is broad and multifaceted. It can be employed to:

- evaluate the effectiveness of instructional interventions through comparisons between experimental and control groups;
- monitor the development of students' competences over time;
- investigate relationships between cognitive, affective, and contextual variables, thereby highlighting complex dynamics.

These applications make quantitative analysis a strategic tool not only for assessment but also for educational design, as it enables the production of robust empirical evidence to support instructional decisions.

However, alongside its strengths, the limitations inherent in the quantitative approach must also be considered. The need to reduce complex phenomena to numerical variables can lead to the loss of relevant nuances, particularly those related to individual or socio-cultural contexts in which educational processes unfold. Moreover, the generalisability of results is strictly dependent on the representativeness of the sample and on adherence to the statistical assumptions underlying the analyses (Bryman, 2016). Without careful critical reflection on these aspects, data interpretation risks being partial or misleading.

It is therefore evident that quantitative analysis constitutes a powerful approach capable of providing generalisable and replicable evidence; however, it requires a deliberate and rigorous application, based on conceptual clarity, data quality, and accurate interpretation of results.

5.2.2.1 The Likert scale

The Likert scale, introduced by Rensis Likert (1932), constitutes one of the most widely used instruments for capturing opinions, attitudes, and perceptions in educational and social research. It is a psychometric tool based on a series of declarative items, to which respondents indicate their degree of agreement or disagreement on an ordinal scale, usually comprising 5 or 7 points. Its strength lies in the simplicity of administration and its high capacity to collect systematic and comparable data on constructs that are not directly observable, such as motivation, satisfaction, or self-perceived competence (Boone & Boone, 2012). From a methodological perspective, Likert scales are considered ordinal measures, as the scores reflect an increasing or decreasing order of opinion intensity without guaranteeing that the distance between consecutive values is exactly the same. Nevertheless, in social and educational research practice, the scores are often treated as interval variables to allow the calculation of means, standard deviations, and further statistical analyses (Carifio & Perla, 2008; Jamieson, 2004). A critical aspect concerns the validity of Likert scales, which must be ensured through careful item construction, avoiding ambiguous or leading formulations, and verifying that the set of questions adequately covers the dimensions of the construct under investigation (DeVellis, 2016).
Analytically, data collected via Likert scales can be processed using different approaches. Basic analysis involves calculating descriptive statistics (frequencies, percentages, means, standard deviations) to identify central tendencies and response dispersion. More advanced analyses may include correlation tests, factor analysis, or regression models, depending on the complexity of the research. It is important to emphasise that statistical significance should always be complemented by an assessment of practical relevance, avoiding reductive interpretations (Cumming, 2013).

In the present study, the Likert scale was employed within the Q.3 satisfaction questionnaire, administered at the conclusion of the educational activities to collect students' perceptions and levels of satisfaction with the experimental proposals. The questionnaire comprised 23 items, each evaluated on a 5-point scale (1 = "Not at all" to 5 = "Extremely"). The aim was to systematically investigate students' subjective experience, considering aspects such as expectations and prior knowledge, organisation, self-assessment and impact on curricular learning, evaluation of the teaching strategies, relational climate and motivation, and overall satisfaction.

For each item, weighted means were calculated using the following formula (Alonazi et al., 2019):

$$\bar{y} = \frac{\sum_{i=1}^{k} y_i f_i}{N} \tag{5.1}$$

where y_i represents the value of the Likert scale category (1 to 5 in this study), f_i the absolute frequency of responses for y_i, $N = \sum f_i$ the total number of respondents, and k the number of scale categories (5 in this case).

These weighted means allow the overall orientation of responses to be summarised while accounting for their distribution along the scale. This method, together with subsequent graphical representation, enabled the immediate visualisation of satisfaction peaks and perceived critical points, highlighting which aspects of the learning experience generated greater consensus and which, conversely, required further reflection or intervention.

The use of the Likert scale at this stage of the experimentation provided a quantitative assessment of students' affective and motivational components, complementing the qualitative analysis of their conceptions. This methodological choice is consistent with the literature recommending the use of mixed instruments to obtain a broader, triangulated understanding of educational processes (Creswell & Plano Clark, 2017). In this way, the investigation does not merely assess cognitive evolution but also considers emotional and subjective dimensions, which are essential for evaluating the overall effectiveness of an educational intervention.

Chapter 6

Analysis of Results

The analysis of the results represents the moment when the educational experience is transformed into shareable knowledge, where students' voices, researchers' observations, and the collected evidence converge into a synthesis that conveys the deeper meaning of the undertaken process. Following the experimental phase, this chapter serves as a space of re-composition: numbers, words, and traces of interaction intertwine to narrate how students experienced, interpreted, and transformed the proposed activity.

Each datum, each percentage variation or trend, is not regarded merely as a quantitative outcome, but as an indicator pointing to more complex cognitive, relational, and affective processes. The purpose is not simply to measure, but to recognise the traces of understanding, doubt, discovery, and change that accompanied students throughout the TLS.

From this perspective, numerical results acquire both interpretative and narrative value: they tell of learning in progress, of ideas being reshaped, and of attitudes evolving. The following analysis, which integrates quantitative and qualitative data, aims to provide a comprehensive, coherent, and meaningful account of the educational pathway, allowing the richness of students' thinking processes and participation to emerge.

6.1 Phenomenographic analysis of questionnaires Q.1 and Q.2

Questionnaires Q.1 and Q.2 (Appendices A and B) were administered at three distinct stages of the TLS: respectively, before the start of the experimental work, at the end of the macroscopic phase, and finally, after the completion of the mesoscopic phase. This temporal structure was designed to monitor the evolution of students' conceptions of surface phenomena throughout the entire educational intervention, allowing an assessment of the extent to which the introduction of mesoscopic modelling, mediated by SPH simulations, fostered conceptual change compared to an exclusively macroscopic approach.

The adoption of two distinct instruments (Q.1 and Q.2) also made it possible to diversify the contexts of investigation, exploring different aspects of students' understanding of surface phenomena and ensuring a more robust and in-depth triangulation of data.

The general aim of this section is therefore to illustrate the qualitative transformations observed in students' patterns of thought, highlighting the progressive shifts from phenomenological and descriptive explanations to increasingly abstract, model-based explanations consistent with the language of science. In keeping with the research perspective outlined in Chapter 4, the focus was not on the formal correctness of the answers, but on the different ways in which students construct meaning, negotiate their representations, and move across various registers of explanation and representation. From this viewpoint, the analysis focused on processes of conceptual construction and reorganisation rather than on the mere level of terminological or symbolic accuracy.

The data analysis was conducted using a phenomenographic approach, aimed at exploring the qualitative variation in the experiences and ways of understanding a phenomenon (Marton, 1981; Marton & Booth, 1997). In this framework, each response was regarded as an individual expression of a particular way of conceiving the physical phenomenon, reflecting a specific level of conceptual abstraction and a differing ability to connect empirical observations with theoretical models.
Phenomenography enables the construction of a finite set of categories of description, each representing a mode of understanding the object of study. The categories identified, while progressively emerging from the systematic comparison of students' responses, were also conceptually anchored in the literature on mental models in physics and on the construction of scientific meaning (Greca & Moreira, 2002; Sperandeo-Mineo et al., 2006).
The three main categories of understanding, already presented in the previous chapter, are as follows:

1. Everyday profile, centred on direct observation of phenomena and the use of everyday language;

2. Descriptive profile, in which intuitive references to the investigated phenomena emerge, although not yet fully formalised;

3. Explicative profile, characterised by model-based, abstract explanations consistent with the physical principles governing surface phenomena.

An additional indicator, termed "no answer", was introduced to encompass all instances in which students either did not provide an answer or expressed a thought that could not be interpreted within the adopted conceptual framework. These categories were not conceived as rigid or mutually exclusive compartments but rather as regions within a cognitive continuum, along which

students' responses may be positioned gradually or display forms of hybridisation.
Each response was assigned to a given category according to the predominant mode of meaning-making expressed by the student, that is, the prevailing interpretative strategy within their discourse: empirical-intuitive in the everyday profile, descriptive and partially causal in the descriptive profile, and formally explicative in the explicative profile.
The coding of responses was carried out collaboratively by the three researchers involved in the design and implementation of the TLS.
Triangulation played a central role in validating the category system: each response was independently examined and classified by each researcher, and interpretative divergences were discussed until a shared consensus was reached. This systematic comparison procedure ensured greater construct validity and internal reliability of the phenomenographic categories, strengthening coherence across the different analytical stages.
All histograms and graphical representations presented in the following sections derive directly from this triangulated and jointly agreed coding process and thus constitute a visual synthesis of the collective evolution of students' models of understanding.

This section will therefore present the results corresponding to the three questionnaire administration stages, with the aim of describing and interpreting the overall evolution of students' conceptions throughout the educational pathway.
The detailed discussion of these results, their pedagogical implications, and their significance in relation to the theoretical framework will be developed in the following chapter.

6.1.1 Diagnostic results (pre-test)

The first administration of questionnaires, Q.1 and Q.2, conducted before the implementation of the TLS, aimed to explore students' initial conceptions of surface phenomena. This diagnostic phase made it possible to outline the conceptual framework from which the students began, providing essential elements for assessing the effectiveness of the educational intervention. Through these diagnostic tools, it was possible to interpret and identify students' pre-existing ideas, misconceptions, and early attempts at modelling.

Questionnaire Q.1

The analysis of the responses to questionnaire Q.1 highlights the predominance of the everyday profile, which accounts for 44.1% of the total.

Students tend to describe the observed phenomena using empirical language, drawing upon direct experiences or everyday observations. A proportion of 30.2% of the responses falls within the descriptive category, where more articulated explanations emerge, though often lacking formalisation or coherence with scientific language. Only 15.4% of the responses can be classified as explicative, indicating an initial level of conceptual abstraction and a tendency to interpret surface phenomena in terms of physical principles (e.g. adhesion and cohesion forces). Finally, 10.3% of students did not provide an answer or produced responses that could not be interpreted within the adopted phenomenographic framework.

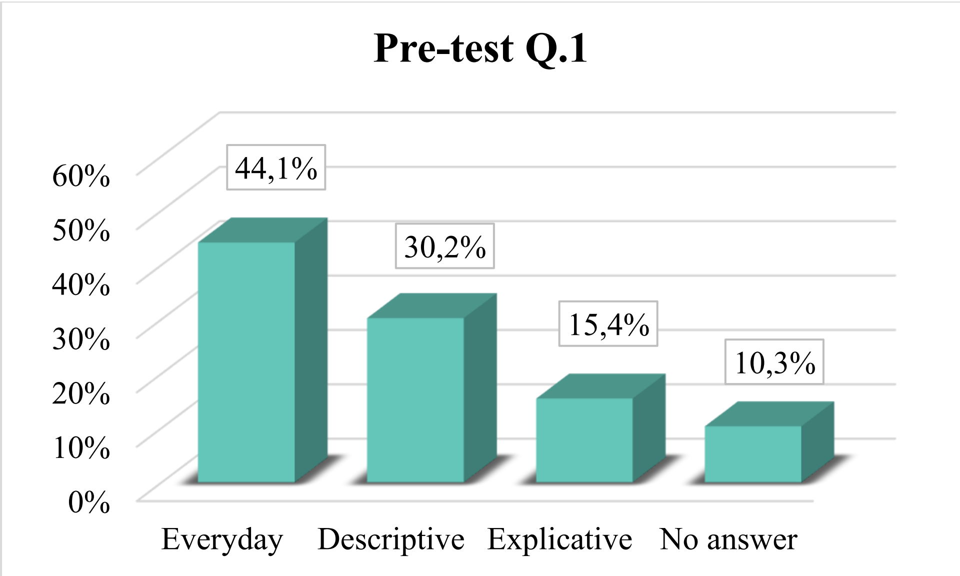

Figure 6.1: Percentage distribution of responses to pre-test Q.1 according to epistemological profiles.

Overall, the Q.1 results reveal an initial picture strongly rooted in everyday experience, in which phenomenological explanations prevail over conceptual modelling. However, the presence of around 30% of intermediate responses suggests the existence of an underlying cognitive potential upon which the educational intervention could build.

Below are some representative excerpts for each category.

Everyday profile

- Item 3: *"The sponge fills with water and swells because it has absorbed the liquid."*
- Item 5: *"Hot water is used because it dissolves the dirt stains more easily."*

These responses are limited to the description of observable aspects, showing empirical reasoning based on direct experience.

Descriptive profile

- Item 3: *"The sponge absorbs water because the material it is made of has small holes that allow the water to enter."*
- Item 5: *"Hot water changes the properties of the substance (the stain) on the fabric, making it easier to remove."*

Identification of salient elements of the phenomena, variables, observable quantities or regularities, emerge, though without a formalised physical language.

Explicative profile

- Item 3: *"The sponge absorbs water through capillarity, caused by adhesive forces between the water and the material and cohesive forces within the water."*
- Item 5: *"Hot water is more effective in removing stains because it increases the kinetic energy of the molecules, facilitating the breaking of bonds between the dirt and the fabric fibres."*

These explanations correctly integrate physical concepts and microscopic interaction references, demonstrating model-based understanding.

Questionnaire Q.2

The analysis of the responses to questionnaire Q.2 shows a less balanced distribution compared to Q.1, with a significant increase in non-responses (22.4%) and an overall decrease in descriptive explanations. This trend reflects the higher conceptual complexity of the proposed questions, which required a more explicit activation of theoretical knowledge and the ability to connect observable phenomena with the underlying physical models.
The everyday category represents 39.2% of the total: the responses are still based on intuitive experiences or superficial descriptions of the phenomena.
The descriptive category accounts for 21.6%, where students attempt to introduce more formalised physical concepts, although in a partial or imprecise manner.
Finally, 16.8% of the responses can be classified as explicative, demonstrating correct use of scientific language and a coherent understanding of surface tension and capillary action.

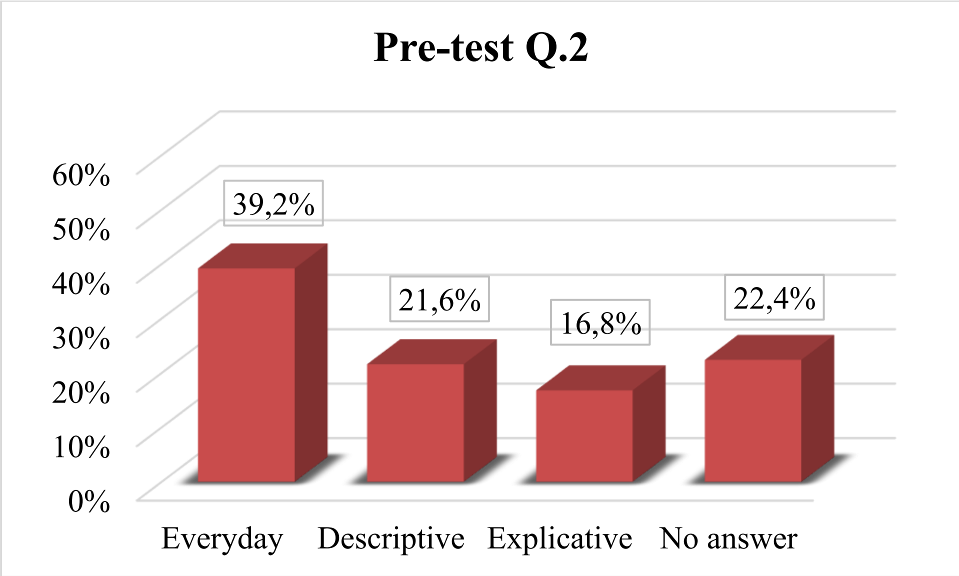

Figure 6.2: Percentage distribution of responses to pre-test Q.2 according to epistemological profiles.

Overall, Q.2 reveals greater difficulty compared to the previous questionnaire, but also the presence of promising conceptual nuclei suggesting the onset of transitional processes towards more model-based thinking.
The high proportion of non-responses (22.4%) instead indicates an initial gap between students' intuitive language and the required level of formalisation, highlighting the need for an instructional intervention that facilitates a gradual access to modelling concepts.

Below are some representative excerpts for each category.

Everyday profile

- Item 1: *"Water sticks to the glass because it is smooth."*
- Item 3: *"The little boat moves because the drops create waves on the water that push it forward."*

These responses are limited to describing observable aspects, showing empirical reasoning based on direct experience.

Descriptive profile

- Item 1: *"Water rises in the tube because it is attracted by the walls of the container."*
- Item 3: *"When the soap touches the water, it reacts with it and generates a force that pushes the boat to move."*

Identification of salient elements of the phenomena, variables, observable quantities or regularities, emerge, though without a formalised physical language.

Explicative profile

- Item 1: *"A concave meniscus forms because the adhesive forces between water and glass are stronger than the cohesive forces between water molecules, causing the edges to rise."*
- Item 3: *"Soap reduces the surface tension behind the boat, creating an imbalance that propels it towards the area where the tension is greater."*

These explanations correctly integrate physical concepts and microscopic interaction references, revealing a model-based understanding.

6.1.2 Results after the macroscopic phase (intermediate test)

The second administration of the questionnaires took place at the end of the macroscopic activities, during which students observed and interpreted phenomena related to surface tension through direct qualitative experiments.
This phase aimed to promote an initial conceptual re-elaboration of everyday experiences and to encourage the development of more articulated descriptions of physical phenomena.
The analysis of responses to questionnaires Q.1 and Q.2 makes it possible to assess the extent to which engagement with experiments fostered a shift from an empirical to a descriptive understanding, characterised by a more appropriate use of scientific language and a greater focus on observable processes.

Since questionnaires Q.1 and Q.2 maintained the same structure and wording across all stages of administration, no additional excerpts of student responses are reported in this section. The categories of understanding remain those identified in the previous phase (pre-test); what changes, and will therefore be analysed here, concerns the distribution and evolution of the frequencies associated with the different cognitive profiles.

Questionnaire Q.1

The analysis of the responses to questionnaire Q.1 in the second administration reveals a substantial rebalancing in the distribution of understanding profiles compared with the pre-test. The percentages show a significant decrease in everyday responses (27.3%), accompanied by a considerable increase in the descriptive category (40.7%) and a notable rise in explicative responses (24.0%). The percentage of no answer responses decreases further (8%), indicating greater student participation and confidence in formulating personal explanations.

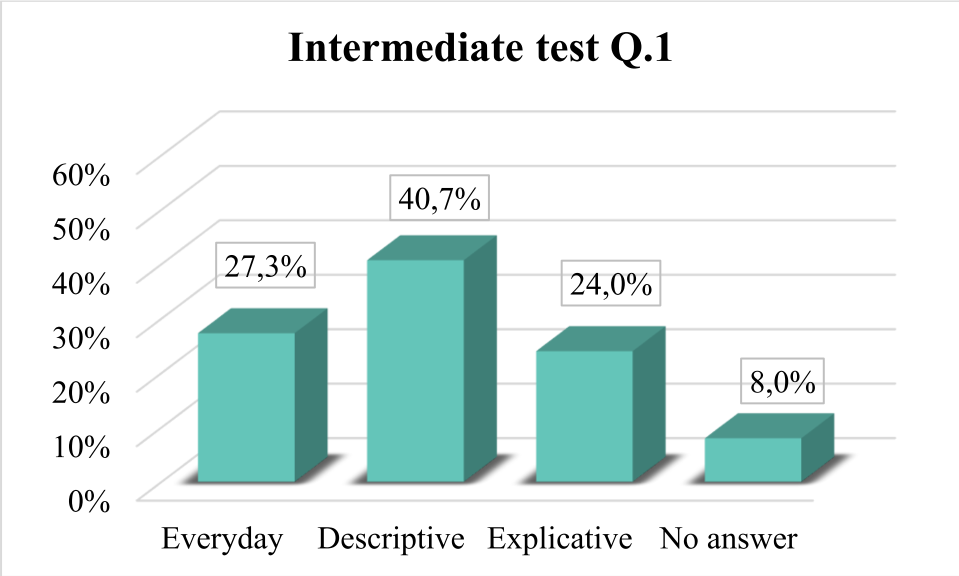

Figure 6.3: Percentage distribution of responses to intermediate test Q.1 according to epistemological profiles.

These results suggest that, following the macroscopic experimental activities, students developed a deeper awareness of the phenomena observed and began to integrate causal elements and scientific language into their explanations. The progressive shift towards the descriptive and explicative profiles indicates a gradual transition from an empirical to a more conceptual understanding, although traces of initial spontaneous thinking remain.

Below are some representative excerpts for each category.

Everyday profile

- Item 1: *"The level of the liquid rises."*
- Item 8: *"Because the pan is non-stick, the oil spreads. With water, however, you can see the drops."*

These responses are typical of spontaneous common-sense reasoning: the observation is immediate, without reference to physical mechanisms, scientific concepts, or relevant variables.

Descriptive profile

- Item 1: *"Initially, with the soaked biscuit, the liquid level increases; subsequently, it decreases slightly because the biscuit is porous and absorbs part of the liquid."*
- Item 8: *"The oil in the non-stick pan spreads evenly, whereas the water forms drops. This happens because oil has a lower surface tension and therefore spreads more easily."*

These responses correctly identify what occurs, but do not make explicit the physical mechanism governing the phenomena. The explanations are coherent but remain at a general level.

Explicative profile

- Item 1: *"The liquid, before immersion, is in a state of equilibrium determined by cohesion forces. When the biscuit enters the milk, the liquid molecules interact with those of the biscuit: the adhesion forces are stronger than the cohesion, and the liquid is drawn into the pores of the biscuit, changing the level."*
- Item 8: *"The oil does not form drops because its cohesion forces are weaker and the adhesion forces with the pan's surface are stronger. Its low surface tension allows it to spread into a continuous film, whereas water, with stronger cohesion forces and poor adhesion to the non-stick material, tends to gather into drops."*

These responses employ causal models and microscopic concepts to explain the phenomena. They do not merely describe "what happens" but clarify why it happens, drawing on formalised theoretical mechanisms.

Questionnaire Q.2

As for questionnaire Q.2, the results of the intermediate test confirm the trends observed in Q.1. The percentage of everyday responses decreases further (20.8%), while the descriptive category becomes predominant (43.5%), followed by a significant increase in explicative responses (31.3%). Non-responses (no answer) are residual (4.4%), indicating a level of cognitive engagement now extended to the entire class group.

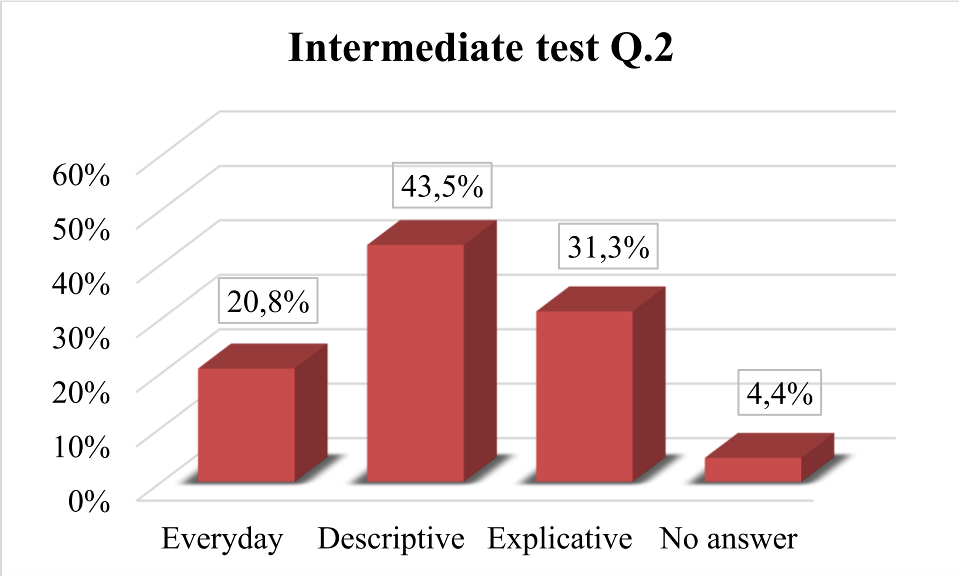

Figure 6.4: Percentage distribution of responses to intermediate test Q.2 according to epistemological profiles.

This pattern shows that, after the macroscopic phase, students began to connect empirical experience with more abstract concepts such as surface tension and cohesive and adhesive forces. Compared with Q.1, the questions in Q.2 already required a more explicit articulation of physical principles, and the results show that many students effectively made a qualitative leap towards model-based explanation, albeit with uneven levels of depth.

Below are some representative excerpts for each category.

Everyday profile

- Item 4: *"N/m."*
- Item 11: *"Because the bonds break."*

These are generic, indeterminate explanations, lacking explicit references and based on practical ideas rather than scientifically contextualised reasoning.

Descriptive profile

- Item 4: *"The units of surface tension are N/m and J/m².*"
- Item 11: *"Soap reduces the surface tension of water, causing it to spread evenly across the surface instead of forming a drop."*

These responses describe what the student knows but do not provide deeper causal explanations or connections to underlying models.

Explicative profile

- Item 4: *"The units of surface tension are N/m and J/m². N/m derives from the definition γ = F/l: force is measured in Newtons and length in metres. J/m², on the other hand, stems from the energetic interpretation of surface tension, as the energy required to increase the free surface area of the liquid."*
- Item 11: *"Soap reduces surface tension because its surfactant molecules interpose between water molecules, weakening cohesion forces. When cohesion decreases, adhesion forces with the surface become predominant: this is why the drop does not remain compact but spreads across the surface."*

These responses introduce molecular mechanisms, provide causal relationships, and offer an explanation linking microscopic and macroscopic references.

6.1.3 Results after the mesoscopic phase (post-test)

The third and final administration took place at the end of the mesoscopic activities, during which students used SPH (Smoothed Particle Hydrodynamics) simulations to explore the dynamics of particle interactions and to understand the microscopic origin of surface tension.
In this phase, the pedagogical objective was to consolidate and deepen conceptual understanding, fostering the reconciliation between the descriptive and explicative levels through scientific modelling.

As in previous stages, no new examples of student responses are presented here, since questionnaires Q.1 and Q.2 were identical in all administrations. The phenomenographic categories remain unchanged; the focus of this section lies in analysing how experience with mesoscopic simulations altered the distribution of students' responses.

Questionnaire Q.1

The analysis of the responses to questionnaire Q.1 in the third and final administration shows a significant advancement in conceptual understanding. The distribution of categories reveals a clear predominance of explicative responses (51%), accompanied by a marked decrease in the everyday (16.4%) and descriptive (26.3%) categories. The percentage of no answer responses (6.3%) remains low, confirming active and conscious participation by students in the final stage of the learning process.

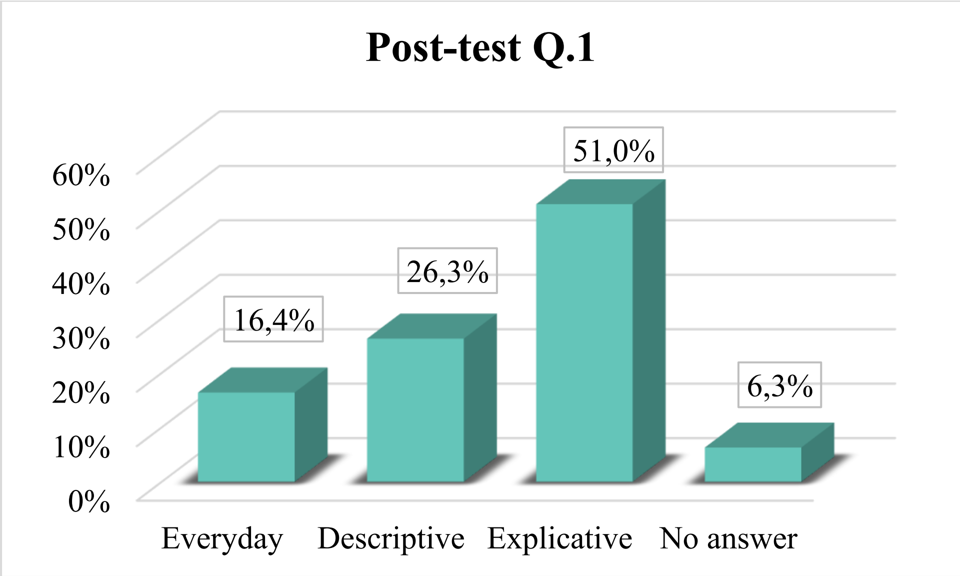

Figure 6.5: Percentage distribution of responses to post-test Q.1 according to epistemological profiles.

This trend indicates that, following the mesoscopic activities and SPH simulations, students were able to reformulate their explanations in model-based terms, referring to more abstract physical concepts and the role of particle interactions. Comparison with previous phases highlights a stable shift towards explicative understanding, reflecting the progressive integration of empirical experience, mesoscopic representations, and theoretical principles.

Below are some representative excerpts for each category.

Everyday profile

- Item 4: *"It is used to remove dirt from clothes."*
- Item 9: *"Because it has little hairs on its legs that allow it not to sink."*

These are intuitive and immediate explanations, typical of everyday experience, with no descriptions of the phenomena or explicative elements.

Descriptive profile

- Item 4: *"Detergent facilitates the removal of dirt by reducing surface tension and dissolving fats."*
- Item 9: *"The insect walks on water thanks to surface tension, which supports its weight without letting it sink. Its legs distribute the weight, preventing the water film from breaking."*

These responses identify the relevant variables but do not detail the underlying mechanism, nor do they introduce microscopic models or structured causal references.

Explicative profile

- Item 4: *"Detergent contains surfactants that lower the surface tension of water and have a dual nature: one part hydrophilic, which binds to water, and one part hydrophobic, which binds to fats. In this way, dirt molecules are surrounded and trapped, detached from the fabrics, and then removed during rinsing."*
- Item 9: *"The insect can walk on water thanks to the surface tension generated by cohesion forces between water molecules. Its hydrophobic legs, covered with hairs that trap air, reduce adhesion with the liquid and distribute the weight over a wide area."*

These responses employ a complete and coherent scientific model. The reasoning is causal, modelled, and anchored in concepts from chemistry and fluid physics.

Questionnaire Q.2

Regarding questionnaire Q.2, the post-test results confirm and amplify the trend already observed in the intermediate phase. The explicative category reaches 49.1% of responses, almost half of the sample, while the descriptive category accounts for 34.5% and the everyday category drops to 12.8%. No answer responses decrease further (3.6%), indicating a high level of cognitive engagement and expressive confidence.

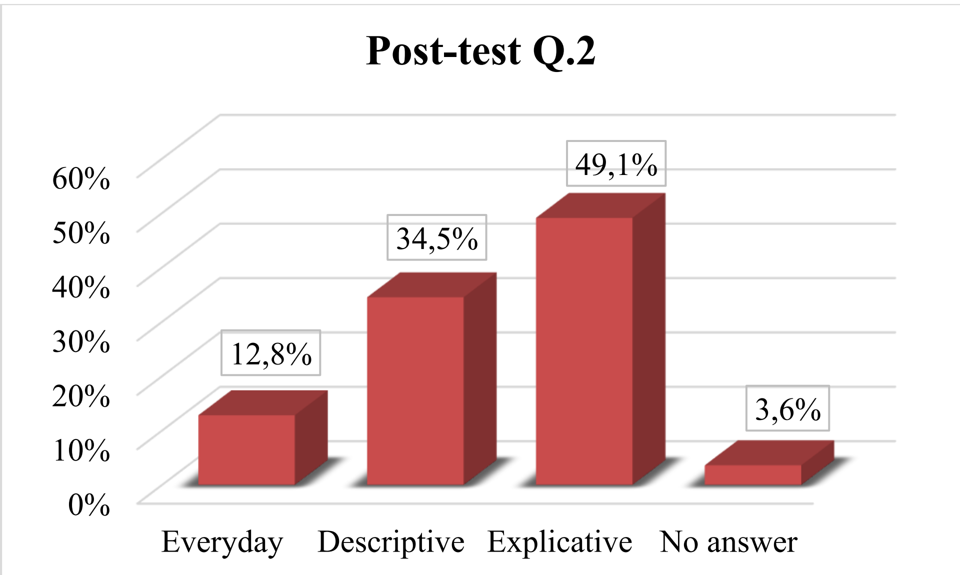

Figure 6.6: Percentage distribution of responses to post-test Q.2 according to epistemological profiles.

The increase in explicative responses demonstrates that, following the introduction of mesoscopic modelling through SPH simulations, students achieved a deeper and more formalised understanding of surface phenomena. Their explanations not only incorporate references to cohesive and adhesive forces but also reveal a clear ability to connect macroscopic and microscopic levels, signalling genuine internalisation of the underlying physical model.

Below are some representative excerpts for each category.

Everyday profile

- Item 7: *"They are forces that allow the liquid to adhere or not to the walls of a container."*
- Item 9: *"The rise of a liquid within a capillary, a phenomenon known as capillarity, depends on several physical quantities connected to each other."*

These responses provide a vague description and use general language, without precise references.

Descriptive profile

- Item 7: *"Adhesion forces act between molecules of different materials, whereas cohesion forces act between molecules of the same material."*
- Item 9: *"The rise of a liquid within a capillary depends on the surface tension of the liquid, the radius of the capillary, and the density of the liquid."*

These responses give correct definitions but do not explain the role of physical quantities.

Explicative profile

- Item 7: *"Adhesion forces are attractive interactions between molecules of different substances, for example between water and glass in a capillary tube. Cohesion forces act between molecules of the same liquid and are responsible for the formation of droplets and for surface tension."*
- Item 9: *"The rise of a liquid in a capillary depends on surface tension, the capillary radius, the liquid density, gravity, and the contact angle. Higher surface tension and a smaller radius increase the rise, whereas higher density reduces it. The contact angle determines the wettability of the capillary wall. All these factors are described by Jurin's law."*

These responses are provided using appropriate scientific language and introduce the causal mechanisms underlying the phenomena.

6.1.4 Summary of results

Questionnaire Q.1

The comparative analysis of data from the three administrations of questionnaire Q.1 highlights a progressive transformation in the distribution of understanding categories, reflecting a gradual evolution in the way students interpret surface phenomena.

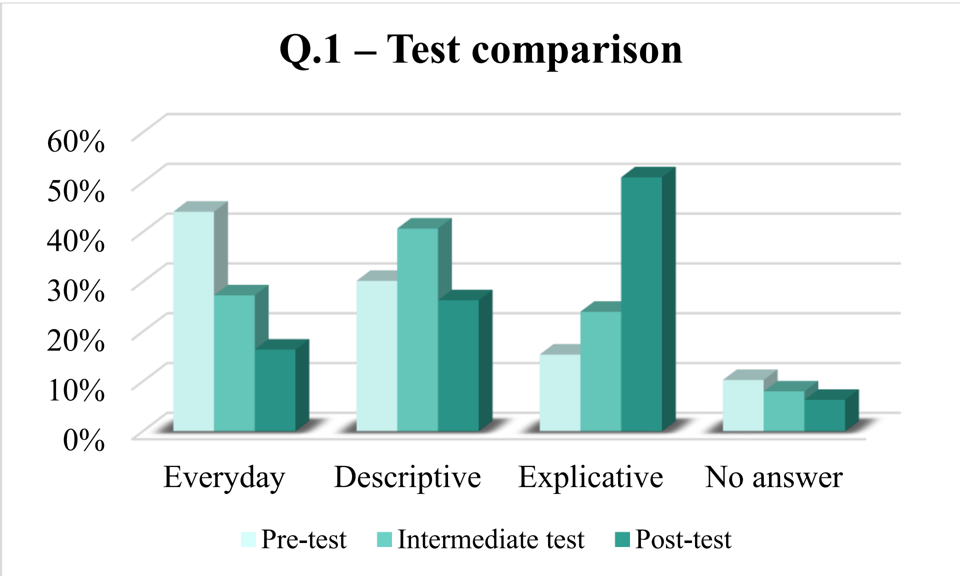

Figure 6.7: Distribution of responses in the four epistemological categories (Everyday, Descriptive, Explicative, No answer) across the three test phases for Questionnaire Q.1.

In the pre-test, responses were strongly concentrated in the everyday and descriptive categories, indicating an understanding primarily empirical and linked to everyday experience. Explicative explanations represented only a limited fraction, while a proportion of non-responses was still present.
With the intermediate test, a phase of cognitive transition emerges, in which responses are more evenly distributed across the three main categories. The weight of everyday thinking decreases, while more structured descriptions increase, accompanied by a noticeable rise in explicative explanations. This suggests that the macroscopic activities promoted greater attention to the physical aspects and observable properties of phenomena, although full theoretical formalisation had not yet been achieved.

In the post-test, the distribution changes further: the explicative category becomes dominant, exceeding half of the total responses. The everyday and descriptive categories decrease substantially, indicating that most students achieved a more abstract and model-based form of understanding. The overall pattern visible in the histogram thus reveals a steady migration from empirical to conceptual explanations, with a consistent reduction in missing responses and a strengthening of scientific language.

Questionnaire Q.2

The pattern of results for questionnaire Q.2 follows a trajectory similar to that of Q.1, but with more pronounced changes and a faster transition towards higher levels of understanding, consistent with the more conceptual nature of its items.

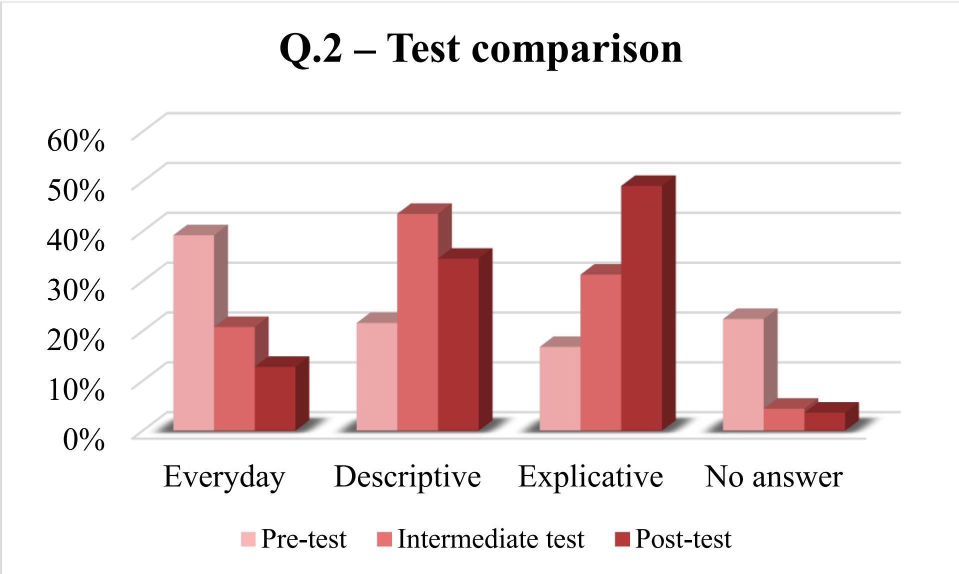

Figure 6.8: Distribution of responses in the four epistemological categories (Everyday, Descriptive, Explicative, No answer) across the three test phases for Questionnaire Q.2.

In the pre-test, responses were mainly distributed between the everyday and descriptive categories, with a smaller proportion in the explicative category. Students therefore tended to provide explanations based on direct observation, rarely linked to underlying physical principles.

During the intermediate test, the descriptive category strengthens and becomes predominant, while the explicative category shows a significant increase. The everyday category decreases to a marginal percentage, signalling an initial

overcoming of purely intuitive conceptions. Students begin to include references to forces and molecular interactions, although still inconsistently.
In the post-test, the distribution changes radically: the explicative category emerges as the main one, followed by the descriptive, while the everyday becomes residual. The responses display a high degree of coherence and a stronger command of scientific language, with explicit references to cohesion, adhesion, and surface tension. The overall histogram clearly illustrates this linear and coherent evolution towards conceptual formalisation, with a progressive reduction of intuitive responses and a consolidation of model-based explanations.

6.2 Thematic analysis: worksheets, clinical interviews, researchers' logbooks and student feedback

The qualitative analysis of the materials collected (worksheets, clinical interviews, researchers' logbooks, and student feedback) was conducted through thematic analysis (Braun & Clarke, 2006), with the aim of identifying, analysing, and interpreting significant patterns in the ways students constructed and re-elaborated their understanding of surface phenomena. This approach made it possible to delineate a conceptual and processual map through which to trace the progressive development of meaningful and lasting learning among students, in relation to the various stages of the TLS.
The process was articulated in three main phases:

- Independent initial coding: Each researcher constructed a provisional codebook (Appendix F), developing a system of labels and operational definitions designed to describe the behaviours, verbal expressions, and cognitive strategies identified in the various materials. In this phase, the coding was intentionally open and descriptive, allowing the meanings attributed by students to their learning experiences to emerge spontaneously, without imposing any predefined categories.
- Triangulation and negotiation: The three initial codebooks were subsequently compared collegially during peer debriefing sessions (Appendix G). Through an iterative process of comparison, discussion, and refinement, the researchers identified correspondences among similar codes, merged redundant categories, and redefined labels to improve semantic clarity and coherence. This process resulted in the definitive codebook (Appendix H), produced as a shared and stable output of the research group.

- Code–observable association: The codes thus defined were then related to the observables described in Appendix I, which constitute the interpretative dimensions used to read the results. This association made it possible to link each code to specific learning indicators (for example: appropriation of concepts and forms of representation, development of reasoning lines, metacognition, etc.), thereby providing a coherent framework between empirical evidence and theoretical categories.

Following the code-observable association phase and the subsequent validation and quality-control step (see Chapter 5), a further coding process was initiated to standardise data analysis and ensure interpretative consistency among the researchers.

In this phase, each researcher re-examined the entire corpus, including worksheets, interviews, logbooks, and feedback, systematically applying the final codebook, which served as a common reference for classifying textual and observational segments.

During this second round of coding, it became apparent that there was not always complete agreement in the attribution of codes to the same text fragments or observational units. Some discrepancies stemmed from interpretative differences related to the level of inference adopted (descriptive or conceptual), while others reflected varying emphasis placed by each researcher on specific aspects of interaction or on the language used by students. In other cases, the divergences were due to differing judgements about the extent of the units considered relevant for coding.

To ensure methodological transparency and reliability, the percentage of agreement among researchers was calculated for each activity analysed. This percentage was defined as the ratio between the number of codes assigned identically by at least two researchers and the total number of codes attributed by at least one researcher. In other words, for each activity, the number of textual or observational segments for which at least two researchers had assigned the same code was divided by the total number of codes collectively attributed by the three analysts.

Although this value does not constitute a statistical indicator in the strict sense, it provides an estimate of the internal coherence and interpretative robustness of the analytical process.

Residual discrepancies were then discussed collegially until a reasoned and documented agreement was reached. This comparison did not aim to enforce an artificial consensus, but rather to clarify the reasoning underlying the different interpretations and to establish a shared criterion for the definitive attribution of codes. The outcome of this phase is a validated and consolidated version of the coding, which serves as the basis for the quantitative representation of the results.

It is important to emphasise that the histograms presented in the following paragraphs therefore show the frequencies of the observables derived from the coding agreed upon after the final negotiation phase, and do not include the divergences observed during the preliminary stage. Through this process of triangulation, negotiation, and collegial validation, it was possible to achieve an intersubjective and controlled reading of the results, ensuring consistency between the methodological rigour of the qualitative analysis and the robustness of the reported data.

6.2.1 Results from the worksheets

The operational worksheets comprised a corpus of nine experimental activities: four pertaining to the macroscopic phase and five to the mesoscopic phase (see description in Chapter 4). Each worksheet was analysed using the codes from the final codebook (Appendix H, Table H.1).
During coding, the meaning units (phrases or response sequences) were segmented and annotated with one or more relevant codes. Each code was then linked to one or more observables according to the criteria specified in Appendix I.

To ensure a transparent and systematic account of the adopted coding method, representative excerpts from students' responses will be reported in the presentation of the results. These excerpts illustrate the assigned codes and the underlying interpretative reasoning. Each quotation is accompanied by a reference to the question (identified by an example label, e.g. Q1, Q2, etc.) and the student (S1, S2, etc.), ensuring traceability and transparency in the analytical process.

The histograms presented in the following section represent the percentage distribution of the associated observables emerging from each of the nine worksheets, distinguishing between the two phases of the TLS. These distributions will allow, in the subsequent chapter, for a discussion and analysis of the evolution of the cognitive and social dimensions investigated.

6.2.1.1 Macroscopic approach

Qualitative experiment worksheet No. 1

For this activity, the level of agreement among researchers prior to further collegial discussion was 82.9%.

The results show that the most frequently identified dimensions in students' responses were Evolution of common-sense conceptions to scientific ones (Obs. 1.2, 18.8%) and Metacognition (Obs. 3.3, 16.9%), revealing significant

metacognitive reflection and a conceptual evolution towards scientifically grounded forms of reasoning. This suggests that many students, during and after the experiment, reconsidered their initial conceptions, connecting them to explanations more consistent with the underlying physical models.
The dimensions related to the cognitive domain, namely Development of reasoning lines (Obs. 2.2, 6.1%) and Recognition and evolution of personal cognitive/learning styles (Obs. 2.4, 7.2%), indicate that the construction of coherent reasoning and awareness of one's own cognitive processes appeared less consolidated.
The following histogram displays the percentage distribution of the emergent observables.

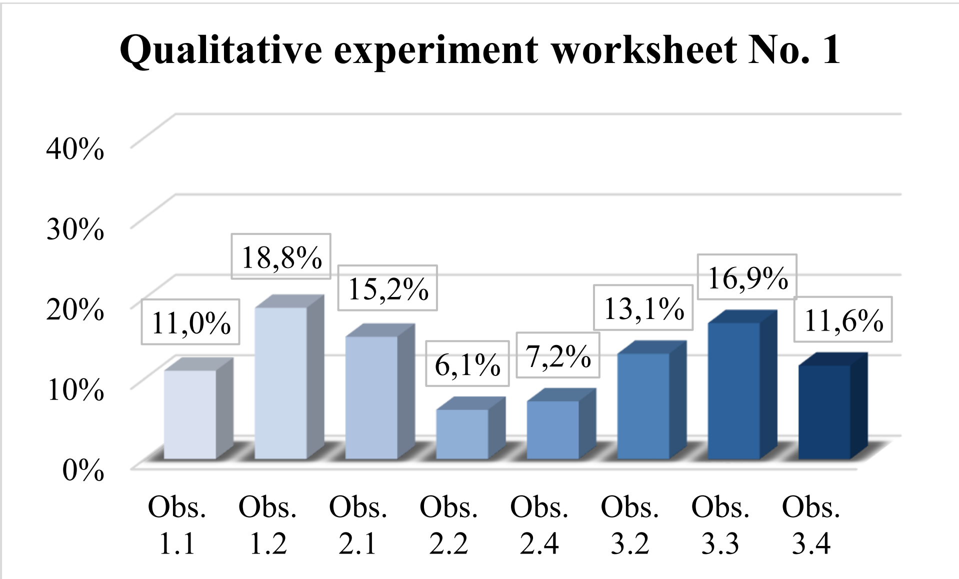

Figure 6.9: Percentage distribution of observables emerging from the analysis of the first qualitative experiment.

Representative excerpts are reported below, with references to codes reported in Appendix I.

Example – Critical awareness (Obs. 1.1 – Obs. 2.2 – Obs. 3.3), Proactive attitude (Obs. 2.2 – Obs. 3.2)

Q2, S1: *"One could also try with a hair or with something very light, but with the right shape to make it rest on the water. We could sprinkle some pepper on the surface and then touch it with soap: this way, by breaking the surface tension, the pieces of pepper would move away."*

This excerpt demonstrates critical awareness, as the student reflects on the factors influencing surface tension (weight, shape) and autonomously proposes a variant of the experiment, revealing a proactive attitude and an active understanding of the phenomenon.

Example – Interpretive models (Obs. 1.1 – Obs. 2.2 – Obs. 3.3)

Q4, S2: *"We saw that the paperclip seemed to rest on a sort of invisible net."*

The expression "invisible net" illustrates the construction of an intuitive interpretive model: the student employs a metaphor to describe the role of surface tension, seeking to form a mental representation of the observed physical phenomenon.

Qualitative experiment worksheet No. 2

For this activity, the level of agreement among researchers prior to further collegial discussion was 88.4%.

The analysis of relative frequencies reveals a pattern analogous to that of the previous experiment. Alongside the most prominent observables (Obs. 1.2 – 17.6%; Obs. 3.3 – 18.1%), there is a strengthening of interpersonal and social competences (Obs. 2.1 – 14.9%) and appropriation of concepts and representational forms (Obs. 1.1 – 12.8%). These observables indicate the activation of collaborative dynamics and an increasing conceptual mastery in the description of phenomena.
The following histogram displays the percentage distribution of the emergent observables.

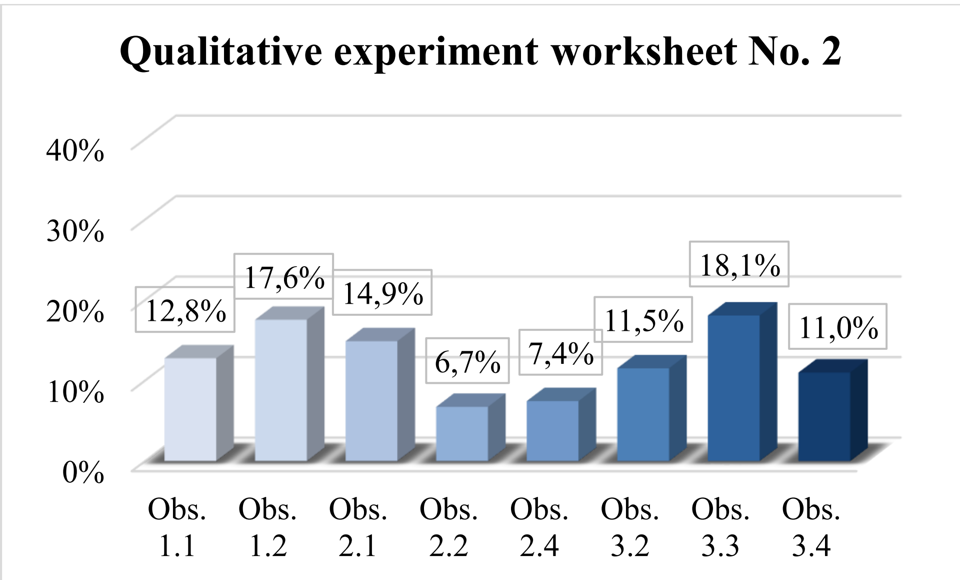

Figure 6.10: Percentage distribution of observables emerging from the analysis of the second qualitative experiment.

Representative excerpts are reported below.

Example – Critical awareness (Obs. 1.1 – Obs. 2.2 – Obs. 3.3), Discussion and negotiation (Obs. 2.1 – Obs. 3.2 – Obs. 3.4), Exploratory drive (Obs. 3.2)

Q3, S6: *"We placed the two frames in the soapy water and saw that the soap remains inside the frames, creating a surface. Some forces (I think it is surface tension) make the two mobile sides move towards the centre. When we try with small metallic objects or even our fingers, still inside the flexible frame, we see that the surface tension does not break immediately."*

The student demonstrates critical awareness by linking empirical observations to scientific concepts (surface tension) and shows an exploratory drive through experimentation with different objects. The use of reflective language and peer interaction further highlights a dynamic of discussion and negotiation of ideas.

Example – Operational description (Obs. 1.2)

Q4, S28: *"The metal frame, when taken out of the soapy water, tends to close towards the rigid rod, while in the flexible frame the threads almost form a semicircle."*

This excerpt illustrates an operational description of the observed phenomenon, with attention to the behaviour of the frames. The student documents the experimental results precisely, without engaging in theoretical explanations, typical of a code focused on observation and operational reporting.

Qualitative experiment worksheet No. 3

For this activity, the level of agreement among researchers prior to further collegial discussion was 85.9%.

The highest percentages were recorded for observables Obs. 1.1 (17.7%) and Obs. 1.2 (19.7%), both exceeding half of the total. This finding suggests a conceptual shift among students from everyday intuitions to more scientific formulations. It is likely that the structure of the activity (experimentation + discussion) facilitated this conceptual restructuring.

Other observables, such as Development of reasoning lines, Obs. 2.2, (7.3%) and Recognition and evolution of personal cognitive/learning styles, Obs. 2.4, (2.0%), were significantly lower.
The following histogram displays the percentage distribution of the emergent observables.

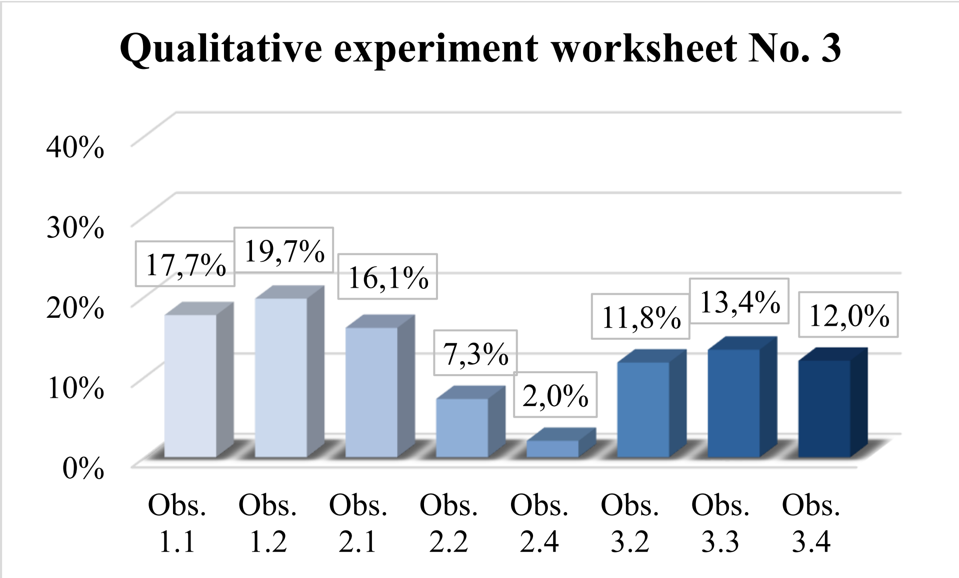

Figure 6.11: Percentage distribution of observables emerging from the analysis of the third qualitative experiment.

Representative excerpts are reported below.

Example – Projection (Obs. 2.2 – Obs. 3.3), Recall of previous knowledge (Obs. 1.2)

Q1, S4: *"I would add some dye to the water and then pour it into the capillary tubes to observe its behaviour. Theoretically, the narrower the tube, the higher the liquid will rise."*

The student exhibits projection by anticipating the outcome of the experiment and refers to prior knowledge of liquid behaviour in capillaries, showing the recall of previously acquired concepts.

Example – Operational description (Obs. 1.2), Scientific language (Obs. 1.1 – Obs. 1.2)

Q3, S32: *"I fill one of the two glasses with water and add some dye, then fold a piece of absorbent paper and place it as a bridge between the glasses. We* *notice that the water passes through the paper thanks to adhesive forces and will continue to flow until the water levels in the two glasses are equal."*

This excerpt represents a detailed operational description, documenting the experiment step by step. The use of terms such as adhesive forces indicates a scientific language consistent with the coding and with an understanding of the physical principles underlying the phenomenon.

Qualitative experiment worksheet No. 4

For this activity, the level of agreement among researchers prior to further collegial discussion was 83.6%.

The observables with the highest percentages were Obs. 2.1 (19.3%) and Obs. 3.3 (16.4%), both in the medium-high range. The experience evidently stimulated social interaction (group work) and, in parallel, reflection on one's own learning. The activity seems to have been perceived as highly collaborative, with peer exchange acting as a metacognitive trigger.
It is also noteworthy that observable Obs. 3.4 (13.8%) is comparable to the others in the medium-high range, suggesting that the proposed activities elicited active engagement and intrinsic motivation among students.
The remaining observables, by contrast, show very low percentages, some almost null, such as Obs. 2.4 (2.1%), indicating a distribution strongly skewed towards specific learning aspects.
The following histogram displays the percentage distribution of the emergent observables.

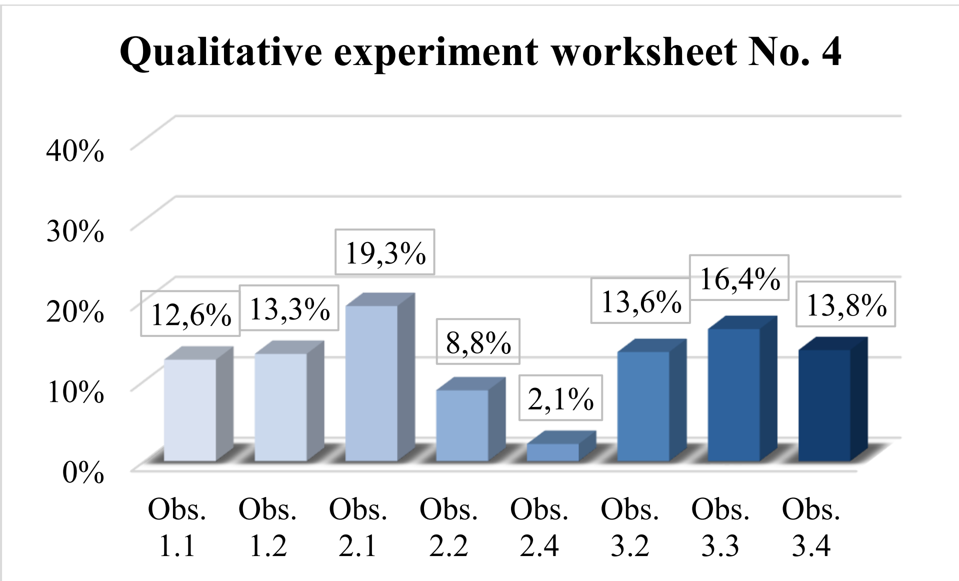

Figure 6.12: Percentage distribution of observables emerging from the analysis of the fourth qualitative experiment.

Representative excerpts are reported below.

Example – Plurality of languages (Obs. 2.4 – Obs. 3.3), Critical awareness (Obs. 1.1 – Obs. 2.2 – Obs. 3.3), Well-being (Obs. 2.1 – Obs. 3.4)

Q4, S34: *"The experiment really helped me to understand better why surface tension breaks and what happens at that moment: I noticed a movement in the water that I had never seen before. I really enjoyed discovering this with my own eyes."*

The excerpt highlights the combined use of descriptive and conceptual language ("breaking surface tension", "movement in the water"). The student demonstrates an intention to engage in metacognitive reflection to understand a previously unknown phenomenon. The sense of well-being is evident in the positive and personally satisfied tone.

Example – Proactive attitude (Obs. 2.2 – Obs. 3.2)

Q2, S3: *"I would repeat the same experiment, but I would try placing small pieces of paper or confetti on top."*

The student shows a proactive attitude, suggesting modifications to the original experiment to explore new effects. The excerpt illustrates curiosity and a willingness to experiment, features typical of this code.

6.2.1.2 Mesoscopic approach

Simulation-based activity worksheet No. 1

For this activity, the degree of agreement among researchers, prior to further collegial discussion, was 91.8%.

Once again, there is a predominance of Obs. 1.1 (19.3%) and Obs. 1.2 (22.5%), both markedly higher than the others. The clear predominance of these observables reflects the conceptual consolidation achieved through the simulation activities.
It is worth noting the increase in Obs. 2.4 (4.6%), suggesting that graphical representation provided a more consistent contribution to knowledge construction for some students.
The remaining observables are distributed across medium or low levels, with minimal differences among them.

The histogram below displays the percentage distribution of the emergent observables.

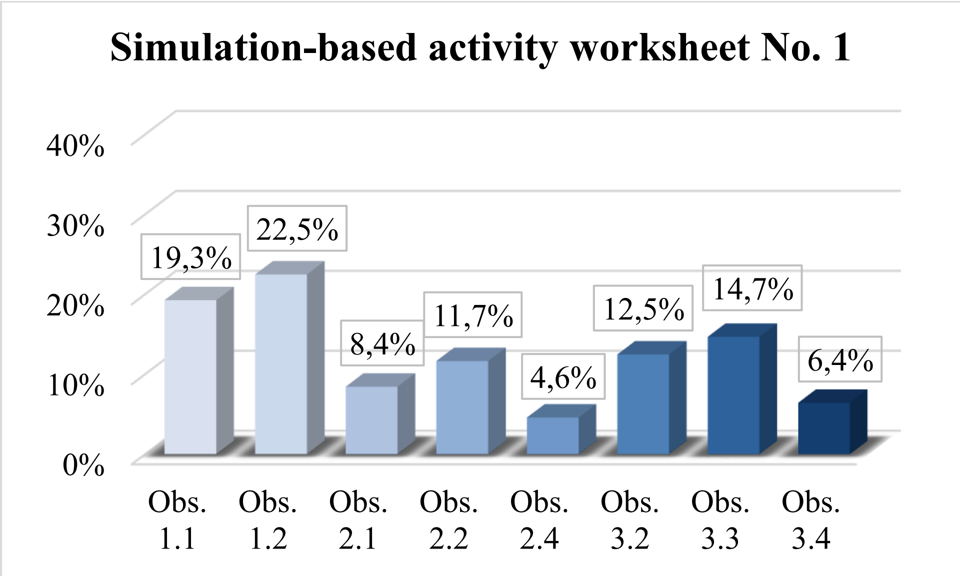

Figure 6.13: Percentage distribution of observables emerging from the analysis of the first mesoscopic-simulative experiment.

Representative excerpts are presented below.

Example – Comprehension tools (Obs. 1.2 – Obs. 2.4 – Obs. 3.3), Well-being (Obs. 2.1 – Obs. 3.4), Exploratory drive (Obs. 3.2)

Q2, S26: *"I found it very useful to see how the forces act on each particle. It helped me to better understand the overall behaviour of the drop, and it made me even more curious to modify the parameters."*

It is evident that the use of simulations was essential for this student to grasp complex concepts. The sense of well-being emerging from the excerpt is associated with curiosity and the desire to experiment further, clear signs of genuine satisfaction in the learning process.

Example – Shared construction (Obs. 1.2 – Obs. 2.1 – Obs. 3.2 – Obs. 3.3)

Q4, S12: *"During the discussion with my classmates, we managed to clarify each other's doubts and to better understand what was happening in the simulation."*

This excerpt clearly refers to the collective construction of knowledge through dialogue, collaboration, and the integration of different perspectives.

Simulation-based activity worksheet No. 2

For this activity, the degree of agreement among researchers, prior to further collegial discussion, was 88.1%.

The highest percentage corresponds to Obs. 3.3 (18.4%), which clearly exceeds the others, followed by Obs. 3.2 (15.8%) with slightly lower yet still relevant values. It appears that this activity was perceived by students as a reflective moment, both individual and collective, as indicated by Obs. 2.1 (11.5%), which led to the development of growth-oriented attitudes, such as error tolerance and a willingness to improve.
The remaining observables are all below these values.
The histogram below displays the percentage distribution of the emergent observables.

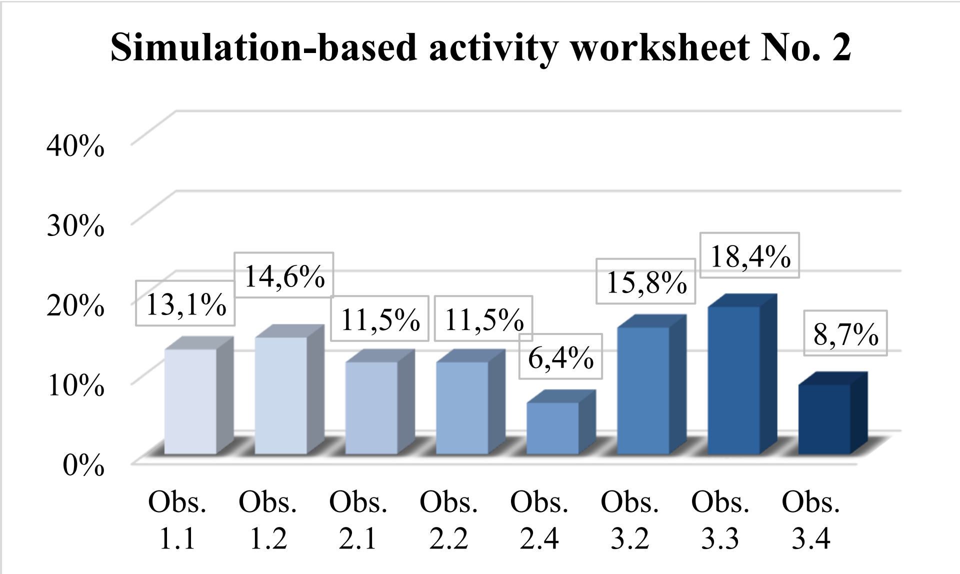

Figure 6.14: Percentage distribution of observables emerging from the analysis of the second mesoscopic-simulative experiment.

Representative excerpts are presented below.

Example – Common-sense reasoning (Obs. 1.1 – Obs. 1.2)

Q1, S21: *"I think the drop changes shape because intermolecular forces and gravity act together and pull it downwards, as if they were stretching it."*

This excerpt employs a recognisably intuitive language typically used to explain a complex physical phenomenon in everyday life.

Example – Scientific language (Obs. 1.2 – Obs. 1.2), Critical awareness (Obs. 1.1 – Obs. 2.2 – Obs. 3.3), Discussion and negotiation (Obs. 2.1 – Obs. 3.2 – Obs. 3.4), Shared construction (Obs. 1.2 – Obs. 2.1 – Obs. 3.2 – Obs. 3.3)

Q3, S9: *"The discussion made me realise that the shape of the drop depends on a balance between cohesive forces, gravity, and pressure. I noticed that each force plays a different role depending on the simulation conditions. Talking with others helped me to grasp this complexity and to use more precise terms to describe it."*

The excerpt reveals an appropriate use of technical terminology, along with an explicit awareness of the variability of conditions. It also demonstrates collective reflection and engaged dialogue, both of which reinforce understanding.

Simulation-based activity worksheet No. 3

For this activity, the degree of agreement among researchers, prior to further collegial discussion, was 97.1%.

The observables Obs. 1.2 (21.1%) and Obs. 3.2 (18.2%) are dominant. Students acknowledged conceptual progress, accompanied by increased confidence in their own improvement, hence the rise in growth mindset.
Moreover, Obs. 3.3 (16%), linked to Metacognition, also reaches a significant percentage. This suggests that encouraging reflection on the strategies adopted can foster attitudes oriented towards improvement.
Other categories display a relatively undifferentiated distribution.
The histogram below displays the percentage distribution of the emergent observables.

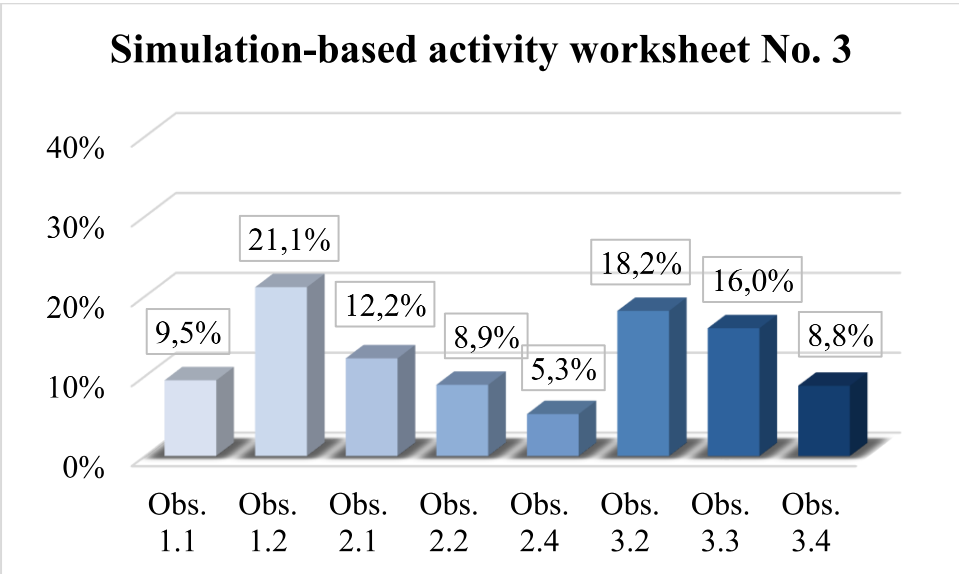

Figure 6.15: Percentage distribution of observables emerging from the analysis of the third mesoscopic-simulative experiment.

Representative excerpts are presented below.

Example – Shared construction (Obs. 1.2 – Obs. 2.1 – Obs. 3.2 – Obs. 3.3), Well-being (Obs. 2.1 – Obs. 3.4), Discussion and negotiation (Obs. 2.1 – Obs. 3.2 – Obs. 3.4)

Q4, S9: *"The discussion with my classmates helped me to look at the problem from different perspectives and to better understand how adhesive and cohesive forces influence particle behaviour. It was enjoyable to discuss together and understand how microscopic phenomena affect macroscopic ones."*

The student clearly expresses how group dialogue and shared peer knowledge enhanced their understanding of the simulated phenomenon. The excerpt is written in a distinctly positive tone regarding the learning experience.

Example – Scientific language (Obs. 1.2 – Obs. 1.2)

Q1, S8: *"Between the particles of the liquid and those of the walls, cohesive forces act and form menisci, that is, the curvature of the liquid in contact with the container."*

This code is identified through the accurate use of scientific–physical terminology (cohesive forces, menisci).

Simulation-based activity worksheet No. 4

For this activity, the degree of agreement among researchers, prior to further collegial discussion, was 98.7%.

Here too, the highest percentages correspond to Obs. 1.2 (20.8%), Obs. 3.3 (19.1%), and Obs. 3.2 (13.4%). As with the previous activity, this experiment promoted both conceptual change and awareness of the learning process that produced it, as well as an attitude oriented towards improving one's understanding.

The remaining observables show a marked gap, with Obs. 3.4 (6.4%) reaching its lowest value, indicating some relational difficulties within small groups.

The histogram below displays the percentage distribution of the emergent observables.

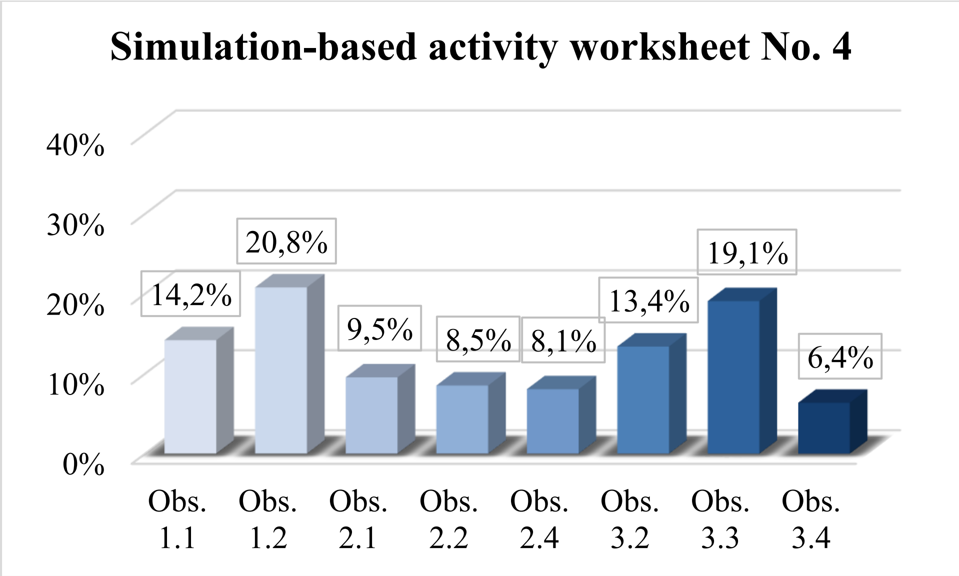

Figure 6.16: Percentage distribution of observables emerging from the analysis of the fourth mesoscopic-simulative experiment.

Representative excerpts are presented below.

Example – Recall of previous knowledge (Obs. 1.2)

Q2, S32: *"The way the particles interact determines the curvature of the surface and how much the solid becomes wet. The simulations confirmed what we had studied in theory."*

The student explicitly recalls previously acquired knowledge, integrating it with the new experience.

Example – Comprehension tools (Obs. 1.2 – Obs. 2.4 – Obs. 3.3)

Q4, S24: *"Through the simulations I truly understood how adhesive and cohesive forces behave when a solid meets water. Seeing the particles move made the mechanism clear to me."*

The selected code is evident in the use of simulation as a visual aid for conceptual understanding.

Simulation-based activity worksheet No. 5

For this activity, the degree of agreement among researchers, prior to further collegial discussion, was 90.7%.

The observables Obs. 1.2 (22.8%) and Obs. 3.3 (20.0%) remain among the most frequent, with similar and markedly higher values than the others. The distribution appears stable and consistent with previous experiments. It is evident that the proposed activities promote conceptual restructuring while simultaneously fostering metacognitive reflection.
An increase is observed in Obs. 1.1 (15.6%), showing that students can transfer the acquired content into communicative or symbolic forms typical of scientific discourse.
Obs. 2.2 (10.0%) also rises again compared to recent simulations, where a decline in argumentative coherence had been observed. Students have resumed producing more structured explanations and better-articulated reasoning lines, indicating that the more recent activities have reactivated inferential construction processes.
The histogram below displays the percentage distribution of the emergent observables.

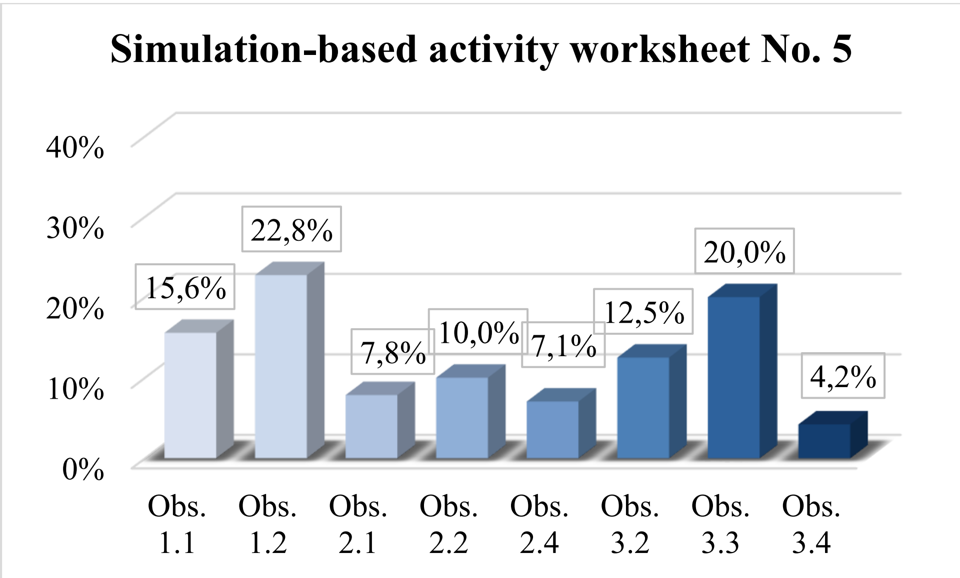

Figure 6.17: Percentage distribution of observables emerging from the analysis of the fifth mesoscopic-simulative experiment.

Representative excerpts are presented below.

Example – Discussion and negotiation (Obs. 2.1 – Obs. 3.2 – Obs. 3.4)

Q5, S22: *"Discussing with my classmates helped me a lot, because on my own I would not have been able to understand certain conceptual steps properly."*

Collaboration and peer dialogue are evident in the importance attributed to discussion and exchange during the learning process.

Example – Critical awareness (Obs. 1.1 – Obs. 2.2 – Obs. 3.3), Recall of previous knowledge (Obs. 1.2), Scientific language (Obs. 1.2 – Obs. 1.2)

Q3, S20: *"If the interaction force between the liquid and the surface is weak, the liquid particles attract each other more strongly and try to reduce contact with the surface, forming an almost spherical drop. It is the same principle we studied in the theoretical part."*

This excerpt demonstrates the precise use of physical terminology, along with a well-considered reflection on the conditions necessary for the phenomenon to occur. The final sentence also reveals a clear connection to theoretical knowledge.

6.2.1.3 Summary of results

Cumulative qualitative worksheets results

The overall analysis of the four qualitative activities reveals a balanced distribution of the observables, with some noteworthy trends.
The highest percentages correspond to Obs. 1.2 (17.4%), Obs. 3.3 (16.3%), and Obs. 2.1 (16.2%), indicating that, across the worksheets, students devoted greater attention to re-elaborating their initial conceptions into more scientific forms of thinking, engaging in metacognitive reflection, and valuing social interactions during experimental activities. These three dimensions thus emerge as the most representative cores of the qualitative experiences, in which collective negotiation and awareness of one's own cognitive process appear to have accompanied the progressive construction of scientific meaning.
Observables Obs. 1.1 (13.4%), Obs. 3.2 (12.4%), and Obs. 3.4 (12.0%) show intermediate values, suggesting that the appropriation of scientific representations, the perception of personal growth, and well-being during the activities were consistently present, though less prominently than the dominant categories. Notably, the non-negligible contribution of well-being confirms that the qualitative experiences were perceived as engaging and positive.
The percentages for Obs. 2.2 (7.2%) and Obs. 2.4 (5.0%) are considerably lower, referring respectively to the development of coherent reasoning patterns and the recognition of one's own cognitive styles. Their limited occurrence indicates that these dimensions emerged less frequently in the responses.
Overall, the percentage distribution shows that, in the qualitative phase, the experience was primarily perceived as a space for shared construction and personal reflection rather than as a moment of logical-conceptual structuring,

confirming the exploratory and participatory nature of this first stage of the learning process.

The following histogram illustrates the percentage distribution of the observed categories.

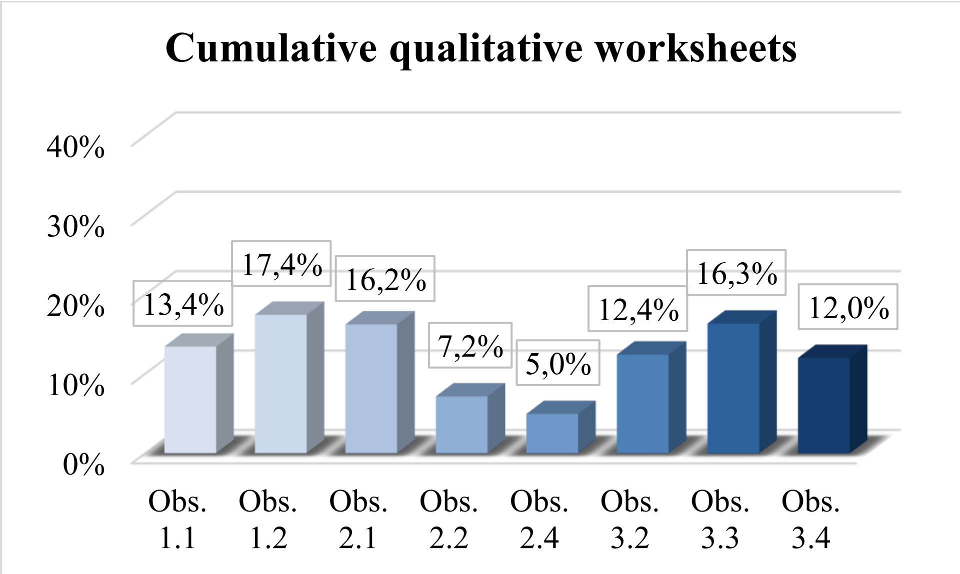

Figure 6.18: Percentage distribution of observables emerging from all macroscopic activities.

Cumulative simulation worksheets results

The overall analysis of the five simulation-based activities shows a distribution of observables that reflects a shift towards more conceptual and metacognitive dimensions. The highest percentages were recorded for Obs. 1.2 (20.1%) and Obs. 3.3 (17.6%), followed by Obs. 1.1 and Obs. 3.2 (both at 14.5%). These values indicate that, across all SPH-based simulation activities, students placed particular emphasis on transforming their initial conceptions into explicative scientific reasoning and on consciously reflecting upon their cognitive and learning processes.

Observables Obs. 2.1 (10.0%) and Obs. 2.2 (10.3%) display slightly lower but still meaningful values, suggesting that social skills and the development of structured reasoning continued to play a role, albeit less central than the cognitive dimensions. Conversely, Obs. 2.4 (6.2%) and Obs. 3.4 (7.0%) represent the least frequent categories, signalling a limited explicit reference to individual learning styles and less attention to emotional or well-being-related aspects.

The distribution of percentages highlights that, during the simulated activities, students' focus shifted towards more formalised cognitive re-elaboration, characterised by the construction of coherent explicative reasoning and greater awareness of their own thought processes, with a gradual decline in relational and emotional components.

The following histogram illustrates the percentage distribution of the observed categories.

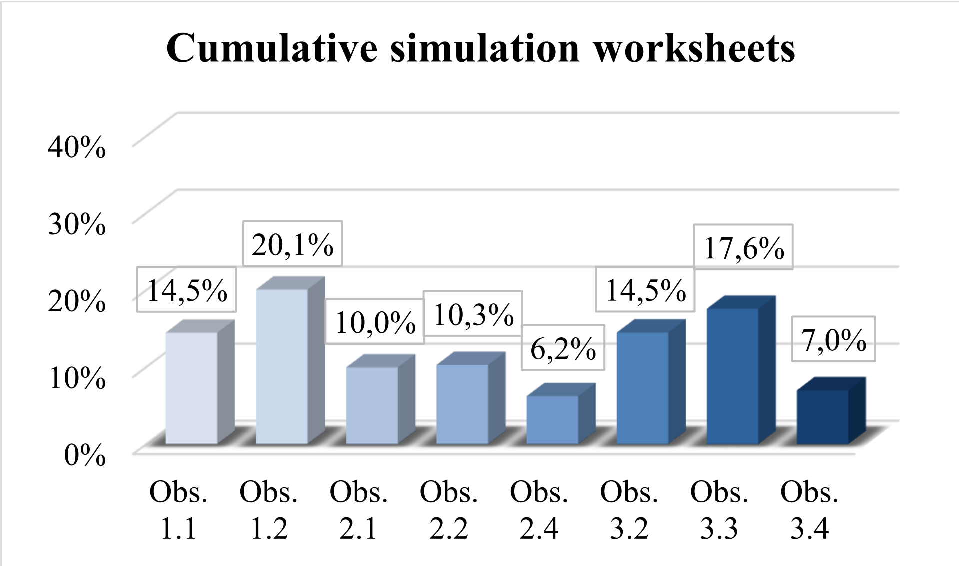

Figure 6.19: Percentage distribution of observables emerging from all mesoscopic activities.

Comparing results between macro and meso worksheets

The comparison between qualitative and simulated activities reveals several significant variations in the distribution of observables. In the qualitative activities, relational and affective dimensions were more prominent, with relatively high values for Obs. 2.1 (16.2%) and Obs. 3.4 (12.0%), whereas in the simulations these categories decreased to 10.0% and 7.0%, respectively. This trend suggests that, during the initial experimental stages, social interactions and perceived well-being were expressed more frequently than in the simulated environment.
At the same time, the simulations show an increase in the observables related to conceptual re-elaboration and metacognitive reflection. The percentages for Obs. 1.2 (20.1%) and Obs. 3.3 (17.6%) are higher than those recorded in the qualitative phase (17.4% and 16.3%), indicating a greater occurrence of references to conceptual transformation and awareness of learning processes. Obs. 1.1, related to the appropriation of scientific representations, also shows a slight increase (from 13.4% to 14.5%), suggesting a more direct engagement with formal models and scientific descriptions.

Smaller differences are observed for Obs. 3.2 and Obs. 2.2, both showing modest growth in the simulations, while Obs. 2.4, although remaining the least represented in both contexts, rises moderately (from 5.0% to 6.2%).
The comparison therefore highlights a transition from a distribution strongly characterised by interpersonal and affective dimensions to one more oriented towards conceptual and metacognitive aspects, where reflective and cognitive elaboration components acquire relatively greater weight.

The following comparative histogram shows the distributions for the macroscopic and mesoscopic activities.

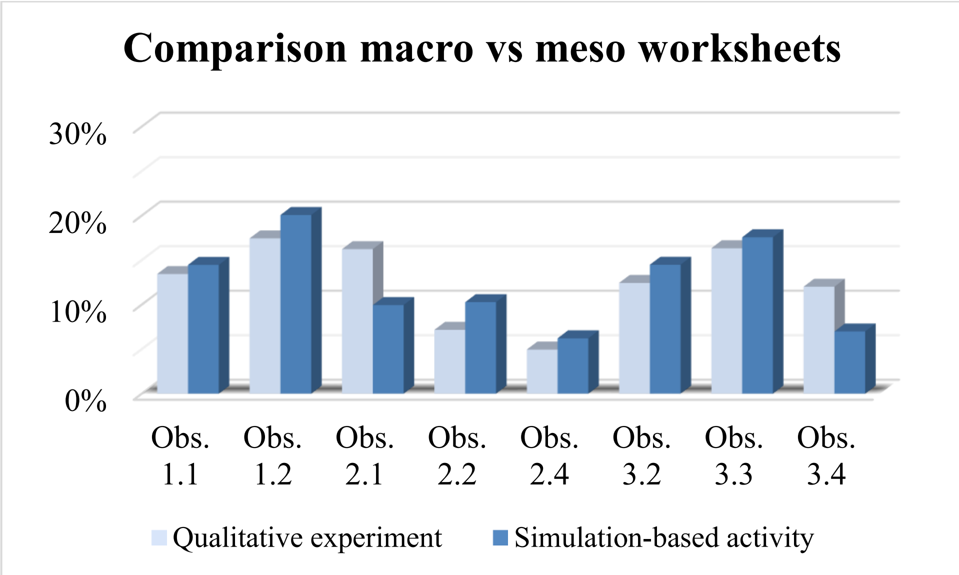

Figure 6.20: Comparison of percentage distributions of observables emerging from worksheets during macroscopic and mesoscopic activities.

6.2.2 Clinical interview results

The clinical interviews were conducted at the conclusion of each of the nine experimental activities, with the aim of exploring in depth the students' conceptual construction processes and assessing the level of awareness achieved regarding the phenomena studied. Each interview revolved around two main questions designed to stimulate metacognitive reflection and elicit the reasoning strategies employed during the activities.

Each activity, both macroscopic and mesoscopic, was structured according to a cyclic framework articulated in five phases: individual prediction, small-group discussion, experimental observation, collective re-elaboration, and plenary discussion. The questions posed during the individual interviews revisited the conclusions drawn in the collective discussions, asking students whether they considered them consistent with their own observations and personal beliefs. The dialogue then continued in an open, reflective manner, exploring how the phenomenon had been understood, reinterpreted, and linked to relevant physical models, while also probing conceptual connections, encountered difficulties, and the motivations behind interpretative choices.

The full transcriptions of the interviews were subsequently subjected to thematic analysis, following the same procedure adopted for the operational worksheets and employing the codes from the final codebook (Appendix H, Table H.1). Each unit of meaning was identified, segmented, and coded, and the results were then triangulated among the researchers to ensure interpretative coherence and reliability. Representative excerpts from students' responses are presented throughout the results section. Each quotation is accompanied by a reference to the interviewed student (S1, S2, etc.), ensuring traceability and transparency in the analytical process.
The frequencies of the emergent observables are presented in nine histograms, each corresponding to the interview conducted at the end of a specific activity.

6.2.2.1 Macroscopic approach

Qualitative experiment interview No. 1

For this activity, the inter-rater agreement among researchers, prior to collegial discussion, was 89.3%.

The predominance of metacognition (Obs. 3.3 – 21.0%) indicates that the interviews primarily encouraged reflection on students' thinking and learning strategies rather than the description of disciplinary content. Interpersonal skills (Obs. 2.1 – 14.8%), though lower, reveal that students attributed significant value to peer interaction and group work. The growth mindset (Obs. 3.2 – 12.3%) completes the picture, suggesting that students not only reflected on what they had learned but also on their own personal development.
The remaining observables show homogeneous levels.
The following histogram illustrates the percentage distribution of the emergent observables.

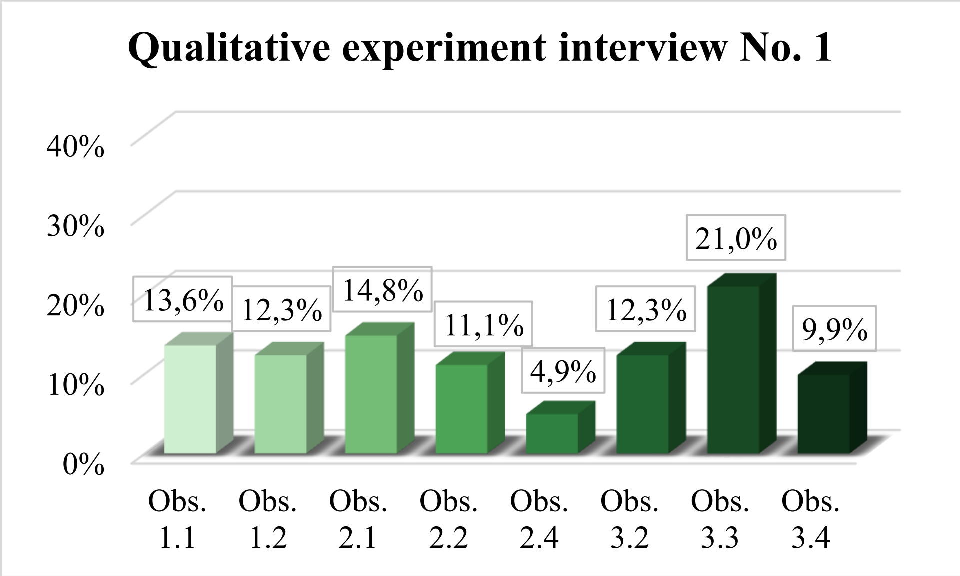

Figure 6.21: Percentage distribution of observables emerging from interviews related to the first qualitative experiment.

Below are some representative excerpts.

Example – Critical awareness (Obs. 1.1 – Obs. 2.2 – Obs. 3.3)

S8: *"After the collective discussion, I realised that objects can stay on the water even without the napkin. They do not actually float because they are not submerged: it is surface tension that supports them."*

This code emerges in the conscious revision of one's own reasoning and the clarification of a previous misconception.

Example – Scientific language (Obs. 1.2 – Obs. 1.2)

S23: *"At first, I thought surface tension broke only when the object was too heavy. Then I understood that it remains intact as long as the weight force is smaller than the constraint force keeping the object on the water surface."*

The excerpt shows the correct use of scientific terminology, such as weight force and constraint force.

Qualitative experiment interview No. 2

For this activity, the inter-rater agreement among researchers, before collegial discussion, was 95.2%.

The highest percentages were recorded for Obs. 2.1 (20.9%), Obs. 3.2 (19.4%), and Obs. 3.3 (17.9%), indicating that students frequently referred to collaborative dynamics, awareness of their own improvement, and metacognitive reflection on their learning processes. These aspects suggest that the interview primarily facilitated the expression of the social and reflective dimensions of the experience, rather than the conceptual elaboration of disciplinary content. A significant percentage was also observed for Obs. 3.4 (13.4%), showing a widespread perception of well-being and positive engagement during the activity. Notably, Obs. 2.4 was entirely absent, indicating that students did not spontaneously refer to their own cognitive styles or personal learning strategies.
The following histogram illustrates the percentage distribution of the emergent observables.

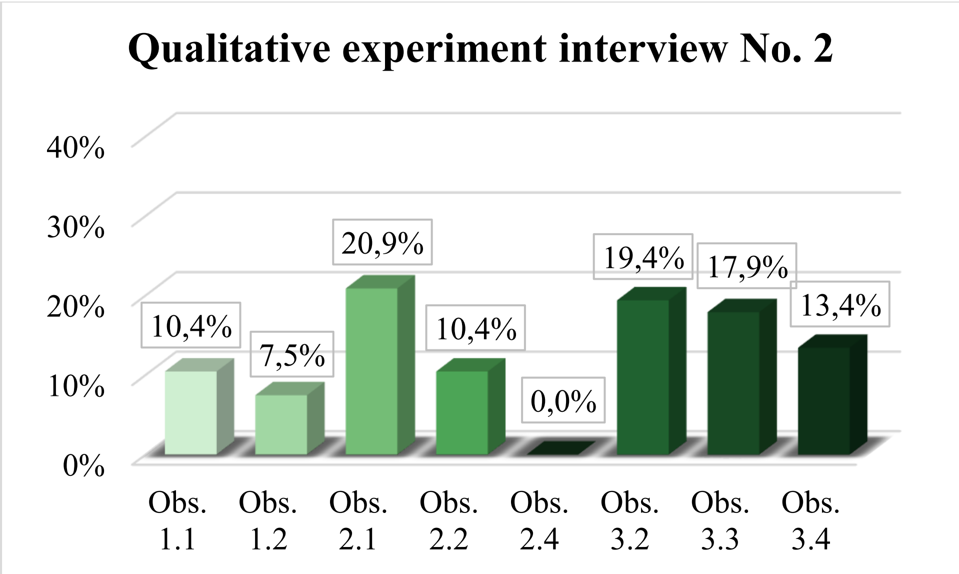

Figure 6.22: Percentage distribution of observables emerging from interviews related to the second qualitative experiment.

Below are some representative excerpts.

Example – Scientific language (Obs. 1.2 – Obs. 1.2), Shared construction (Obs. 1.2 – Obs. 2.1 – Obs. 3.2 – Obs. 3.3)

S21: *"In my opinion, what we said in the plenary discussion made sense. At first, I was not convinced, but then I was persuaded by the idea that the needle 'breaks' the bonds between the water and the filter, altering the surface tension."*

The excerpt shows correct use of the concept of bond and an understanding of its consequences on surface tension. It also reveals an explicit reference to meaning construction during the collective discussion.

Example – Shared construction (Obs. 1.2 – Obs. 2.1 – Obs. 3.2 – Obs. 3.3), Discussion and negotiation (Obs. 2.1 – Obs. 3.2 – Obs. 3.4), Well-being (Obs. 2.1 – Obs. 3.4)

S29: *"I agree with what the group decided. At first, I was a bit confused but talking to my classmates and understanding how they reasoned helped me. It was also pleasant to exchange ideas."*

The excerpt highlights a productive collective exchange that supported comprehension. It also shows how dialogue and the opportunity to view the phenomenon from different perspectives helped the student gain greater awareness of the phenomenon. The positive tone of the experience is evident in the final remark.

Qualitative experiment interview No. 3

For this activity, the inter-rater agreement among researchers, before collegial discussion, was 92.3%.

The highest percentages for Obs. 2.1 (25.3%) and Obs. 3.4 (18.7%) indicate that, during the interviews, students emphasised relational dynamics and perceived well-being, underscoring the positive role of interaction and collaboration in the learning context. Conversely, the very low percentages for Obs. 2.2 (4.0%) and Obs. 1.1 (6.7%) reveal a limited presence of references to structured reasoning or the development of scientific representations.
The following histogram illustrates the percentage distribution of the emergent observables.

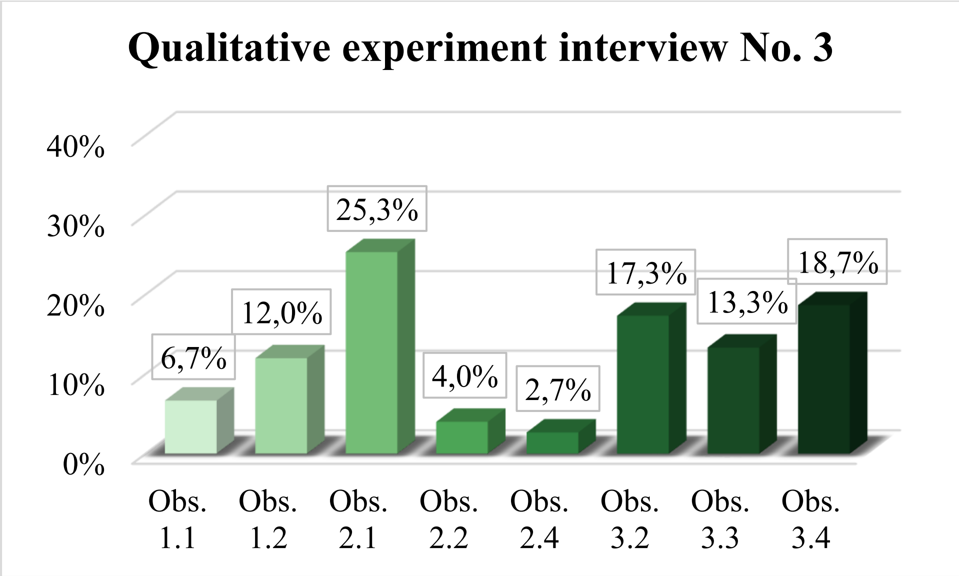

Figure 6.23: Percentage distribution of observables emerging from interviews related to the third qualitative experiment.

Below are some representative excerpts.

Example – Well-being (Obs. 2.1 – Obs. 3.4), Exploratory drive (Obs. 3.2)

S18: *"I had never thought that water could rise to different heights in capillary tubes. Experiencing it and testing it myself surprised me and made me realise there is a relationship between the height and the tube's diameter."*

This excerpt reveals two complementary dimensions. The Well-being code emerges in the satisfaction and sense of wonder the student expresses upon discovery. At the same time, the Exploratory drive code is recognised in the curiosity stemming from direct experience: observing the phenomenon arouses a desire to understand the relationship between height and diameter, reflecting an active attitude of inquiry and discovery.

Example – Exploratory drive (Obs. 3.2), Proactive attitude (Obs. 2.2 – Obs. 3.2)

S22: *"During the experiment, I noticed that the dye moved more slowly than water. I thought it might be because it is denser. I tried changing the amount of absorbent paper and the water level to see how the result varied, and I saw that it changed."*

The excerpt highlights the student's experimental attitude: they observe, hypothesise, and empirically verify their intuition. Rather than merely recording what happens, the student displays curiosity leading to further exploration. The

Proactive attitude code is justified by their self-directed behaviour: the student consciously modifies the experimental parameters to test their hypothesis, showing initiative and autonomy.

Qualitative experiment interview No. 4

For this activity, the inter-rater agreement among researchers, prior to collegial discussion, was 86.4%.

Once again, high values were recorded for Obs. 2.1 (21.3%) and Obs. 3.3 (19.9%), indicating that students focused mainly on collaborative aspects and metacognitive reflection regarding their understanding of the phenomena. Although lower, Obs. 3.2 (15.4%) confirms the presence of references to personal growth and the willingness to reconsider previous ideas. The remaining observables show markedly lower values, signalling a reduced incidence of conceptual elaboration (Obs. 2.2) or disciplinary content (Obs. 1.1) compared with reflective and relational dimensions.
The following histogram illustrates the percentage distribution of the emergent observables.

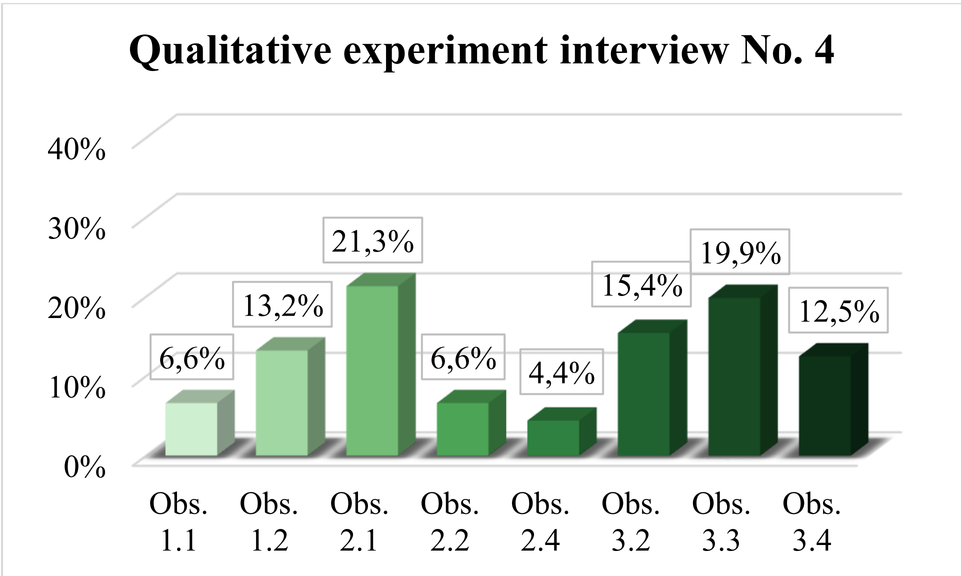

Figure 6.24: Percentage distribution of observables emerging from interviews related to the fourth qualitative experiment.

Below are some representative excerpts.

Example – Common-sense reasoning (Obs. 1.1 – Obs. 1.2)

S35: *"I thought turmeric would not react, but it did. Maybe I expected no change because I saw it as a 'dry' spice, something that could not dissolve or react with water."*

The Common-sense reasoning code clearly emerges from the explanation provided. The student uses non-technical language that remains coherent with their perceptual experience.

Example – Projection (Obs. 2.2 – Obs. 3.3), Critical awareness (Obs. 1.1 – Obs. 2.2 – Obs. 3.3)

S14: *"So, not all spices are soluble? I don't really know, but I think the ones we used aren't because they seemed more 'reactive'. The talcum powder, instead, being soluble, created a film that changed the surface tension of the water."*

The excerpt demonstrates the student's ability to formulate personal hypotheses about material behaviour, projecting their interpretation beyond immediate observation. Simultaneously, a comparative reflection between different materials (spices and talcum powder) emerges, accompanied by an awareness that their properties influence the observed phenomenon.

6.2.2.2 Mesoscopic approach

Simulation-based activity interview No. 1

For this activity, the degree of agreement among researchers prior to further collegial discussion was 86.6%.

The highest percentages for Obs. 3.2 (17.5%) and Obs. 3.3 (15.4%) indicate that during the interviews, students continued to frequently refer to their perception of personal growth and to reflection on their own cognitive processes, thus confirming the centrality of self-reflective dimensions. However, there was an increase in Obs. 2.2 (11.4%), signalling a greater presence of structured reasoning and logical connections in the explanations provided, an element less evident in the earlier phases. Obs. 2.4 (5.3%) also shows a slight rise, suggesting that some students began to refer to their own cognitive styles or personal learning modes, albeit still to a limited extent.
The following histogram displays the percentage distribution of the observed indicators.

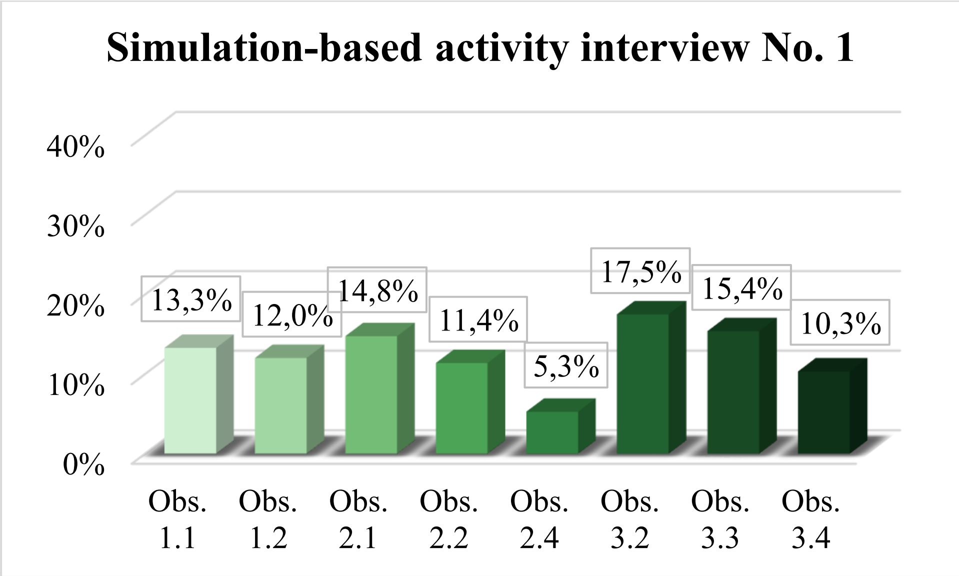

Figure 6.25: Percentage distribution of observables emerging from interviews related to the first mesoscopic-simulative experiment.

Representative excerpts are presented below.

Example – Well-being (Obs. 2.1 – Obs. 3.4), Comprehension tools (Obs. 1.2 – Obs. 2.4 – Obs. 3.3)

S8: *"The mesoscopic model helped me a lot. Seeing on the screen how forces act between particles allowed me to really understand what happens inside the droplet. Without that representation, I would not have managed."*

The simulation here clearly acts as a tool for cognitive mediation: the graphical representation enables the student to construct a more solid understanding of the phenomenon. Well-being emerges from the explicit satisfaction expressed regarding successful understanding.

Example – Critical awareness (Obs. 1.1 – Obs. 2.2 – Obs. 3.3), Scientific language (Obs. 1.2 – Obs. 1.2)

S10: *"We saw that pressure and intermolecular forces balance each other to keep the system stable. However, I think that the inner particles exert weaker forces because they are balanced by those surrounding them."*

The accurate use of physical terms such as pressure forces, intermolecular, and balanced highlights an appropriate use of scientific language. Furthermore, the student critically reflects on the model, formulating a personal interpretation regarding the balance of forces.

Simulation-based activity interview No. 2

For this activity, the degree of agreement among researchers prior to further collegial discussion was 85.6%.

Once again, Obs. 3.2 (18.1%) and Obs. 3.3 (15.9%) prevailed, confirming the students' tendency to focus on their awareness of personal improvement and on the metacognitive reflection that emerged during the interview. However, an increase in Obs. 1.2 (14.8%) indicates a shift away from common-sense conceptions towards a more coherent and systemic form of learning. Conversely, the decrease in Obs. 3.4 (8.2%) suggests a reduced presence of references to well-being or emotional involvement during the activity.
The following histogram shows the percentage distribution of the observed indicators.

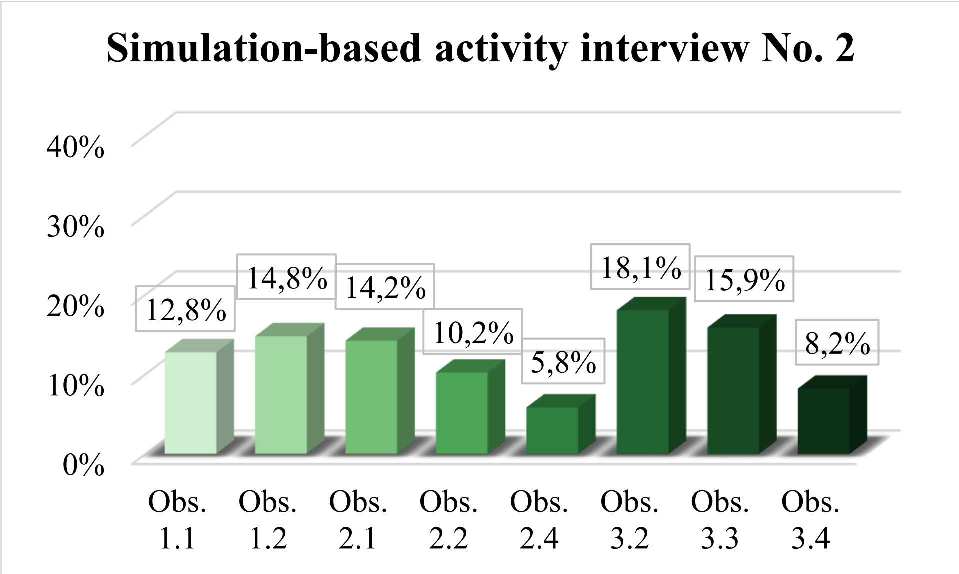

Figure 6.26: Percentage distribution of observables emerging from interviews related to the second mesoscopic-simulative experiment.

Representative excerpts are presented below.

Example – Plurality of languages (Obs. 2.4 – Obs. 3.3)

S36: *"In the large group, we talked a lot about the effect of gravity on the droplet's deformation. However, I also tried to explain it by drawing a diagram of the forces, because I find it easier to reason visually rather than by imagining it."*

The student integrates verbal and visual languages (the drawing of the force diagram) to build personal understanding.

Example – Comprehension tools (Obs. 1.2 – Obs. 2.4 – Obs. 3.3), Discussion and negotiation (Obs. 2.1 – Obs. 3.2 – Obs. 3.4)

S9: *"Through the discussion I better understood how the forces within the droplet balance each other and that gravity is not always the most important one. It depends a lot on how strong the interactions between liquid particles are, and thanks to the simulations it was possible to modify these interactions and see the results directly."*

This excerpt reveals an aware use of simulations as tools for visualising and understanding the relationships among the forces at play. The dialogue with peers, which enables the student to revise prior conceptions and grasp the complexity of the phenomena, arises from a shared process of reinterpretation.

Simulation-based activity interview No. 3

For this activity, the degree of agreement among researchers prior to further collegial discussion was 89.8%.

A significant increase was observed in Obs. 2.4 (10.6%) and Obs. 2.2 (12.4%), evidencing a stronger tendency among students to recognise their cognitive styles and to structure more coherent and articulated reasoning during the interview. Obs. 3.2 (19.1%) and Obs. 3.3 (19.8%) remain at medium-to-high levels, confirming the continuity of reflective and metacognitive dimensions that were already central in previous simulations. Overall, the data suggest a strengthening of the cognitive dimension, accompanied by growing individual awareness in the way students' approach and explicate phenomena.
The following histogram displays the percentage distribution of the observed indicators.

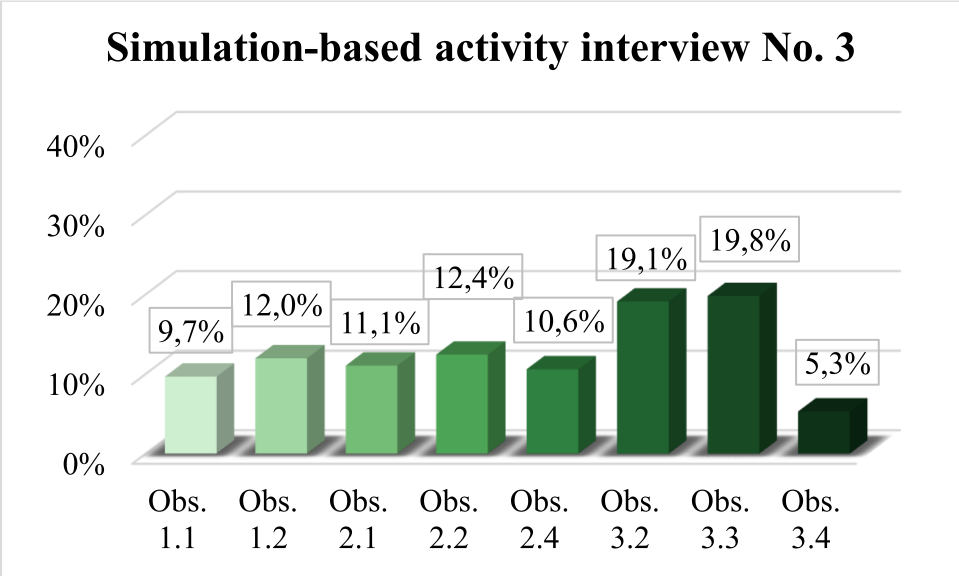

Figure 6.27: Percentage distribution of observables emerging from interviews related to the third mesoscopic-simulative experiment.

Representative excerpts are presented below.

Example – Interpretive models (Obs. 1.1 – Obs. 2.2 – Obs. 3.3)

S25: *"The conclusions reached by the large group are only partly compatible with my initial observations. I admit I had interpreted the meniscus shape differently; I thought that in mercury adhesion was stronger than cohesion, while in water it was the opposite. Later I discovered that it is exactly the other way round."*

The Interpretive models code refers to the student's ability to elaborate a personal explicative model, regardless of its correctness, by using scientific concepts to interpret the observed differences.

Example – Comprehension tools (Obs. 1.2 – Obs. 2.4 – Obs. 3.3)

S20: *"Thanks to the two simulations, I better understood the direction of the force vectors. I did not expect that the combination of pressure and intermolecular forces would so clearly determine the behaviour of water and mercury."*

The student's attribution of a mediating role to the simulation in making abstract concepts visible is evident.

Simulation-based activity interview No. 4

For this activity, the degree of agreement among researchers prior to further collegial discussion was 91.7%.

Obs. 3.3 (21.9%) reaches the highest value recorded so far, confirming the strong presence of metacognitive reflection in students' discourse. However, the increase in Obs. 1.1 (15.2%) and Obs. 1.2 (16.1%) is particularly significant, indicating a deeper understanding of scientific representations and a conceptual change that leads students to modify not only their lexical choices but also the underlying reasoning, marking a transition towards a more conscious reconstruction of disciplinary content. In sharp contrast, the decrease in Obs. 3.4 (2.4%) reveals a reduction in emotional and well-being dimensions.
The following histogram displays the percentage distribution of the observed indicators.

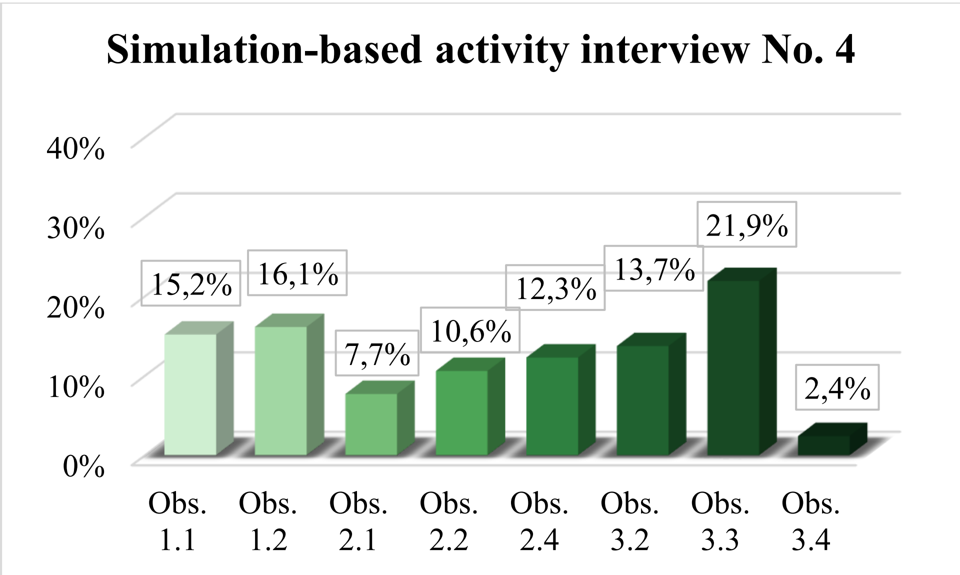

Figure 6.28: Percentage distribution of observables emerging from interviews related to the fourth mesoscopic-simulative experiment.

Representative excerpts are presented below.

Example – Critical awareness (Obs. 1.1 – Obs. 2.2 – Obs. 3.3), Scientific language (Obs. 1.2 – Obs. 1.2)

S6: *"Together with others, we slightly revised our final conclusions: in the first case, pressure forces prevent the molecules from penetrating one another, while the interparticle force is attractive at long distances and repulsive at short ones. Therefore, pressure maintains the distance between molecules but is not* *sufficient to describe a real system. In the second case, surface tension still holds the liquid together, and the object remains on top without sinking. In the third case, however, the ball breaks the surface film and sinks, creating a temporary void in the liquid. The parameters governing adhesion and cohesion effectively explain these differences."*

The precise use of physical terminology (pressure forces, interparticle forces, cohesion, adhesion) clearly identifies the Scientific language code. Moreover, the articulation of the discourse demonstrates a reflective analysis of the different cases, testifying to a high level of critical interpretation.

Example – Shared construction (Obs. 1.2 – Obs. 2.1 – Obs. 3.2 – Obs. 3.3), Well-being (Obs. 2.1 – Obs. 3.4)

S31: *"What I liked about the discussion was that everyone could express their views, and together we figured out what was happening. Now it is clear to me how solid–liquid forces change in the various cases and why different values produce different effects."*

The Shared construction code emerges through the collective dimension of discourse ("everyone could express their views"), which reflects socially constructed learning. Furthermore, a positive emotional tone and a sense of satisfaction are also evident.

Simulation-based activity interview No. 5

For this activity, the degree of agreement among researchers prior to further collegial discussion was 90.5%.

The trend appears substantially stable compared to the previous simulation, with Obs. 3.2 (16.3%) and Obs. 3.3 (19.3%) still prevailing, confirming the centrality of improvement-oriented and metacognitive dimensions in students' discourse. However, Obs. 2.2 (15.1%) shows a significant increase, signalling a strengthened ability to construct and maintain coherent lines of reasoning, an indicator of greater logical structuring in explanations. Conversely, Obs. 2.1 (7.1%) records the lowest value among all simulation interviews, showing a decrease in references to collaborative and interpersonal dynamics.
The following histogram displays the percentage distribution of the observed indicators.

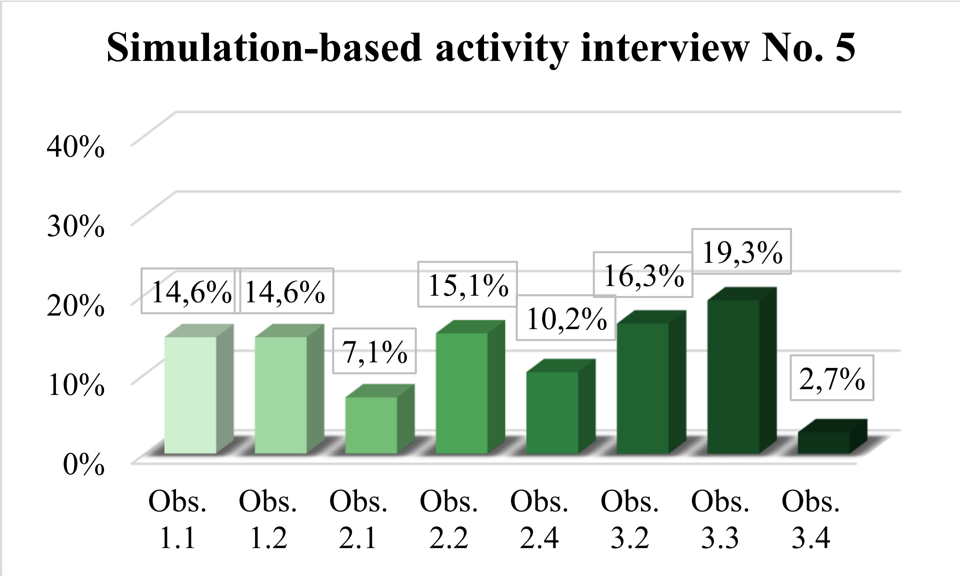

Figure 6.29: Percentage distribution of observables emerging from interviews related to the fifth mesoscopic-simulative experiment.

Representative excerpts are presented below.

Example – Plurality of languages (Obs. 2.4 – Obs. 3.3), Critical awareness (Obs. 1.1 – Obs. 2.2 – Obs. 3.3)

S22: *"I had never thought that the surface material could so significantly change the droplet's behaviour. To understand it better, I also tried an experiment with some objects wetted by water: they helped me realise how the angle and thus wettability vary."*

The student integrates experimental language and direct empirical observation to visualise the phenomenon, demonstrating the use of diverse strategies to grasp a concept. There is also a conscious reflection on the materials influencing wettability.

Example – Shared construction (Obs. 1.2 – Obs. 2.1 – Obs. 3.2 – Obs. 3.3), Discussion and negotiation (Obs. 2.1 – Obs. 3.2 – Obs. 3.4), Well-being (Obs. 2.1 – Obs. 3.4)

S7: *"Talking with my classmates reinforced my initial idea, but it also made me add details I had not considered, like the importance of gravity in the behaviour of the liquid on the surface. Now I understand better the usefulness of dialogue among us. I think I had underestimated it until now."*

This excerpt clearly illustrates the co-construction of knowledge: through dialogue, the student integrates different perspectives into their initial idea. Finally, a sense of both cognitive and relational satisfaction emerges from the collaborative learning experience.

6.2.2.3 Synthesis of results

Cumulative qualitative interviews results

The overall analysis of the interviews conducted at the conclusion of the qualitative activities reveals a distribution of observed indicators that confirms the importance of relational and reflective dimensions in the students' experiences. The highest percentages are recorded for Obs. 2.1 (20.6%), Obs. 3.3 (18.4%), and Obs. 3.2 (15.9%), highlighting that, in oral accounts, students placed particular emphasis on the value of interactions and peer discussion, metacognitive reflection, and awareness of personal improvement.
Obs. 3.4 (13.4%) also shows a significant incidence, indicating that many students expressed a clear sense of well-being and positive engagement associated with the activities. In contrast, Obs. 1.2 (11.7%) and Obs. 1.1 (8.9%) are less frequent, suggesting that conceptual elaboration and the use of scientific representations were referenced to a lesser extent than relational and affective dimensions. The lowest percentages are observed for Obs. 2.2 (7.8%) and Obs. 2.4 (3.3%), which refer, respectively, to the development of structured lines of reasoning and the recognition of personal cognitive styles, elements that students are less inclined to make explicit within the interview context.
Overall, the percentage distribution demonstrates that, in the interviews following the qualitative activities, students prioritised a discursive dimension that was relational, reflective, and affective, presenting an account of the experience centred on interaction, personal awareness, and emotional participation rather than on the formalisation of conceptual content.

The following histogram displays the percentage distribution of the observed indicators.

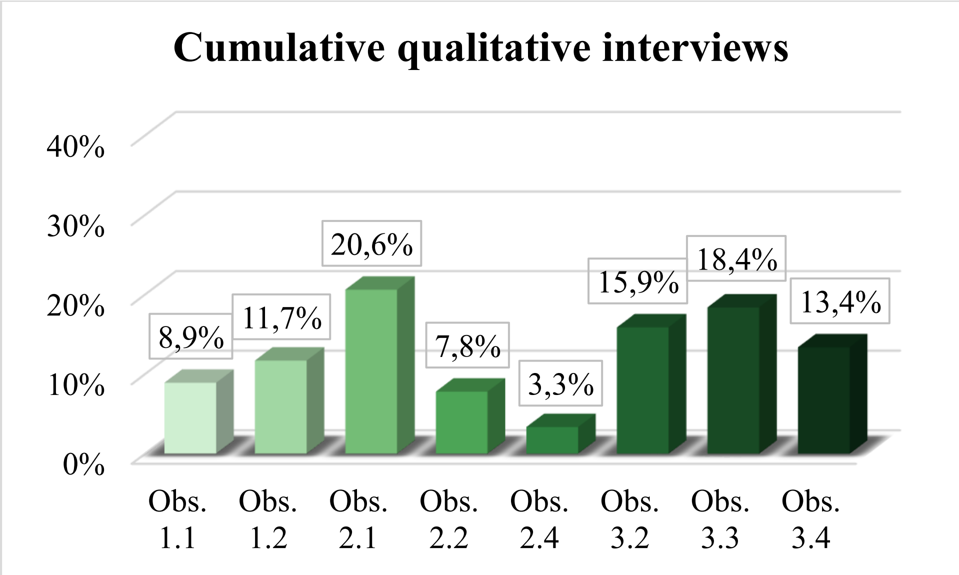

Figure 6.30: Percentage distribution of observables emerging from interviews concerning macroscopic activities.

Cumulative simulation interviews results

The overall analysis of interviews conducted following the simulated activities reveals a distribution of observed indicators reflecting a balance between cognitive and reflective dimensions, with a lower incidence of emotional aspects. The highest percentages are observed for Obs. 3.3 (18.2%) and Obs. 3.2 (17.1%), followed by Obs. 1.2 (13.9%) and Obs. 1.1 (13.1%). These data suggest that students attributed a central role to metacognitive reflection, awareness of their own improvement, and conceptual elaboration of the phenomena observed, often expressed using scientific representations and language.

Obs. 2.2 (11.8%) and Obs. 2.1 (11.3%) maintain intermediate values, indicating that the construction of coherent lines of reasoning and collaborative interactions remained present in the discourse, although they were not among the most recurrent themes. Obs. 2.4 (8.6%) suggests that students showed increased attention to their cognitive styles and personal learning strategies. Meanwhile, Obs. 3.4 (6.0%) reflects a lack of references to well-being and emotional engagement.

The distribution indicates that, in the interviews following the SPH simulations, students demonstrated greater awareness of cognitive processes and disciplinary content, with discourse more oriented towards metacognitive reflection and scientific understanding, whereas emotional and relational aspects were less emphasised.

The following histogram displays the percentage distribution of the observed indicators.

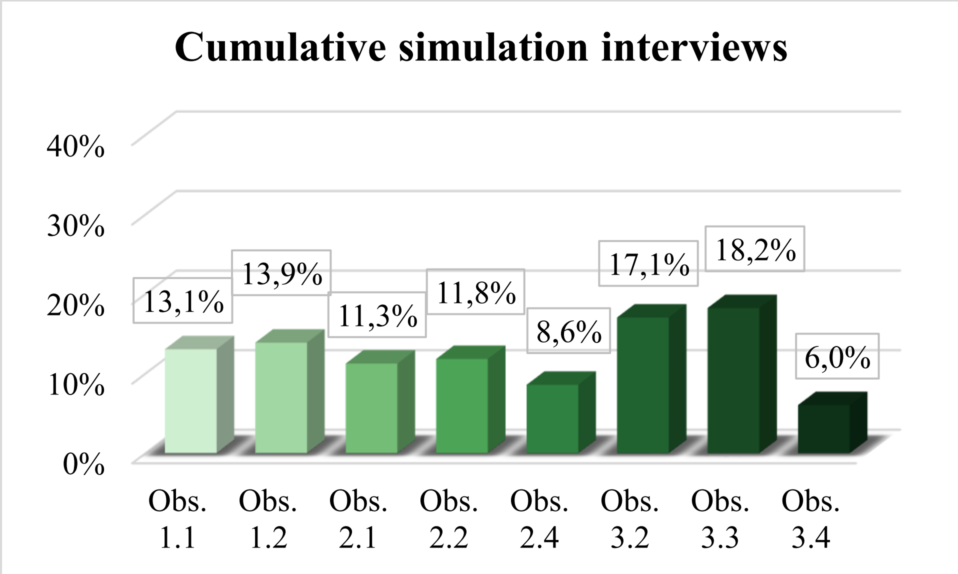

Figure 6.31: Percentage distribution of observables emerging from interviews concerning mesoscopic activities.

Comparing results between macro and meso interviews

A comparison between the interviews conducted after the qualitative activities and those following the SPH simulations reveals a clear shift in the distribution of observed indicators. In the post-qualitative interviews, relational and affective dimensions predominated, with higher percentages for Obs. 2.1 (20.6%) and Obs. 3.4 (13.4%). In contrast, these values decrease to 11.3% and 6.0%, respectively, in the post-simulation interviews, indicating that references to social interaction and perceived well-being were less frequent in the latter.
Conversely, the post-simulation interviews display slightly higher values for categories related to conceptual and metacognitive dimensions. Obs. 3.2 (17.1%) slightly surpasses the corresponding value from the qualitative activities (15.9%), confirming greater awareness of personal improvement. Similarly, Obs. 1.1 (13.1%) and Obs. 1.2 (13.9%) are higher than in the previous interviews (8.9% and 11.7%), indicating increased references to conceptual appropriation and the use of scientific representations.

Obs. 2.2 and Obs. 2.4 show a similar trend, both increasing in the post-simulation interviews (from 7.8% to 11.8% and from 3.3% to 8.6%), indicating a greater presence of references to the construction of lines of reasoning and awareness of personal cognitive styles. Metacognitive dimensions remain

consistently high across both phases, with Obs. 3.3 showing only a slight decrease (from 18.4% for qualitative activities to 18.2% for simulations).
This comparison therefore highlights a shift from discourse focused on relationships, well-being, and shared reflection to discourse more oriented towards conceptual elaboration and individual cognitive awareness, while maintaining continuity in the reflective dimensions previously identified.

The following comparative histogram presents the interviews conducted after macroscopic and mesoscopic activities.

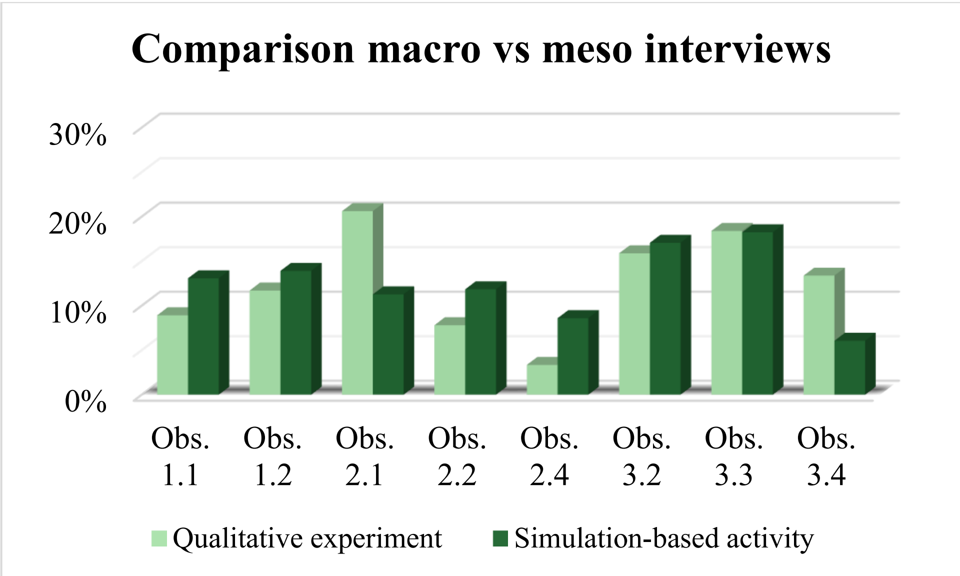

Figure 6.32: Comparison of percentage distributions of observables emerging from interviews during macroscopic and mesoscopic activities.

6.2.3 Researchers' logbook results

The logbooks documented observations collected during the conduct of activities, providing a reflective insight into the cognitive, relational, and communicative processes engaged by the students.
The thematic analysis was carried out following the same coding and triangulation procedures applied to the operational sheets and clinical interviews (Appendices F–H), ultimately employing the seven definitive codes described in Table H.2.
Each logbook was analysed by all three researchers involved, who independently conducted further coding to ensure interpretative consistency and intersubjective validity.

For each logbook, three codings were produced, each corresponding to the work of a single researcher. Subsequently, the results of the three codings were

compared and discussed until a shared agreement was reached; this process led to the creation of an overall histogram for each logbook, representing the agreed synthesis of the three independent analyses.
Finally, the three overall histograms, one for each logbook, were integrated to produce a general histogram, providing a comprehensive overview of the emerging trends. This final graph allows an immediate visualisation of the recurrence and convergence of observations among the researchers, offering a concise representation of the evolutionary dynamics detected throughout the entire educational process.

To enhance transparency in the coding process, selected textual excerpts from the logbooks are also presented as representative examples of the identified categories. These fragments illustrate concretely the connection between the content observed and the assigned codes, facilitating an understanding of the interpretative coherence and the analytical path followed.

6.2.3.1 Research logbook A

For this data category, the level of agreement among the researchers, prior to further collegial discussion, was 92.5%.

Logbook A clearly highlights affective and reflective dimensions, with the highest percentages observed for Obs. 3.4 (28.6%) and Obs. 3.2 (21.4%), indicating a strong presence of references to student well-being and awareness of personal growth during the learning process. These are followed by Obs. 2.1 (14.3%) and Obs. 1.2 (10.7%), which signal the importance attributed to collaborative dynamics and the scientific elaboration of common-sense conceptions. Lower values are observed for Obs. 1.1 (7.1%), Obs. 2.2 (7.1%), and Obs. 3.3 (10.7%), reflecting a more limited presence of references to conceptual appropriation, the construction of structured reasoning, and metacognitive reflection, which are less easily inferred from mere observation of the students. Obs. 2.4 (0%) is entirely absent, indicating that students did not make explicit reference to their personal cognitive styles, and consequently, no such reference was recorded by Researcher A.
Overall, Logbook A presents a picture in which the emotional and individual growth dimensions predominate over logical-conceptual aspects.

The following histogram displays the percentage distribution of the observed indicators.

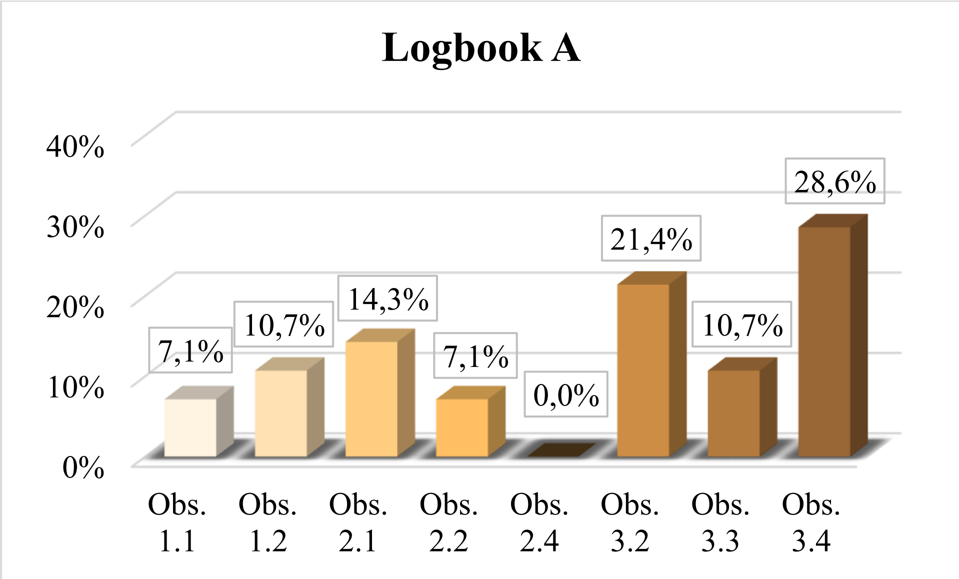

Figure 6.33: Percentage distribution of observables emerging from the analysis of Logbook A.

Representative excerpts.

Example – Active inquiry (Obs. 2.2 – Obs. 3.2), Engagement (Obs. 3.2 – Obs. 3.4)

"During the simulation activity, students demonstrated strong engagement with the software, which, although novel to them, proved to be accessible and stimulating. In particular, the opportunity to modify parameters directly in the Fortran source code elicited curiosity and active participation. This direct manipulation allowed them to explore the relationship between physical variables and system behaviour, fostering an experiential understanding of the numerical modelling process."

This excerpt illustrates active inquiry, where students did not merely observe the simulations but directly manipulated variables to test hypotheses and observe the effects of parameter changes. The engagement dimension emerges from the evident interest and enthusiasm of the students in interacting with the simulation environment, demonstrating intrinsic motivation and sustained attention throughout the task.

Example – Analytical reflection (Obs. 3.3), Collaborative cohesion (Obs. 2.1 – Obs. 3.4), Engagement (Obs. 3.2 – Obs. 3.4), Scientific language competence (Obs. 1.1 – Obs. 1.2)

"The adoption of a methodology inspired by scientific practice had a significant impact. The discussion phase, in which each group reported their observations, was perceived as particularly stimulating. This allowed students to refine their argumentative skills, improving their exposition over time and developing a more critical and reflective attitude. Peer comparison proved essential for consolidating knowledge, and the need to make reasoning explicit facilitated the progressive refinement of scientific language."

The excerpt reflects analytical reflection, with students engaging in metacognitive processes while discussing and revising their reasoning based on peer contributions. Collaborative cohesion is evident in the cooperative atmosphere and mutual support, which enhanced both understanding and communication. Engagement is manifested through active participation and a sense of belonging to a learning community. Finally, scientific language competence is shown in the students' progressive ability to articulate ideas clearly and precisely, aligning their discourse with scientific reasoning conventions.

6.2.3.2 Research logbook B

For this data category, the level of agreement among the researchers, prior to further collegial discussion, was 96.3%.

Logbook B shows a marked predominance of affective and motivational dimensions, with particularly high values for Obs. 3.4 (34.6%) and Obs. 3.2 (23.1%), highlighting the centrality of perceived well-being and awareness of personal growth in the researcher's reflections. These are followed by Obs. 2.1 (19.2%), and at a distance, Obs. 2.2 (7.7%) and Obs. 3.3 (7.7%), indicating a more limited presence of references to collaborative dynamics, structured reasoning development, and metacognitive reflection. Obs. 1.1 (3.8%) and Obs. 1.2 (3.8%) show minimal values, reflecting scarce explicit references to the appropriation of scientific concepts and the elaboration of common-sense notions. Obs. 2.4 (0%) is again absent, confirming that references to individual cognitive styles did not emerge.
Thus, Logbook B provides a picture strongly oriented towards the emotional and relational dimensions, with positive engagement.

The following histogram displays the percentage distribution of the observed indicators.

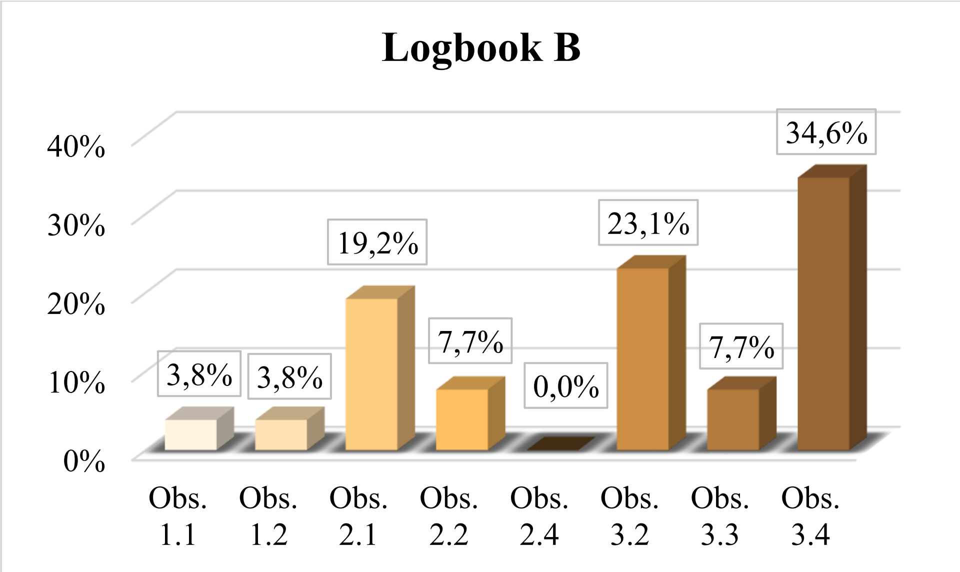

Figure 6.34: Percentage distribution of observables emerging from the analysis of Logbook B.

Representative excerpts.

Example – Managing change (Obs. 2.1 – Obs. 3.4)

"The activity conducted at the macroscopic scale uses modes of representation familiar to students. Unlike the simulated activities, which require a more abstract language and greater proficiency with digital tools, the macroscopic experiences offered an accessible and reassuring entry point. The subsequent transition to simulations initially generated some difficulties and resistance, related to the change in exploration modalities and the need to shift attention from an observational to a modelling perspective."

This excerpt illustrates the management of change, focusing on students' adaptation during the transition from concrete and familiar representations to more abstract, simulation-based learning environments. The initial sense of resistance and cognitive disorientation highlights the challenge of moving from perceptual thinking to modelling-oriented thinking. At the same time, the passage emphasises how structured support through macro-level activities facilitated this transition, allowing students to gradually internalise new epistemic tools and cognitive strategies.

Example – Analytical reflection (Obs. 3.3)

"During collective discussions, a notable capacity for critical reflection emerged among some students, who were able to analyse consciously the

difficulties encountered in group activities. Some recognised that small group work sometimes limited content comprehension, whereas plenary discussions, conducted in a calmer environment guided by the researchers, facilitated a clearer and more conscious elaboration of the concepts addressed."

This excerpt exemplifies analytical reflection, as students not only evaluate their learning outcomes but also identify situational factors influencing them. Their ability to articulate challenges and compare them with more effective learning contexts demonstrates a mature level of metacognitive awareness.

6.2.3.3 Research logbook C

For this data category, the level of agreement among the researchers, prior to further collegial discussion, was 90.8%.

Logbook C confirms the predominance of affective and reflective dimensions, with the highest values recorded for Obs. 3.4 (27.8%) and Obs. 3.2 (22.2%), indicating frequent references to perceived well-being and personal growth as central elements of the observations. These are followed by Obs. 1.2 (13.9%) and Obs. 2.1 (13.9%), reflecting a balanced presence of aspects related to the elaboration of conceptions towards scientific thinking and the role of social interactions in the learning process. Obs. 1.1 (8.3%) and Obs. 2.2 (8.3%) show lower values, suggesting a lesser incidence of references to conceptual appropriation and the development of structured reasoning, while Obs. 3.3 (5.6%) is marginal, with few explicit references to metacognitive reflection. Obs. 2.4 (0%) does not appear, indicating the absence of references to students employed or preferred cognitive styles.
Logbook C thus presents a picture dominated by emotional engagement and growth awareness, albeit with a limited presence of conceptual and collaborative dimensions.

The following histogram displays the percentage distribution of the observed indicators.

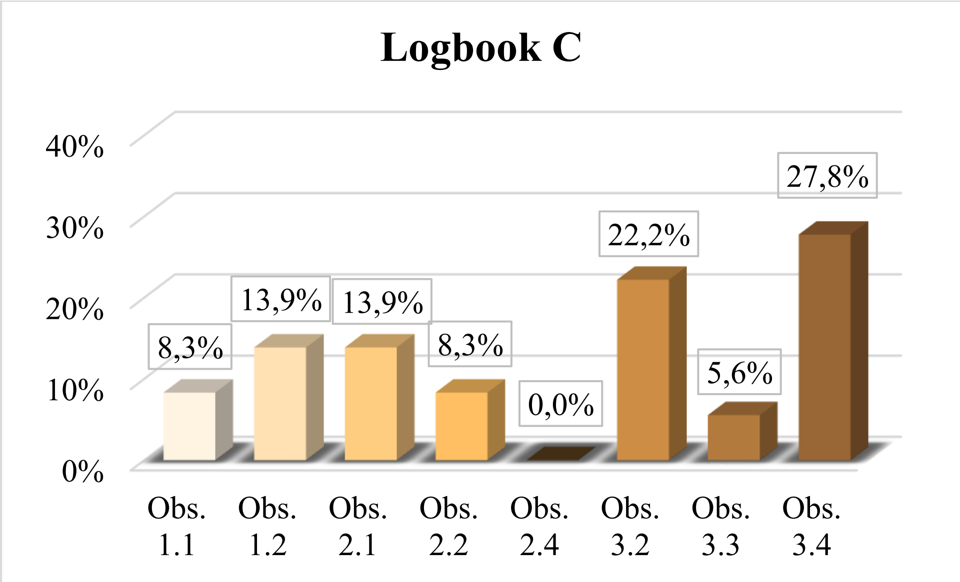

Figure 6.35: Percentage distribution of observables emerging from the analysis of Logbook C.

Representative excerpts.

Example – Evolution of knowledge (Obs. 1.2)

"A significant aspect emerging from observation concerns the progressive transition of students from knowledge based on common-sense conceptions to a more structured and scientifically coherent understanding. During collective discussions and later clinical interviews, it was observed that the introduction of new working modalities and the use of an innovative laboratory environment initially facilitated the overlap of intuitive and formalised knowledge. This tendency progressively shifted towards formalised understanding by the conclusion of the TLS."

This excerpt exemplifies knowledge evolution, capturing the dynamic transformation of students' conceptual frameworks over time. Rather than describing conceptual change as a replacement, the passage highlights a process of integration and reinterpretation, in which intuitive understandings gradually align with scientific reasoning. The researcher recognises that students' knowledge growth is mediated by engagement in authentic scientific practices and the recontextualization of everyday ideas within a more formal epistemic framework.

Example – Active inquiry (Obs. 2.2 – Obs. 3.2), Engagement (Obs. 3.2 – Obs. 3.4)

"Throughout the various qualitative activities, students demonstrated increasing engagement and greater autonomy in exploration. Gradually, they became familiar with the tools and experimental procedures, developing curiosity regarding the possibilities offered by a non-conventional classroom setting. The use of simple and readily available materials was particularly appreciated, making the macroscopic experience more accessible and closer to the school context, thereby fostering a sense of active participation and confidence in their experimental abilities."

This excerpt reflects both active inquiry and engagement, describing how students progressively took ownership of their learning through experimentation and practical exploration. The emphasis on accessible materials and a non-traditional classroom environment highlights how contextual and material factors supported intrinsic motivation. The observed curiosity and growing autonomy demonstrate the shift from guided participation to self-directed inquiry, revealing how engagement can act as a catalyst for deeper scientific understanding.

6.2.3.4 Summary of results

The analysis of the overall histogram, obtained by integrating the three researcher logbooks, presents a comprehensive picture dominated by affective and personal growth dimensions. The highest percentages are recorded for Obs. 3.4 (30%) and Obs. 3.2 (22.2%), indicating frequent references to well-being and awareness of individual development as central aspects in the observations shared by the researchers. These are followed by Obs. 2.1 (15.6%) and Obs. 1.2 (10%), which reflect the importance of social interactions and the elaboration of conceptions towards scientific thinking. Lower values are observed for Obs. 1.1 (6.7%), Obs. 2.2 (7.8%), and Obs. 3.3 (7.8%), while Obs. 2.4 (0%) is absent.

It is important to note, however, that dimensions more directly related to students' cognitive and personal spheres, such as the appropriation of concepts and forms of representation (Obs. 1.1), the development of lines of reasoning (Obs. 2.2), or metacognitive reflection (Obs. 3.3), tend to emerge less frequently in the logbooks, as they are more difficult to detect through external observation. These internal processes, linked to the construction and awareness of thought, are not always immediately visible in behaviour or interactions and may therefore be only partially represented in the researchers' notes.
Overall, the final chart provides a unified view in which emotional engagement, active participation, and personal growth constitute the most recognisable and shared dimensions throughout the TLS.

The following histogram summarises the percentage distributions from the logbooks authored by the three researchers.

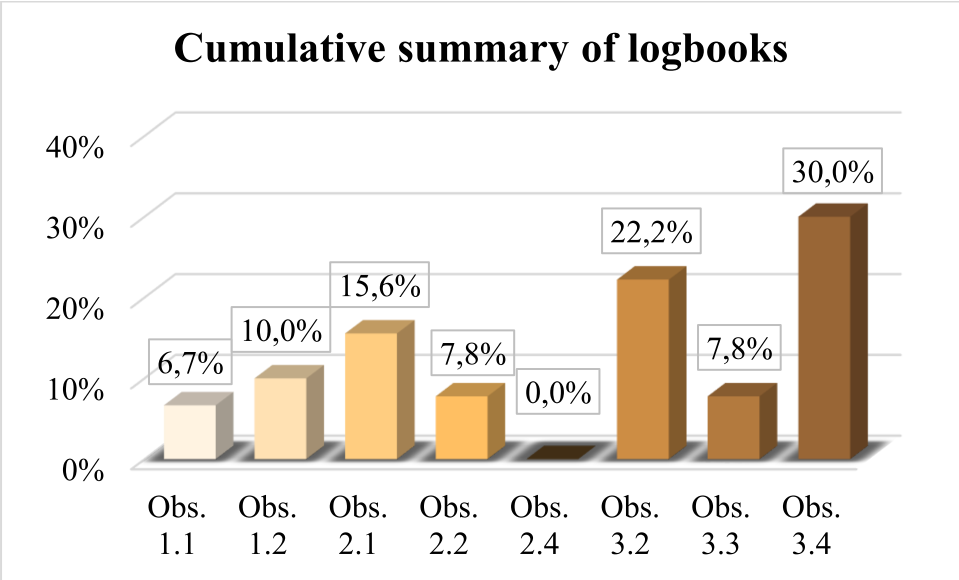

Figure 6.36: Overall percentage distribution of observables emerging from the combined analysis of the three logbooks.

6.2.4 Student feedback results (satisfaction questionnaire Q.3)

The analysis of feedback from Questionnaire Q.3 was conducted similarly to that of other collected data, applying the thematic codes reported in Table H.3. These codes were then linked to the corresponding observable indicators (Appendix I, Table I.3), allowing the frequency with which each dimension appeared in the responses to be quantified via histograms.

As the student feedback constitutes a single data set, only the combined histogram resulting from the post-discussion analysis among the researchers is presented, accompanied by illustrative examples of responses that highlight the identified codes. The quotations are not linked to individual students, as the questionnaire was administered anonymously. This methodological choice ensured participant privacy while promoting greater spontaneity and authenticity in the comments, guaranteeing that the opinions expressed freely reflected students' perceptions and experiences.

The graphical trends thus provide a synthetic representation of how students perceived their own learning, the classroom climate, and the role of the innovative methodologies introduced.

For this data category, the level of agreement among the researchers, prior to further collegial discussion, was 80.1%.

The analysis of Questionnaire Q.3, administered at the conclusion of the TLS, shows a distribution strongly concentrated on affective and reflective dimensions, as evidenced by the highest values for Obs. 3.4 (32%), Obs. 3.3 (28.7%), and Obs. 3.2 (23.3%). These percentages indicate that students, in their feedback, placed greater emphasis on perceived well-being, metacognitive reflection, and awareness of their personal growth during the educational experience. These dimensions relate to the subjective perception of learning, highlighting active engagement and recognition of the formative value of the pathway undertaken.

The observable indicators Obs. 2.2 (6.7%), Obs. 2.1 (5.3%), and Obs. 2.4 (4%) show considerably lower values, signalling that references to structured reasoning development, interpersonal dynamics, and recognition of personal cognitive styles were less frequent in the comments. Obs. 1.1 and Obs. 1.2, concerning the appropriation of scientific concepts and the transformation of common-sense conceptions, are completely absent.

The combined histogram therefore presents a picture in which students tend to describe the experience in terms of personal engagement, self-awareness, and well-being, while cognitive and disciplinary aspects are less explicitly represented in the responses.

The following histogram visualises the percentage distribution of the observed indicators.

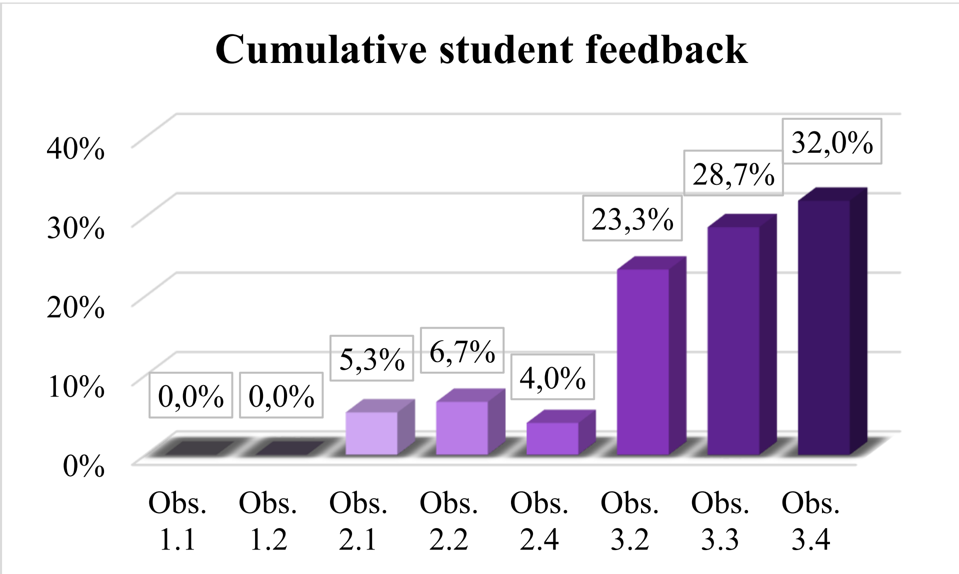

Figure 6.37: Overall percentage distribution of observables emerging from students' written feedback in Questionnaire Q.3.

Representative excerpts.

Example – Broadening perspectives (Obs. 3.2), Cognitive-emotional balance (Obs. 3.3 – Obs. 3.4), Collaborative dynamics (Obs. 2.1 – Obs. 3.4), Expert support (Obs. 2.2 – Obs. 3.4)

"I really enjoyed the course, especially the way we worked in groups: it was stimulating to discuss and find answers together. At first, the topics seemed complicated, but thanks to the researchers' clarifications, I was able to understand them better. However, the lessons were a bit long, and since I had to take the train each time, they eventually became tiring."

The student's reflection highlights peer collaboration as a driver of engagement and shared understanding. The reference to clarifications provided by the researchers emphasises the importance of expert/facilitator support in conceptual understanding and in managing the complexity of the topics explored. The student's willingness to engage with challenging content indicates broader perspectives, demonstrating openness to learning beyond initial difficulties. Finally, the mention of fatigue reveals the cognitive effort required, interpreted as an indicator of the cognitive load associated with extended sessions.

Example – Collaborative dynamics (Obs. 2.1 – Obs. 3.4), Awareness and motivation (Obs. 3.2 – Obs. 3.3), Broadening perspectives (Obs. 3.2)

"The environment was very positive and helped us collaborate better in group work. I think this course made us understand the importance of learning to connect and cooperate in experiments."

The student explicitly recognises the value of peer collaboration within a favourable learning climate, reflecting the emergence of positive social dynamics that facilitated knowledge construction. The awareness of 'learning to connect and cooperate in experiments' suggests progress in metacognitive awareness and a broadening of perspectives regarding scientific learning as a collective process.

Example – Interactive learning (Obs. 2.4 – Obs. 3.4), Expert support (Obs. 2.2 – Obs. 3.4), Awareness and motivation (Obs. 3.2 – Obs. 3.3)

"The topics were interesting, and the methodologies used were more engaging than regular lessons. The researchers' interventions were very helpful in understanding some concepts better. I think this course helped me learn new things about the topics covered."

Appreciation for a more engaging and participatory teaching style highlights the importance of interactive resources in enhancing students' conceptual engagement. The explicit mention of the researchers' contribution reflects the role of expert support as a mediating element in the learning process. The student's recognition of having learned 'new things' indicates broadened perspectives, signalling cognitive expansion and personal growth within the subject area.

Example – Interactive learning (Obs. 2.4 – Obs. 3.4), Broadening perspectives (Obs. 3.2), Awareness and motivation (Obs. 3.2 – Obs. 3.3), Cognitive-emotional balance (Obs. 3.3 – Obs. 3.4)

"I found the topics new and explained in depth. I particularly enjoyed the last lessons, when we used computer programmes to create images showing the forces at play: I did not think it was possible to see them in this way! Perhaps we could not participate fully because the sessions were always in the afternoon after school, which made them a bit tiring. However, I think it was a useful and interesting experience."

The student's enthusiasm for the simulated activities reflects the impact of interactive resources in promoting conceptual visualisation and broadening perspectives, allowing for a new representation of physical phenomena. The expression of surprise, 'I did not think it was possible to see them in this way', marks a moment of conceptual change. Awareness of limited participation and consequent fatigue highlights cognitive-emotional balance, as the student recognises the interaction between engagement, cognitive effort, and emotional energy.

6.3 Quantitative analysis of the satisfaction questionnaire (Q.3)

The analysis of the weighted mean data from the satisfaction questionnaire (Q.3) presents an overall positive picture, consistent with the objectives of the implemented TLS.
In Section 1, concerning expectations and prior knowledge, a marked difference is observed between the two items: the first (3.81) indicates a good level of agreement, showing that students perceived the activities as clear and consistent with their expectations; the second (2.66), however, reflects a lower initial familiarity with the topics addressed.
Section 2, focusing on organisation, displays generally high mean values. The highest score (4.09) reflects a very positive perception of the structure and

management of the learning pathway, while slightly lower scores for the other two items (3.16 and 3.38) indicate that, although the evaluation remained positive, some organisational and/or timing aspects required adaptation on the part of the students.

In Section 3, relating to self-assessment and impact on curricular learning, generally favourable values emerge, particularly in subsection 3.1.2 (4.06), suggesting a clear perception of skill consolidation. Although some items, such as question 3.2 (2.91), show lower values, this result can be attributed to the fact that several students displayed uncertainty in directly linking the experimental experience to traditional curricular learning.

Section 4, concerning the evaluation of teaching strategies, exhibits the greatest variability, with well-distinguished minimum and maximum scores. The highest values (ranging from 4.03 to 4.22), related to aspects such as methodology, the effectiveness of adopted strategies, and active engagement, indicate strong approval of the applied teaching methods. Items with lower scores (around 3 or slightly below) point to moments perceived as more challenging or complex, yet without compromising the overall assessment.

Section 5, focusing on relational aspects, highlights a good level of satisfaction. The means range between 3.19 and 3.91, showing that students appreciated collaboration, dialogue, and classroom climate, elements that contributed to making the experience more participatory and meaningful.

Finally, in Section 6, which gathers general evaluations of the experience, one of the most evident gaps is recorded: question 6.1 (2.91) reflects a more cautious perception, perhaps related to workload or the difficulty of certain activities, while question 6.2 (4.31) indicates a clearly positive judgement of the overall pathway, signalling strong overall satisfaction.

Overall, the data indicate that students perceived the TLS as a well-structured, stimulating, and coherent educational experience, effectively integrating cognitive, operational, and relational dimensions.

The following line chart illustrates the distribution of weighted means associated with students' responses across the different sections of questionnaire Q.3.

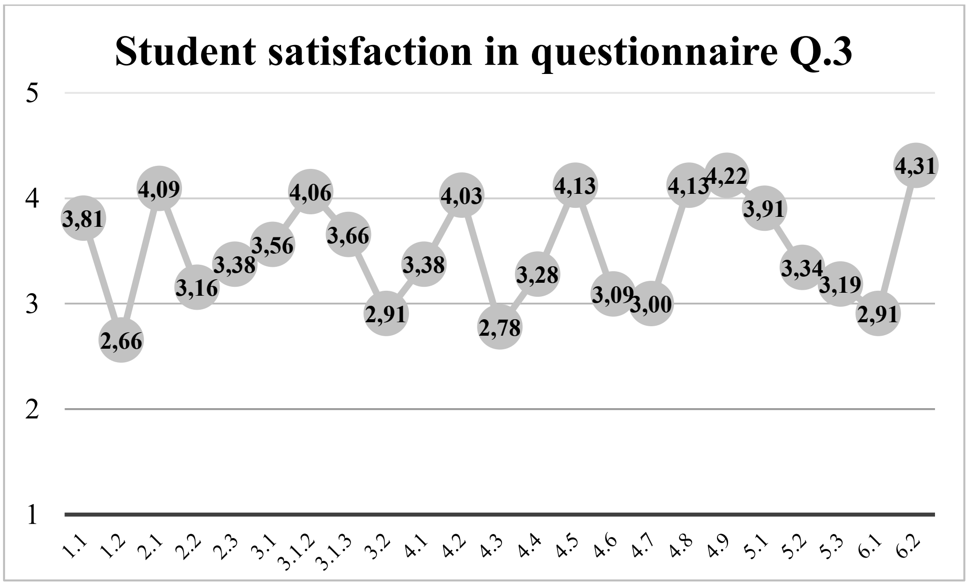

Figure 6.38: Overall distribution of students' responses on a Likert scale (1 = "Not at all" to 5 = "Extremely") for the six sections of Questionnaire Q.3.

Chapter 7

Discussion of Results

Scientific learning cannot be measured solely in terms of the concepts acquired, but rather in the depth with which students are able to interweave knowledge, emotion, and reflection. It is within this interconnection that the authentic meaning of "doing science" takes shape: an experience engaging both mind and body, yet also encompassing personal experience, curiosity, and self-awareness.

From this perspective, the present chapter explores the more personal and complex dimensions of the formative experience proposed by the TLS, analysing not only what students learned, but also how they learned and what they felt in the process.

In the first part of the TLS, activities based on a macroscopic approach to surface phenomena provided fertile ground for cultivating curiosity and collaboration. By building, observing, and discussing together, students were able to experience science as a tangible, shared activity, one made up of gestures, hypotheses, mistakes, and discoveries. In this laboratory space, learning followed the rhythm of action: knowledge arose through direct contact with phenomena, peer interaction, and the pleasure of collective engagement.

The introduction of the mesoscopic approach, based on the use of interactive SPH simulations, represented a turning point: a new space where direct observation of phenomena intertwines with digital representation, and where concrete action gives way to more abstract and self-aware reflection. This transition, from the macroscopic to the mesoscopic, from the tangible to the modelled, is not merely a change of scale, but a genuine shift in both cognitive and emotional perspective. Students no longer simply observe the physical world; they learn to think the phenomenon, to engage in dialogue with it through the model, and to question their own mental representations.

In this chapter, the focus therefore shifts to the qualitative and integrative dimension of the analysis, with the aim of understanding how the TLS has influenced the relational, affective, and metacognitive dimensions of learning. From the collaborative dynamics that gave rise to genuine research communities, to the subtler forms of individual reflection stimulated by the digital environment, the results show how the TLS fostered a profound evolution in the ways of participating in, thinking about, and experiencing science.

To convey this complexity, the analysis intertwines different sources of evidence (worksheets, interviews, researchers' logbooks, student feedback, and questionnaires) thus constructing a rich and coherent picture. What emerges is a mosaic of experiences and perceptions which, when considered as a whole, reflects the transformation of learning into an authentic process of personal and collective construction of scientific knowledge.

7.1 Verification of the research hypothesis through pre-test data (Q.1 and Q.2)

The first phase of analysis, based on questionnaires Q.1 and Q.2 administered prior to the implementation of the TLS, constituted a fundamental diagnostic moment for the verification of the research hypothesis.

Consistent with the methodological framework outlined in Chapter 4, this analysis made it possible to observe that students' prior knowledge does not appear as a coherent and unified system, but rather as a dynamic set of heterogeneous conceptual fragments that are selectively activated according to context (diSessa, 1993). This view, known as the knowledge-in-pieces perspective, suggests that intuitive ideas and early forms of scientific conceptualisation do not evolve linearly, but coexist and reorganise within flexible and often partially incompatible structures. Within this framework, the research hypothesised the presence of mixed models of knowledge (Vosniadou et al., 2008), in which empirical, descriptive, and theoretical components combine in transient ways, forming intermediate cognitive configurations between everyday experience and scientific formalisation.

The aim of this first phase was therefore not to measure a level of competence, but to recognise the epistemic structure underlying students' responses, identifying whether, how, and to what extent different modes of meaning construction coexist within the same explicative discourse.

To this end, phenomenographic coding was conducted according to three epistemic profiles, everyday, descriptive, and explicative, derived from the theoretical framework of scientific modelling (Sperandeo-Mineo et al., 2006; Greca & Moreira, 2002). Each category represents a distinct way of constructing meaning: empirical-intuitive for the everyday profile; interpretative and partially causal for the descriptive profile; and conceptually abstract for the explicative profile.

However, in line with the literature on phenomenography and conceptual change (Marton, 1981; Duit & Treagust, 2003; Taber, 2009), these categories were not treated as discrete classes, but as contiguous regions along a cognitive continuum, within which responses could be placed in a nuanced manner or exhibit local hybridisation.

Each response was attributed to the predominant category of meaning construction, that is, to the mode of reasoning that emerged as dominant in the student's discourse. Such predominance does not refer to the frequency of words or concepts, but to the epistemic structure guiding the explanation. For instance, if a student employs empirical language but attempts to introduce a microscopic

causal mechanism, the response is placed within the descriptive profile; conversely, if a theoretical reference is embedded in a purely intuitive or metaphorical context, the response remains within the everyday profile.
This interpretative criterion makes it possible to identify the direction of the meaning-making process, thereby providing a more refined and dynamic picture of students' reasoning.

The simultaneous presence of elements belonging to multiple epistemic profiles was recorded and interpreted not as a classification difficulty, but as a direct indicator of the existence of mixed models. According to Vosniadou et al. (2008), such hybrid configurations constitute a structural property of evolving knowledge: during conceptual restructuring, students do not abandon their intuitive conceptions but reinterpret them considering new theoretical principles. The coexistence of empirical and theoretical elements within a single response thus represents evidence of a cognitive transition process, in which phenomenological understanding gradually opens towards scientific modelling. This interpretative approach, consistent with the theoretical framework of the TLS, allows the responses to be read not as static outcomes, but as local manifestations of a conceptual construction process that the educational intervention seeks to support and consolidate.

The empirical evidence emerging from the analysis of pre-tests Q.1 and Q.2 confirms the widespread presence of mixed models of knowledge, in which intuitive, descriptive, and theoretical elements coexist within the same response, reflecting the inherent complexity of conceptual construction processes.
In Q.1, although responses classified as everyday were predominant (44.1%), a substantial number of them revealed traces of implicit causality or attempts at generalisation, indicating that students did not merely describe observable phenomena but began to formulate connections that anticipate explanation. This finding is consistent with diSessa's (1993) perspective, according to which intuitive knowledge consists of local fragments (p-prims) that, while not yet organised into a coherent theoretical structure, represent an initial basis for the development of more sophisticated models. The emergence of such hybridisations suggests that even within an apparently empirical profile, there exists a latent tension towards conceptualisation, what Vosniadou (1994) defines as an intermediate phase of reconciliation between pre-existing mental models and scientific knowledge.
In pre-test Q.2, the decrease in descriptive responses and the increase in non-responses should not be interpreted as cognitive regression, but rather as an indicator of the difficulty involved in reorganising conceptual fragments in the absence of a consolidated explicative model. This dynamic is widely documented in the literature on conceptual change (Strike & Posner, 1992; Posner et al., 1982), according to which the transition from an empirical to a theoretical explanation entails a temporary cognitive instability necessary for the restructuring of mental models.

Analysis of the responses reinforces this interpretation: although many students began from perceptual observations, several introduced implicit references to force or interactions between particles, signalling the presence of an evolving understanding. These constitute direct evidence of the transition from a phenomenic to a more descriptive and explicative model, in which everyday language begins to hybridise with the terminology and logic of physics. Below are some examples of responses representative of mixed models:

- Q.1, Item 1: *"When I put the biscuit into the milk, the liquid seems to rise a bit inside the biscuit, because the biscuit absorbs the water, but perhaps there is also something that pulls it upwards."*

This response was assigned to the everyday category, as its predominant component is an experience-based description. However, the attempt at an informal explanation through the notion of attraction, characteristic of the descriptive category, should not be overlooked. The mixed nature of the model is evident in the reference to "something that pulls it upwards," representing an embryonic attempt to introduce causality or physical interpretation.

- Q.1, Item 3: *"The sponge gets wet immediately and the water seems to rise into its holes, trying to fill all the empty spaces."*

The response was placed in the descriptive category, as it combines phenomenic description with an attempt at causal reasoning, namely, the idea that "the water tries to fill the empty spaces." This, however, is not yet formalised in terms of forces or molecular interactions. The model was interpreted as mixed because it merges a perceptual component typical of the everyday profile (direct observation of the phenomenon) with an implicit intuition of a physical principle, signalling an initial transition towards a more explicative mode of thought.

- Q.1, Item 7: *"Water slides off the jacket because the material is smooth and does not let it in, whereas on cotton trousers it stays and soaks them because the fabric absorbs more. Perhaps it depends on the type of fabric or on how the surface is made."*

This response was classified as everyday, as meaning construction is mainly grounded in direct observation and descriptive language linked to everyday experience. Nonetheless, the final reference to the "type of fabric" and the "surface" reveals an initial attempt at causal generalisation that implicitly introduces the ideas of material properties and surface interactions, elements associated with the descriptive profile.

The model is thus mixed, with everyday predominance, as it combines an empirical, observational approach with an emerging intuition of a physical principle (structural and behavioural differences between materials), marking an initial step towards a more conceptual understanding of the phenomenon.

- Q.2, Item 1: *"Water sticks a bit to the glass and for this reason it bends at the edges, as if it wanted to climb up the walls of the tube."*

This response was classified as everyday, since the language remains strongly anchored to direct observation and perceptual experience ("sticks," "bends at the edges"). However, the expression "as if it wanted to climb" introduces an early attempt at intuitive causality that implicitly recalls the concept of interaction between water and glass molecules. This formulation represents a mixed model: empirical description is accompanied by a rudimentary, non-formalised mechanistic explanation, indicating the onset of descriptive-type reasoning.

- Q.2, Item 2: *"The little boat moves because the soap changes the water's tension, breaking the balance that kept it still. Thus, the water behind the boat becomes less 'strong,' and the boat is pushed forward."*

This response was classified as descriptive, as it presents a partial but coherent explanation of the phenomenon in terms of variation of a property of water and a consequent cause-effect relationship ("breaks the balance," "the boat is pushed forward"). However, the formulation also displays progress towards the explicative profile: the notions of balance and difference in "strength" implicitly introduce references to underlying physical concepts (surface tension and unbalanced forces). This response represents a descriptive-explicative mixed model, where the explanation, though not yet formalised through fully correct scientific language, demonstrates the student's ability to establish causal connections and attribute mechanical coherence to the observed phenomenon, signalling an ongoing cognitive reorganisation process.

- Q.2, Item 6: *"Cohesion forces are when water holds itself together, like in drops, while adhesion is when water sticks to something, like glass or leaves."*

The response was classified as everyday, since the language reflects common knowledge and is grounded in concrete examples from everyday life. However, the functional distinction between "water holding itself together" and "water sticking to something" reveals an initial attempt to conceptually organise the observed phenomena. This is thus a mixed model in which direct perception and experiential examples coexist with an implicit, yet emerging categorical intuition already oriented towards a descriptive explanation.

The greater frequency of everyday-descriptive mixed models, compared with descriptive-everyday or descriptive-explicative ones, can be interpreted considering the cognitive structure of prior knowledge and the processes underlying scientific meaning-making. In pre-instructional phases, students tend to develop explanations grounded in direct experience and phenomenologic description, which constitute the first level of conceptual organisation of reality (Mortimer & Scott, 2003). The everyday and descriptive categories are therefore naturally contiguous along the cognitive continuum, as the transition from one to the other does not yet require the explicit introduction of theoretical principles or formalised language, but only an initial attempt to attribute causality to observations.
From this perspective, everyday-descriptive models reflect the most spontaneous and accessible transition for students: experiential description is enriched by intuitive, often partial or analogical, explanations marking the beginning of the conceptual modelling process. By contrast, descriptive-explicative models demand a higher level of cognitive abstraction and consistent use of formalised physical concepts, which, at this early stage, remain unstable or unconsolidated.

Considering the results obtained from pre-tests Q.1 and Q.2, the initial hypothesis is thus confirmed: students' conceptions of surface phenomena take shape as hybrid systems of knowledge in which empirical, descriptive, and theoretical fragments coexist. The collected evidence shows that these elements are not randomly distributed but form internally coherent cognitive structures. Such models reflect a spontaneous attempt to coordinate everyday experience with emerging forms of causal explanation, albeit still lacking an integrated theoretical framework.

From a didactic standpoint, these results provide preliminary empirical support for the need for educational interventions aimed at the progressive restructuring of cognitive models. Students demonstrate a natural inclination to formulate partially coherent explanations but require tools, contexts, and languages that facilitate the transition towards more abstract and formalised explicative forms. The implementation phase of the TLS, centred on qualitative experimentation, simulation, and collective discussion, fits precisely within this perspective, with the aim of promoting an epistemological evolution from intuitive understanding to scientific modelling.

7.2 Interpretation of experimental activities

This section aims to provide an integrated and reflective perspective on the evolution of students' knowledge models and learning practices observed during

the TLS, in continuity with the analytical pathway outlined in the previous chapters.
After outlining in Chapter 4 the methodological framework and the epistemological foundations of the study, centred on the conception of learning as a process of constructing and reorganising knowledge models, and after presenting in Chapter 5 the tools adopted for data collection and analysis, the present chapter seeks to relate the empirical results discussed in Chapter 6 to the research questions and the hypotheses that guided the entire experimental process.
The purpose is not merely to quantify cognitive gain or to verify the acquisition of isolated concepts, but rather to understand how, and in what terms, the educational intervention fostered processes of conceptual transformation: a gradual transition from intuitive, situated, and fragmented forms of knowledge typical of common sense to explicative structures consistent with scientific thinking and physical models.

Consistent with the adopted theoretical framework, and particularly with the view of learning as a multidimensional process, cognitive transformation is analysed by considering the interaction among cognitive, metacognitive, and affective components, which jointly contribute to shaping the quality of the educational experience.
Learning is thus not understood as a mere outcome, but as an emergent process manifesting through the different expressive registers activated by students (verbal, written, gestural, and reflective), and observable through the traces they left throughout the activities.
To make such complexity empirically observable and theoretically interpretable, data analysis was articulated through two complementary methodological approaches, already discussed and described in detail in Chapter 5. Phenomenographic analysis was employed to identify and describe the various ways in which students constructed meaning around the studied phenomena, outlining a continuum of conceptual transformation ranging from common-sense explanations to fully scientific ones. In parallel, thematic analysis made it possible to reconstruct the processes through which such understanding developed, revealing how students re-elaborated their ideas, negotiated meanings, restructured representations, and reflected upon their cognitive pathways.
This dual perspective allows one to grasp both the static dimension (the different "ways of understanding" identified at a given moment) and the dynamic dimension (the transformations leading from one way of understanding to another) of scientific learning.
The two analyses, integrated into a single interpretative reading, capture the complexity of scientific learning understood as an evolving process of meaning construction rather than a linear accumulation of knowledge (Duit & Treagust, 2003).

From this perspective, the following analysis and discussion of the data aim to shed light on the transformative processes that occurred during the TLS, offering a unified and theoretically grounded interpretation of the results.
The interpretation, which will be developed in the following sections, will make it possible to address the research questions and to discuss how the interaction between the macroscopic and mesoscopic approaches enabled the evolution of hybrid knowledge models towards conceptual structures of a more scientific nature, coherent with contemporary physics and the educational purposes of the study.

7.2.1 Answer to the first research question

To what extent do the macroscopic and mesoscopic approaches foster the evolution of the mixed knowledge models initially exhibited by students towards more scientifically grounded models?

The integrated analysis of data from questionnaires Q.1 and Q.2, together with evidence drawn from worksheets and interviews for Obs. 1.1, Obs. 1.2, and Obs. 2.2, allows a detailed response to the first research question, showing how the macroscopic and mesoscopic approaches contributed, distinctly yet complementarily, to the evolution of students' knowledge models.
The decision to use data derived from these three observables stems from their direct coherence with the cognitive nature of the research question, which investigates the transition from intuitive explanations to scientifically grounded representations. Indeed, they allow one to capture the core processes of conceptual transformation: the acquisition and conscious use of concepts and representations (Obs. 1.1), the evolution of common-sense conceptions (Obs. 1.2), and the development of reasoning chains consistent with the physical model (Obs. 2.2).

The pre-test results first confirm the hypothesis that students began with hybrid knowledge models, in which empirical, descriptive, and partially conceptual elements coexisted, an aspect already highlighted in the previous section. This initial configuration reflects the composite nature of common-sense knowledge (Vosniadou, 1994; diSessa, 1993), which provides a fertile yet unstructured foundation for the construction of scientific understanding.

During the first phase of the TLS, centred on macroscopic activities, students were exposed to concrete phenomena related to surface tension, such as capillary rise or the action of surfactants, observed through qualitative experiments.
In this phase, phenomenographic data reveal a clear shift from the everyday to the descriptive profile: explanations were no longer limited to an empirical register ("The water rises because it is absorbed"), but began to include references to material properties or cause-effect relationships ("Water reaches

the leaves through tiny channels inside the tree, which absorb it and make it rise upwards").

This change indicates that the macroscopic approach fulfilled a function of cognitive mediation: it encouraged students to make their intuitions explicit, to confront them with empirical evidence, and to develop an initial structure of conceptual relationships. However, understanding remained anchored at a descriptive level: the forces responsible for the phenomena were neither identified nor represented in a formalised manner. In epistemological terms, students began to construct a phenomenological model coherent with experience, though not yet with theory.

It was with the introduction of the mesoscopic phase, based on SPH simulations, that the most significant transition occurred.

The simulations made it possible to visualise the internal mechanisms underlying surface phenomena, cohesive and adhesive forces, particle interactions, and the role of surface tension, thus translating abstract concepts into observable dynamics.

The effect of this integration is reflected in the marked increase in explicative responses and in the consolidation of modelling processes: students no longer merely described what they observed but began to formulate causal explanations consistent with the scientific representation of the phenomenon. Many post-test responses, in fact, revealed an accurate use of physical terminology and an attempt to connect the macroscopic and microscopic levels ("Water rises from the roots to the leaves due to the phenomenon of capillarity: inside the tree there are thin capillary tubes in which the cohesive forces between water molecules and the adhesive forces between the water and the walls of the tube cause a spontaneous rise of the liquid").

This change is not merely lexical: it represents the transition from fragmented knowledge to a systemic understanding of the phenomenon, in which empirical observations are integrated into a unified explicative model.

At the same time, evidence from the cumulative thematic analysis for Obs. 1.1 (Appropriation of concepts and forms of representation) documents an increased ability among students to appropriate physical concepts and employ them through representational forms increasingly consistent with the scientific model. The percentages related to this observable (13.4% in macroscopic activities and 14.5% in mesoscopic ones in worksheets; 8.9% and 13.1% respectively in interviews) indicate a gradual yet evident progression from a spontaneous to a conscious and functional use of physical terminology.

The qualitative analysis of interviews shows that, after the introduction of SPH simulations, students began to speak more consciously about cohesive forces and surface tension, signalling a growing internalisation of the mesoscopic model and its representations. This shift reflects an epistemic change: students not only recognised new concepts but also began to use them as tools for thinking, explaining, and representing phenomena.

This evolution finds further confirmation in Obs. 1.2 (Evolution of common-sense conceptions to scientific ones), as evidenced in the worksheets (17.4%) and interviews (11.7%) related to macroscopic activities. In the materials produced during this phase, students still displayed uncertainty in distinguishing between observation and explanation, yet the first signs of conceptual awareness had already begun to emerge: empirical language started to intertwine with attempts at causal formulation.
In the subsequent phases, following the introduction of mesoscopic simulations, these same formulations evolved into explanations that explicitly recognised the physical nature of the forces at play, as shown by the percentage increase for the same observable (20.1% in worksheets and 13.9% in interviews). The analysis thus reveals a progressive transformation of the conceptual structure: students' thinking shifted from descriptions based on perceptions and analogies to explanations governed by laws and causal relations.

Further evidence of this process emerges from Obs. 2.2 (Development of reasoning lines), which shows an evolution in students' ability to construct coherent chains of reasoning. The percentages increase from macroscopic activities (7.2% in worksheets; 7.8% in interviews) to mesoscopic ones (10.3% and 11.8% respectively), indicating a consolidation of inferential processes and an enhanced capacity to connect observations, concepts, and causal explanations.
In the initial stages of the TLS, responses tended to be fragmentary or purely descriptive, often lacking a logical structure linking cause and effect. After the experience with simulations, however, arguments became more linear and cohesive: students began to make explicit connections between cohesive and adhesive forces, to justify the observed behaviours, and to integrate multiple representational levels (macroscopic, mesoscopic, and microscopic).

Overall, the results of these three observables indicate that the evolution of knowledge models did not occur through replacement, but through progressive integration. Macroscopic activities acted as an experiential foundation for the emergence of early forms of conceptual awareness, while mesoscopic activities, by enabling the visualisation of particle interactions, provided a cognitive bridge between direct experience and theoretical representation.

From an interpretative standpoint, the combined results of the phenomenographic analysis in the intermediate and post-tests of Q.1 and Q.2, together with the thematic analysis of the worksheets and interviews collected during the experimental activities, reveal that the macroscopic and mesoscopic approaches operate synergistically, fulfilling the educational function of a double mediation: the macroscopic approach anchors learning in experience and enables meaning-making from the sensible world, while the mesoscopic approach provides the theoretical framework through which experience can be transcended and the phenomenon understood in terms of general principles.

The integration of these two representational levels thus produces a transformative effect: understanding shifts from a logic of “seeing” to a logic of “modelling”, in which observations become the object of explanation rather than mere description.

A comparison with the literature shows that these findings are consistent with the conceptual change paradigm (Strike & Posner, 1992; Posner et al., 1982) and with research on scientific modelling (Greca & Moreira, 2002; Gilbert & Justi, 2016), both of which emphasise the importance of intermediate and multimodal representations in fostering cognitive restructuring.
SPH simulations prove to be highly effective tools for triggering these processes of conceptual transition: they allow students to manipulate complex concepts visually, thereby creating a bridge between what is observable and what must be inferred.

From this perspective, the results fully address the first research question. The TLS does not merely transmit knowledge; it functions as a transformative device capable of fostering the evolution of students’ hybrid knowledge models towards scientifically grounded and conceptually integrated configurations.

7.2.2 Answer to the second research question

To what extent does a mesoscopic approach, based on the use of interactive simulations, promote students’ learning?

The second research question is addressed through a cross-analysis of various data sources (worksheets, interviews, logbooks, and feedback), aimed at understanding how the introduction of the mesoscopic approach, based on the use of SPH simulations, fostered deeper and more conscious learning processes. Although the analytical framework of the TLS is based on eight observables, this section focuses primarily on the five not yet discussed: Obs. 2.1 (Enhancement of interpersonal and social skills), Obs. 2.4 (Recognition and evolution of personal cognitive/learning styles), Obs. 3.2 (Growth mindset), Obs. 3.3 (Metacognition), and Obs. 3.4 (Well-being in learning). The remaining three (Obs. 1.1, Obs. 1.2, and Obs. 2.2), which are closely related to the cognitive dimension and have already been examined in connection with the first research question, are here considered implicitly as an interpretative background. This choice avoids conceptual redundancy and allows the discussion to concentrate on the complementary dimensions of learning (social, affective, and metacognitive), which enable a more comprehensive understanding of the impact of the mesoscopic approach on students’ educational experience.
It should also be specified that, although sharing the same logic of thematic analysis, logbooks and feedback differ from worksheets and interviews in their epistemic nature. They are, in fact, tools of reflective and subjective observation. The logbooks collect the researchers’ perspective on the lived experience of the

teaching sequence, documenting relational dynamics, difficulties, and mediation strategies observed in students during the activities. Student feedback, on the other hand, provides direct access to the individual perception of the learning experience, revealing emotions, awareness, and reflections developed at the end of the TLS. For this reason, evidence from these sources is not integrated quantitatively with the others but discussed qualitatively and complementarily, with the aim of providing a deeper understanding of the meaning students attributed to their experience and of the evolution of their relationship with scientific knowledge.

Observable 2.1 ("Enhancement of interpersonal and social skills") highlights how the TLS had a significant relational impact, fostering modes of interaction and collaboration that were closely intertwined with cognitive processes. During the first phase, centred on macroscopic activities, the educational experience was characterised by an intense participatory dimension in which the collective design and execution of experiments gave rise to an authentic research community. Students designed and built their own experimental apparatuses, sharing ideas, dividing tasks, and negotiating operational strategies to observe surface phenomena. The high percentages recorded for this observable (16.2% in the worksheets and 20.6% in the interviews) confirm the central role of collaboration in this stage of the process. Learning here emerges as a genuinely social process: dialogue and cooperation constitute not only the means to solve practical problems but also the space for negotiating meaning. Through discussion and comparison of hypotheses and observations, students developed transversal social skills such as listening, mediation, and shared responsibility, strengthening the affective and relational dimensions of the experience.

With the introduction of mesoscopic activities based on SPH simulations, the social dimension of learning took on a qualitatively different configuration. The percentages related to this same observable (10% in the worksheets and 11.3% in the interviews) indicate a reduction in the explicit reference to interpersonal skills. This, however, should not be interpreted as a weakening, but rather as a transformation in the way collaboration occurred. The digital environment demands a more functional than relational cooperation: students must agree on which parameters to modify, decide how to interpret them, and discuss the effects of the observed variations. Collective action thus gives way to more analytical reflection.

The researchers' logbooks highlight how this new configuration produced "a very high level of individual concentration, with shorter but more targeted exchanges." Interaction, therefore, shifted from the social to the cognitive level: the simulation became an epistemic partner with which students began to "dialogue" to test, correct, and consolidate their hypotheses. In the feedback, some students explicitly recognised this change, noting that "you had to pay more attention to understand what was happening," a sign of increased cognitive responsibility.

In this sense, the transition from macroscopic to mesoscopic activities marks a shift from a concrete and situated cooperation (Lave & Wenger, 1991), centred on shared action, to a more reflective and autonomous form of participation. With the introduction of mesoscopic activities, this social dimension does not disappear but rather becomes internalised: collaboration transforms into a form of socially shared regulation of learning (Hadwin et al., 2011), where the control and reflection on cognitive processes are shared yet internalised within the individual. Interaction thus becomes not only interpersonal but also intrapersonal, oriented towards the autonomous regulation of thought.

Observable 3.4 ("Well-being in learning") provides a significant perspective on the relationship between students' emotional and motivational conditions and the learning modes promoted by the TLS. The data reveal a clear distinction between the two phases of the process: perceived well-being was markedly higher during macroscopic activities (12% in the worksheets and 13.4% in the interviews) compared to mesoscopic ones (7% and 6% respectively). This trend confirms a pattern already observed for Obs. 2.1, emphasising how experiential learning situations, where students can manipulate real materials, observe tangible phenomena, and collaborate actively, foster a higher degree of satisfaction, emotional involvement, and sense of belonging to the group.

During the macroscopic phase, direct contact with concrete experience and the opportunity to design and perform experiments generated widespread enthusiasm and genuine engagement. Working in small groups, students built a cooperative learning environment that helped reduce performance anxiety and enhance intrinsic motivation. In this phase, well-being was thus the result of a balance between emotional involvement and shared knowledge construction.

With the introduction of mesoscopic activities, the emotional and motivational framework partially shifted. Although SPH simulations represent a powerful cognitive tool, they required a higher level of abstraction and conceptual management, shifting the centre of learning from an experiential and collaborative plane to a more analytical and individual one. The need to interpret graphical dynamics, manage numerical parameters, and comprehend the relationships between particles led to an increased cognitive load and a reduction in the immediate gratification derived from practical action.

Students' feedback on macroscopic activities frequently included expressions such as "working together helped us understand better," attesting that the cooperative dimension and the tangible nature of the experience fostered a widespread sense of efficacy and curiosity. Conversely, several students remarked that they found the simulations "more difficult but clearer," expressing a tension between cognitive challenge and emotional satisfaction.

This apparent decrease in well-being should be interpreted as an indicator of a shift towards a different formative balance within the TLS: from the positive emotions associated with shared action to subtler yet more enduring emotions linked to deep understanding and cognitive awareness. In this light, the TLS demonstrates that well-being in learning does not derive solely from the immediate pleasure of experience but also from the sense of mastery and personal growth accompanying conceptual elaboration. This interpretation aligns with Pekrun's control-value theory (2006), according to which positive academic emotions emerge when students perceive control over their learning and assign value to the activities performed. Similarly, in line with Deci and Ryan's self-determination theory (2000), the satisfaction of the needs for competence, autonomy, and relatedness forms the foundation of motivational well-being, which can manifest both in experiential collaboration and in autonomous cognitive challenge.

Observable 2.4 ("Recognition and evolution of personal cognitive/learning styles") offers particularly insightful evidence for understanding how different modes of activity influenced students' recognition and re-elaboration of their cognitive and learning styles. Although the quantitative data show modest percentages, they reveal a meaningful trend: during macroscopic activities, percentages were 5% in the worksheets and 3.3% in the interviews, whereas in mesoscopic activities they increased to 6.2% and 8.6% respectively. This progression suggests that the introduction of simulations significantly fostered a more conscious awareness of individual learning processes.

During macroscopic activities, students worked mainly in groups and through experiential engagement, privileging a learning-by-doing approach. This mode undoubtedly encouraged active exploration and collaboration yet placed less emphasis on individual reflection about learning strategies. The explanations emerging in this phase were often limited to descriptions of the experience, without analysing how each student was understanding or processing the phenomenon. In other words, the focus lay on what was being observed, rather than on how learning was occurring.

With the introduction of mesoscopic activities based on SPH simulations, the situation changed noticeably. The higher percentages indicate that interaction with a digitally mediated learning environment fostered more explicit reflection on cognitive processes. The simulations introduced a visual and dynamic dimension that enabled students to see otherwise invisible phenomena, such as interactions between particles, cohesive and adhesive forces, or the action of surface tension. This form of representation acted as a cognitive bridge between the abstract and the concrete, facilitating self-awareness in learning.

Student feedback clearly shows that many recognised the effectiveness of the visual channel as a privileged means for understanding complex concepts. Several comments highlight that "seeing what happens inside the liquid" or "observing the forces in action" made physical principles more accessible and intuitive, principles that, in purely macroscopic experimentation, had been harder to internalise. This awareness marks a crucial step: students not only learn content but also begin to reflect on how they learn, recognising the power of visual and interactive representations in constructing meaning.

From a theoretical standpoint, these results are consistent with literature on visual metacognition and multimodal scientific learning (Ainsworth, 2006;

Gilbert et al., 2008), which emphasises how the variety of representational codes (verbal, graphical, dynamic) enhances awareness of one's cognitive strategies. In this sense, the mesoscopic environment does not merely act as a technological aid but functions as a reflective tool capable of rendering thought visible and stimulating processes of self-assessment and self-regulation.

Observable 3.2 ("Growth mindset") highlights the progressive development of positive cognitive attitudes towards challenge and learning, confirming that the TLS acted not only on the conceptual level but also on the motivational and epistemic planes. The data show a notable increase between the macroscopic and mesoscopic activities (from 12.4% to 14.5% in the worksheets and from 15.9% to 17.1% in the interviews), which, although numerically modest, reveals a meaningful transformation in students' perception of their own learning process. During the macroscopic activities, the design and direct execution of experiments offered students the opportunity to experience error first-hand. The difficulties encountered generated moments of collective discussion and reflection, fostering the development of cooperative attitudes. However, in many cases, the error was not immediately understood. Without subsequent discussion within the community of practice, it would have remained devoid of genuine cognitive elaboration. Indeed, a hands-on experiment does not easily allow one to "go back" and precisely analyse the cause of an error, but only to repeat the experience, with the risk of unintentionally altering the initial conditions and failing to grasp the true nature of the problem.

With the introduction of the mesoscopic activities, based on SPH simulations, the development of growth mindset progressively consolidated. The possibility of pausing, modifying, and restarting the simulation, changing parameters and observing in real time the effects of such changes, transformed learning into an iterative and self-aware process. In this controlled environment, error acquired an exploratory value: no longer an obstacle, but a starting point for understanding the causal relations between phenomena. The simulations allowed students to observe visually and immediately the consequences of their choices, making the process of revision not only possible but cognitively meaningful. Each error thus became an opportunity for cognitive freedom, a space for autonomous experimentation that stimulated curiosity, perseverance, and, most important, confidence in one's own capacity for improvement.

In their logbooks, the researchers observed a new attitude among the students, more exploratory and self-assured: "they are not afraid to make mistakes; they try, go back, and try again," wrote one teacher-researcher, emphasising how the digital environment had diminished the perception of error as failure, instead fostering a disposition of curiosity and persistence.

This attitude reflects a crucial shift: from a traditional conception of knowledge, centred on experimental correctness, to a dynamic understanding in which learning arises from the continuous interplay between hypothesis and observation. In line with Dweck's (2006) perspective, the TLS thus promoted a mindset open to change. Simulations proved to be effective tools for reinforcing such a disposition, as they offer a safe environment in which to explore, fail, revise, and retry, making tangible the principle that knowledge is progressively constructed through experience.

Observable 3.3 ("Metacognition") further deepens the reflective and self-regulatory dimension of scientific learning, showing how the interplay between practical activities and digital simulations progressively enhanced students' awareness of their own cognitive processes. The data reveal high and relatively stable values between the two phases of the TLS: from 16.3% to 17.6% in the worksheets, and from 18.4% to 18.2% in the interviews. This continuity, far from indicating stagnation, reflects a qualitative consolidation of metacognitive reflection, which evolved from being shared and situated to becoming more autonomous and internalised.

In the macroscopic activities, metacognition emerged primarily through dialogue, collaboration, and shared reflection. Students collectively planned the stages of the experiment, discussed operational strategies, and reflected together on the most effective ways to observe and interpret phenomena. Peer discussion thus became a powerful catalyst for reflective thinking. This form of collective metacognition, developed within a cooperative learning environment, enabled students to make their mental processes explicit and to recognise the importance of planning, monitoring, and revising their experimental strategies.

With the transition to the mesoscopic activities, metacognitive reflection gradually evolved towards a more individual and abstract dimension. The SPH simulations required control over variables and visual interpretation of the dynamics among particles, placing students in a position where they had to monitor their own cognitive processes in real time, formulate predictions, and verify them through the simulated experience. The mesoscopic environment therefore provided a space for personal reflection, where students learned to observe not only what occurred in the digital model, but also what they expected to occur, comparing their hypotheses with the actual results. In this sense, the mesoscopic context became a "cognitive laboratory," in which students observed not only physical phenomena but also their own mental strategies, making reflection an integral component of scientific activity.

Students' feedback clearly reflects this dual nature of metacognitive reflection, collective in the macroscopic activities and more individual in the mesoscopic ones. Many students noted that, during the practical experiments, "by talking together we understood better what we were doing," while others commented that the simulation helped them to "understand what may really happens, not just what I thought was happening." These observations reveal that both phases supported awareness of one's own thinking, albeit in different forms: in the macroscopic activities through peer discussion and negotiation of meaning, and in the mesoscopic activities through a more autonomous process of verification and analysis of one's own mental representations. In both cases, reflection emerges as a constitutive element of scientific learning.

This finding aligns with constructivist perspectives, according to which the construction of scientific knowledge is accompanied by conscious reflection on one's own thinking mechanisms. From this standpoint, metacognition is not a separate activity from scientific practice but represents one of its structural components, enabling learners to monitor, control, and restructure their own learning strategies. Similarly, these results are consistent with socio-constructivist views of learning (Vygotsky, 1978; Bruner, 1990), which recognise in dialogic reflection and peer interaction a powerful catalyst for metacognitive development, later evolving into more autonomous and internalised forms through the mesoscopic environment.

The results emerging from the five observables considered outline a coherent and nuanced picture of the formative function of the mesoscopic approach. The introduction of SPH simulations fostered a progressive transformation of learning, from a predominantly experiential and collaborative mode to a more reflective and self-aware one, supporting the transition from situated cooperation to more autonomous processes of cognitive and metacognitive regulation. While the macroscopic activities represented an essential moment for generating participation, motivation, and a sense of belonging, the mesoscopic activities expanded the cognitive potential of the TLS, offering students the opportunity to analyse, verify, and conceptually elaborate their own hypotheses. The simulation thus functioned as an intermediate space of thought between concrete experience and theoretical abstraction, capable of promoting not only conceptual understanding but also reflection on one's own way of learning.
Ultimately, the mesoscopic approach fostered deeper and more self-aware scientific learning, integrating the cognitive and affective dimensions within a unified path of epistemic growth. The experience demonstrates that genuine understanding of phenomena arises not from action or reflection taken in isolation, but from their continual interaction, a process through which the learner becomes the author and regulator of their own scientific knowledge.

7.3 Interpretation of data from the satisfaction questionnaire (Q.3)

The overall analysis of the results from the satisfaction questionnaire (Q.3) confirms the pedagogical soundness of the TLS and the coherence between its design objectives and the students perceived experience. Taken as a whole, the scores reveal a high degree of satisfaction and a generally positive evaluation of the activities, with internal variations that reflect the complexity and richness of the proposed educational pathway.

Already in the first section, dedicated to expectations (question 1.1, mean value of 3.81) and prior knowledge (question 1.2, mean value of 2.66), a significant result emerges: students perceived the activities as clear, well-structured, and consistent with their expectations, while at the same time recognising their initial limited familiarity with the topics addressed. This gap between perceived clarity and prior knowledge suggests that the TLS successfully introduced a new conceptual domain, that of surface phenomena, in an accessible and progressive manner, managing to stimulate curiosity without generating disorientation. The initial lack of familiarity, far from being a limitation, represents a pedagogical strength: students were confronted with concepts not immediately known to them, thereby engaging in a genuinely meaningful learning process.

The second section, concerning organisation, further confirms the effectiveness of the learning pathway. The high average values reflect a widespread appreciation for the structure and management of the TLS, which were perceived as orderly and coherent (questions 2.1 and 2.3, with mean values of 4.09 and 3.38, respectively). The slightly lower evaluations (question 2.2, mean value of 3.16) indicate that some students felt the need for a temporal or operational adjustment, likely due to the alternation between experimental activities, guided reflections, and moments of digital simulation. This, however, constitutes a constructive challenge, since the very variety of activities represents one of the defining features of the TLS: dynamic, multi-level learning inevitably requires a degree of flexibility and redefinition of one's cognitive rhythms.

The third section, devoted to self-assessment and the impact on curricular learning, paints an equally encouraging picture. The higher averages indicate that students perceived a genuine consolidation of acquired competences, acknowledging both personal and disciplinary enrichment (question 3.1, with a mean value of 3.56; question 3.1.2, with a mean value of 4.06; question 3.1.3, with a mean value of 3.66). The lower values (question 3.2, mean value of 2.91), by contrast, point to some difficulty in directly linking the TLS experience with traditional curricular content, a predictable outcome, considering the innovative nature of the programme, which functions more as an integrative than a substitutive approach to standard teaching. These results suggest that the TLS acted as a complementary learning space, fostering the development of transversal and reflective competences rather than the mere reinforcement of school-based knowledge.

The fourth section, focused on the evaluation of teaching strategies, shows the highest degree of approval, highlighting that students recognised the validity of the adopted methodologies and their effectiveness in promoting participation, curiosity, and understanding (questions 4.1 to 4.9, with mean values of 3.38, 4.03, 2.78, 3.28, 4.13, 3.09, 3.00, 4.13, and 4.22, respectively). The lower scores correspond to moments of greater cognitive complexity, probably related to the introduction of SPH simulations or to the need to integrate different representations (macroscopic, graphical, and symbolic). Nevertheless, these challenges were experienced as stimulating rather than frustrating, indicating a positive balance between difficulty and satisfaction, fully consistent with constructivist models of scientific learning.

The fifth section, dedicated to the relational dimension, confirms the quality of the cooperative climate developed throughout the experience. The scores (questions 5.1 to 5.3, with mean values of 3.91, 3.34, and 3.19, respectively) reveal that students perceived an inclusive environment grounded in dialogue and collaboration. This finding aligns with the qualitative evidence gathered through logbooks and interviews, which had already highlighted the emergence of a genuine learning community characterised by trust, attentiveness, and mutual support. The social dimension of learning, already identified as central in Observables 2.1 and 3.4, is thus confirmed also in the subjective perception of well-being and interpersonal relationships within the laboratory setting.

Finally, the sixth section, which gathers overall evaluations of the experience, provides particularly telling evidence of the general level of satisfaction. Although some prudence appears in certain aspects (question 6.1, mean value of 2.91), likely linked to workload and cognitive challenge, the final assessment of the TLS demonstrates broad and genuine appreciation (question 6.2, mean value of 4.31). In other words, students recognised in the TLS not merely an interesting activity but a complete and meaningful educational experience capable of combining scientific rigour with personal engagement.

Taken as a whole, the satisfaction questionnaire thus portrays an image consistent with the findings from the previous observables: the TLS was perceived as an innovative, stimulating, and formative pathway in which learning became a lived, reflective, and shared experience. The high level of satisfaction expressed by students is not merely an indicator of didactic success, but also confirmation that the mesoscopic approach, based on interactive modelling, can foster emotional engagement, intrinsic motivation, and cognitive awareness: the three essential dimensions of authentic and lasting learning.

Chapter 8

Conclusions, limitations and research perspectives

At this stage, it is appropriate and look back.

The preceding pages have accompanied a journey that unfolded between concrete experience and abstraction, between observation and modelling, between initial intuitions and the progressive construction of meaning. Along this path, students were given a voice as they sought to interpret familiar phenomena through new tools, testing their ideas, reorganising language, and experimenting with different ways of "doing science."

Looking back also entails recognising that every pedagogical choice opens possibilities, but inevitably closes others. The Teaching-Learning Sequence proposed and validated in this thesis generated spaces for understanding, engagement, and conceptual restructuring, yet it remained bounded by specific limits determined by the context, the time available, the participants involved, and the mediations enacted. Making these boundaries explicit is not an exercise in formal caution, but a necessary step to attribute significance and robustness to the evidence obtained.
At the same time, what remains unsaid or only glimpsed does not represent a deficiency, but rather an opportunity. The dynamics observed, the transformations recorded, and the tensions revealed suggest avenues of research that extend beyond this particular study, raising questions regarding knowledge consolidation, skill transfer, and the extension of the sequence to other educational contexts.

From this perspective, this concluding chapter serves as a space for synthesis and projection: a place where the results are related to their educational implications, where limitations become tools for critical interpretation, and where the undertaken experience demonstrates its generative potential.
Here, the journey reaches a form of fulfilment, not as a definitive closure, but as a threshold towards new possibilities for investigation and educational design.

8.1 Conclusions

The discussion of results presented in Chapter 7 allows a systematic focus on the effectiveness of the TLS in supporting tangible development both in students' knowledge models and in their ways of participating in and reflecting on surface phenomena. The complex set of evidence collected (questionnaires, worksheets, interviews, researchers' logbooks, and student feedback) provides a coherent and consistent picture, in which learning is conceived as a layered and dynamic process. This process unfolds along a path leading from direct experience to conceptual formalisation, and from the description of phenomena to their modelling.

Within this interpretative framework, two complementary lines of analysis can be distinguished: on the one hand, the identification of the principal findings emerging from the study; on the other, their pedagogical interpretation, to understand which dimensions of scientific learning were most enhanced and which still present scope for development. The following sections examine both perspectives, highlighting how the TLS operated simultaneously on conceptual, cognitive, participatory, and affective levels, thereby making a significant contribution to the understanding of scientific knowledge construction processes in school contexts.

8.1.1 Main research results

The results emerging from the pre-tests (Q.1 and Q.2) indicate that students did not start from a complete absence of knowledge, but from a heterogeneous cognitive repertoire, weakly integrated and marked by frequent discontinuities. Their responses, often difficult to categorise within a single epistemological profile, show the coexistence of elements belonging to the three identified profiles (everyday, descriptive, and explicative). Within the same work, phenomenological descriptions linked to everyday experience coexist with intuitive attempts at causal explanation and fragments of conceptual knowledge not yet supported by a coherent theoretical structure.
This hybrid configuration (Vosniadou et al., 2008) confirms what was argued by diSessa (1993) and Vosniadou (1994) regarding the layered and non-linear nature of spontaneous knowledge: students do not construct scientific concepts as ordered sequences, but as sets of "conceptual islands," which may remain isolated, come into conflict, or be selectively mobilised in different contexts. In the case of surface phenomena, such conceptual islands emerged both in observations of liquid behaviours and in sometimes inappropriate references to terms such as "force," "tension," or "attraction."

The educational intervention acted as a device for cognitive restructuring, facilitating the transition from intuitive but incoherent explanations to more integrated and theoretically grounded forms of modelling. This process was made possible by the integration of two complementary representational levels, designed to support the conceptual progression of students.

The macroscopic level played a fundamental role as the starting point of conceptual transformation. Through the design and direct execution of experiments, students were able to make their intuitive ideas explicit, formulate hypotheses and expectations, and confront empirical evidence often in contrast with initial conceptions. This direct experience promoted the emergence of a more articulated and specific descriptive language: worksheets and interviews show references to material properties such as "absorption" or "container shape," demonstrating a first attempt to construct networks of causal relations between observations and explanations. However, the macroscopic level alone was insufficient to provide complete scientific concepts. Rather, it acted as a catalyst for curiosity and shared reflection, creating a fertile cognitive and emotional context for the introduction of more abstract tools and facilitating the transition to modelling.

The introduction of the mesoscopic level, through SPH simulations, represented the turning point of the sequence, in which direct experience was transformed into scientific modelling. Visualisation of inter-particle interactions allowed students to overcome the perceptual limitations of real experience, observing dynamics invisible to the naked eye, such as the forces of cohesion, adhesion, and the action of surface tension. This level made it clear how the macroscopic behaviour of the liquid emerges from the balance of internal and external forces.

Data from the post-tests (Q.1 and Q.2), together with worksheets and interviews related to the mesoscopic phase, show a progressively more accurate and coherent use of physical language: terms such as "force," "interaction," "surface tension," and "attraction" are no longer used in isolation, but integrated into coherent chains of reasoning capable of describing system dynamics. This evolution represents not merely a lexical improvement, but a genuine epistemological reorganisation: students begin to conceive the phenomenon not as a simple observable fact, but as the result of a complex system of interactions.

The integration of the two levels proved crucial: the macroscopic level provided an experiential and observational anchor, while the mesoscopic level introduced an exploratory environment in which abstract concepts could be made visible, interrogated, and progressively reorganised. In this way, the sequence promoted measurable cognitive development, both in the quality of explanations and in the students' increasing ability to mobilise coherent models to interpret complex physical phenomena.

8.1.2 Implications for scientific learning

The analysis of data collected during the TLS demonstrates that the process of scientific learning developed across multiple dimensions, intertwining cognitive, metacognitive, social, and well-being aspects in an integrated manner. The two representational levels, macroscopic and mesoscopic, operated complementarily, yet with significant differences regarding the aspects of learning they enhanced or left less stimulated.

The macroscopic level played a key role in fostering experiential and collaborative learning, within which students engaged in an environment characterised by a strong sense of relational well-being and emotional security. The opportunity to work side by side, to engage in spontaneous discussion, and to construct meaning collectively created an inclusive and supportive climate, in which each participant felt legitimised to contribute and express their ideas. The "doing together" functioned as a crucial mechanism for reinforcing group cohesion, generating a learning experience perceived as positive, welcoming, and motivating. Constant peer interaction also facilitated the collaborative construction of knowledge, significantly contributing to mutual trust and emotional engagement in scientific activity.
The affective dimension was therefore particularly robust: students exhibited high levels of comfort, active participation, and willingness to engage in dialogue, indicating that shared activities acted as a powerful catalyst for intrinsic motivation.
However, this richness in relational and experiential terms was not accompanied by an equally marked advancement in deeper epistemic dimensions. Observations indicate that, although the macroscopic level stimulates curiosity and participation, it primarily consolidates phenomenological descriptions and common-sense explanations, without naturally leading to conceptual restructuring or the construction of stable explanatory models. Reasoning remains anchored to immediate perception and often does not progress towards forms of abstract causality; the growth mindset associated with trial-and-error experimentation, although present in practical interactions, does not translate into explicit revision of mental models.
This limitation does not represent a flaw of the methodology, but an intrinsic characteristic of the representational level: macroscopic activities emphasise doing and observing, rather than necessarily articulating the invisible dynamics governing the phenomena. Consequently, essential elements of scientific learning, such as the transition from intuition to conceptually grounded explanations, the development of formalised reasoning chains, or the adoption

of an epistemic approach oriented towards self-guided revision, are less stimulated. In the absence of a further level of modelling, there is a risk that knowledge remains fragmented: students recognise *what occurs*, but not yet *why it occurs*.

Conversely, the mesoscopic level, introduced through SPH simulations, required a greater cognitive and metacognitive effort, focusing on autonomous reflection and deep understanding of phenomena. Students were confronted with the necessity of comparing their mental models with invisible dynamics, reformulating explanations, and constructing coherent causal chains to describe particle behaviour. This process promoted a substantial enhancement of metacognitive skills: awareness of one's own thinking processes, self-regulation, and the ability to transfer reasoning strategies to novel contexts were all significantly developed. In motivational terms, the satisfaction derived from understanding phenomena and achieving conceptual mastery reinforced cognitive engagement, guiding students towards a scientific mindset characterised by critical observation, hypothesis revision, and iterative experimentation.
However, the greater complexity and individual focus of the mesoscopic approach also entail a clear limitation in terms of social interaction and general well-being. Unlike the macroscopic level, where direct peer interaction and collaboration are central, the simulations demand personal concentration and autonomous reflection, reducing opportunities for social interaction and collective negotiation of meaning. In this regard, the mesoscopic approach enhances cognitive, metacognitive, and growth-mindset competencies, but neglects collaborative and relational dimensions, which remain fundamental for shared learning and the construction of a scientific community of practice.

The combination of the two representational levels thus constitutes a particularly effective educational strategy, as each level enhances distinct yet complementary aspects of scientific learning. The macroscopic level provides an experiential and motivational anchor, facilitating access to phenomena, promoting social interaction, and supporting collaborative dynamics. The mesoscopic level, on the other hand, introduces the conceptual complexity typical of models, stimulating abstraction, scientific reasoning, metacognition, and increasing cognitive autonomy. This integration allows a continuous engagement with the main dimensions of scientific learning: from the construction of conceptual knowledge to intellectual growth, and to the progressive acquisition of mental habits oriented towards modelling and critical thinking.

Within this framework, one of the most significant outcomes concerns the consolidation of students' ability to navigate between different levels of representation. This competence, widely recognised in the literature as foundational to expert scientific thinking (Ainsworth, 2006; diSessa, 2004; Gilbert, 2008), requires not only accurate reading of heterogeneous registers, but also the ability to establish functional relationships between them. The iterative transition from the macroscopic dimension, focused on direct observation of phenomena, to the mesoscopic dimension, where the same phenomena are reinterpreted through particle interactions, fostered a progressive development of representational flexibility (Ainsworth, 2006).

In line with diSessa's (2004) perspective on the role of coordination among representational systems in developing disciplinary competence, students began to recognise that the same physical situation can be described from different perspectives, each providing specific epistemic affordances (Gilbert & Treagust, 2009). This exercise in translation and recomposition between registers enabled not only comprehension but also the justification of the links between levels, consolidating a unified view of the phenomenon.

The deliberate integration of the two levels therefore does not merely combine different approaches, but generates a learning pathway that fosters deep and lasting learning. The construction of scientific knowledge and the development of advanced cognitive skills proceed in a mutually reinforcing manner, enabling students to interpret and model complex phenomena with competence, autonomy, and increasing epistemic awareness.

8.2 Research limitations

Despite the positive outcomes emerging from the implementation of the TLS, it is necessary to acknowledge certain methodological limitations that may affect the interpretation and generalisation of the collected data. A critical analysis of these constraints allows the results to be contextualised, identifies the conditions that facilitated their effectiveness, and provides points of reflection for future implementations.

Three main aspects merit attention: the heterogeneity of the student sample, which may influence the variability of responses and the transferability of results; the relatively short duration of the intervention, which does not allow for a full monitoring of the stability of knowledge models and developed competences; and the methodological preparation of secondary school teachers, which represents a critical factor for the effectiveness and replicability of the TLS.

Each of these limitations is discussed in the following sections, with particular attention to theoretical and pedagogical aspects, in order to provide a comprehensive and rigorous evaluation of the conditions under which the TLS can operate successfully.

8.2.1 Participant heterogeneity

A significant methodological limitation of the present research concerns the size, composition, and recruitment procedures of the student sample involved in the study.

The group consisted of 36 fourth-year secondary school students, a relatively small number for studies aiming to draw generalisable inferences regarding scientific learning. While such a sample size is adequate within the context of qualitative research oriented towards reconstructing thinking processes, it nevertheless limits the possibility of conducting robust statistical analyses or reliably interpreting potential differences among subgroups.

Beyond numerical considerations, the composition of the sample is also methodologically significant: participation was markedly imbalanced in terms of gender, with a pronounced predominance of male students (29 males and 7 females). This imbalance is not merely a descriptive statistic but assumes particular significance in light of established international literature documenting how female participation in STEM activities is systematically influenced by a complex interplay of socio-cultural, cognitive, and affective factors.

As shown by Bian et al. (2017), even in the early years of primary school, girls tend to internalise the notion that intellectual excellence is more typically associated with males. This belief can have a lasting impact on their self-efficacy perceptions and willingness to engage in cognitively challenging activities. Similarly, studies such as those by Charlesworth and Banaji (2019) highlight how factors such as self-perception of ability, access to female role models, social representation of scientific disciplines, and the learning environment significantly influence not only girls' retention in STEM pathways but also their decision to participate in extracurricular scientific activities.

Considering this theoretical framework, the observed gender imbalance should be interpreted not as a contingent anomaly, but as an indicator of structural disparities in perceived opportunities and identification with science. This disparity is particularly evident in the specific context of this research, as the TLS was offered as a voluntary extracurricular activity within a PCTO programme (Percorsi per le Competenze Trasversali e per l'Orientamento). In such a framework, enrolment appears to more directly reflect personal orientations, subjective perceptions, and levels of familiarity with scientific practices, making any asymmetries in participation more visible.

In this respect, the lower female participation can be seen as a consequence of self-selection processes influenced by persistent gender representations: science continues to be culturally imagined as a discipline requiring traits such as confidence, competitiveness, and logical-mathematical ability, traditionally associated with masculinity (Cheryan et al., 2017). Moreover, within the Italian school context, female students may, in some cases, receive less explicit encouragement to pursue scientific enrichment activities, particularly when these involve experimental or laboratory tasks.

Finally, the nature of the PCTO project itself significantly contributed to shaping the sample. Since the TLS was offered as a voluntary, extracurricular activity conducted over a limited time outside school hours, it is likely that it primarily attracted students already interested in scientific subjects or who perceived themselves as sufficiently competent to engage with a conceptually and operationally demanding programme. This dynamic reflects well-documented patterns in national and international literature, where students who voluntarily choose additional STEM activities tend to have higher self-efficacy, stronger orientation towards scientific careers, and a greater sense of belonging to disciplinary communities (Wang & Degol, 2017). Consistent with these statistical trends, these students are typically more numerous among males, contributing to the gender imbalance observed in this study.

However, sample composition cannot be explained solely in terms of gender. It is plausible that those who chose to participate in the TLS possessed, directly or indirectly, favourable cultural capital: a family environment valuing learning, prior exposure to science, or simply domestic conversations on scientific topics. Previous experiences in scientific and laboratory contexts, along with digital competence levels, likely also played a selective role. These dimensions influence students' ability to perceive science as an accessible and meaningful domain, facilitating interaction with digital tools, complex visualisations, and multi-level models. In this sense, participation in the TLS reflects not only individual interest but also the convergence of socio-cultural conditions that predispose some students, more than others, to engage in extracurricular scientific activities.

It is therefore plausible that some outcomes observed in the TLS, for instance, the willingness to revise one's explanations or the rapidity with which certain students grasped the connection between macroscopic phenomena and mesoscopic models, were at least partially mediated by such individual traits.

It is important to emphasise, however, that the small group size enabled the research team to conduct close observation of students' cognitive and discursive processes, collecting qualitatively rich data through questionnaires, worksheets, interviews, and feedback. This qualitative richness, however, does not compensate for limitations in generalisability: the combination of small sample size, gender imbalance, and socio-cultural self-selection necessitates caution in extending the results to other educational contexts.

Consequently, future research should involve larger, gender-balanced, and more socio-culturally diverse samples to verify the robustness of the observed dynamics and to determine whether the same learning processes can emerge under more representative conditions.

8.2.2 Duration of the intervention

A further significant limitation of the study concerns the relatively short duration of the TLS, which prevented a comprehensive monitoring of the medium- and long-term effects on students' knowledge models and developed competences. Although the programme included laboratory activities, such as macroscopic experiments and mesoscopic simulation sessions, the overall time devoted to these activities remained insufficient to allow for a fully in-depth exploration of the phenomena and to verify the stability of conceptual transformations over the medium term.

Even though the sequence revealed notable progress, including conceptual reorganisation, the gradual adoption of a more coherent scientific language, and increased metacognitive reflection, research in science education clearly indicates that such gains require extended timeframes, repeated application cycles, and diverse opportunities to reuse concepts in order to consolidate them effectively (Vosniadou, 2008). Without prolonged monitoring, it is impossible to determine whether the observed changes represent enduring transformations or are instead susceptible to cognitive regression in the absence of subsequent experiences that reinforce conceptual anchoring.

The brevity of the intervention also limits the capacity to capture the emergence of more mature cognitive processes, such as transfer, the ability to apply knowledge and models to new or more complex contexts, a key objective in advanced scientific learning (Mestre, 2005). Transfer requires prolonged exposure to variable situations, guided reflection on the deeper meaning of concepts, and opportunities to compare one's model with new evidence. Short instructional sequences, while effective in producing immediate changes, do not allow for assessment of whether students develop genuinely functional and flexible understanding that transcends the specific context of the activity.

Similarly, scientific modelling, which represents one of the core epistemic competences promoted by the TLS, is a process that develops gradually. It requires time to internalise transitions between representational levels, refine the ability to select relevant variables, and recognise the limitations of models (Schwarz et al., 2009). Brief sequences may initiate the process, but they do not permit verification of whether students have consolidated autonomous and transferable strategies for representation and abstraction.

The temporal limitation was further exacerbated by the organisational context in which the intervention took place. The TLS, conducted within the framework of the PCTO programme, is inherently subject to defined timeframes, logistical constraints, integration within specific periods of the school year, and careful planning. The duration of the intervention, constrained by national PCTO regulations and the minimum hours prescribed for different types of institutions, did not allow for the administration of delayed tests weeks or months later, nor for an increase in the number of hours devoted to laboratory activities. Moreover, once the PCTO programme was concluded, it became challenging to recall students for additional evaluative activities, both for organisational reasons and to comply with regulations and responsibilities associated with school-to-work transition programmes.

These constraints rendered the implementation of longitudinal assessment impracticable, preventing monitoring of the stability and evolution over time of students' conceptual models and reasoning strategies. This constitutes a significant limitation, particularly in light of studies demonstrating that the consolidation of scientific concepts requires distributed exposure over time and repeated opportunities to review, discuss, and integrate one's conceptions (Taber, 2009; Linn, 2005).

Despite these limitations, the intervention enabled the collection of qualitatively rich data on the ongoing learning processes during the sequence. Analysis of questionnaires, worksheets, interviews, student feedback, and researcher logbooks provided a detailed insight into how students interact with different representational levels, progressively construct meanings, and reorganise their conceptions.

Although it does not allow for inferences regarding long-term persistence, these findings represent a significant contribution to understanding the cognitive and metacognitive dynamics that the TLS can activate in the short term, offering a solid foundation for future developments aimed at designing and evaluating more extended longitudinal learning pathways.

8.2.3 Limited methodological preparation of school teachers

An additional methodological limitation concerns the central role played by the research team in conducting the intervention and managing the laboratory setting.

Throughout the TLS, the researchers maintained direct and continuous involvement, assuming functions of guidance, facilitation, and cognitive mediation that contributed significantly to the quality of the learning experience. Their intervention extended beyond mere supervision of activities to include the orchestrated facilitation of discussions, support in the transitions between empirical observation and modelling (Windschitl et al., 2008), and the management of moments of conceptual uncertainty through calibrated scaffolding (Tabak, 2004). This type of support enabled students to engage with cognitively demanding tasks, such as constructing causal explanations, representing phenomena at the mesoscopic level, and critically evaluating their own ideas, while maintaining high levels of motivation, attention, and participation. However, this level of mediation also represents a potential limitation in evaluating the applicability and transferability of the TLS to ordinary school contexts.

In many cases, secondary school teachers do not possess specific methodological training or well-established competences in managing inquiry-based, modelling-oriented, or active learning practices (Abell, 2007; Loucks-Horsley et al., 2010).
Research on *teacher professional knowledge* has long highlighted that while many teachers demonstrate strong disciplinary content knowledge, they face greater challenges in developing *pedagogical content knowledge* (Shulman, 1986), that is, the set of competences that enables the transformation of content into meaningful learning experiences through effective teaching strategies, cognitive mediation, and appropriate disciplinary representations.
Teachers typically struggle to sustain instructional practices requiring exploration, peer discussion, conceptual modelling, and complex explanatory reasoning. Such activities demand sophisticated orchestration: guiding without substituting, facilitating without imposing, promoting conceptual restructuring without overly reducing the complexity of phenomena.
This pedagogical balance is difficult to achieve without adequate training in students' cognitive dynamics, the development of scientific competence, and the strategic use of scaffolding (Quintana et al., 2004; Reiser, 2004).

Structural limitations of the school system further compound these challenges: large class sizes, limited time, scarce availability of fully equipped laboratories, and densely packed curricula. These factors can hinder the implementation of experimental activities requiring extended time, collective reflection, management of scientific discussion, and iterative cycles of observation-interpretation-modelling, as envisaged in the TLS. Moreover, many teachers are unfamiliar with advanced digital tools or interactive simulations, limiting their ability to effectively integrate multiple representations and transitions between phenomenological, conceptual, and modelling levels.

The combination of these constraints suggests that the positive outcomes observed during the intervention cannot be attributed solely to the design of the sequence or the instruments used, but also to the presence of a research team with specialised expertise in science education, modelling processes, and cognitive and dialogic scaffolding practices. This implies that replicating the TLS would require targeted investments in teachers' methodological training,

familiarisation with educational technologies, and the development of competences in orchestrating complex inquiry-based learning environments.
Only with a consolidated pedagogical *repertoire*, competences in mediating modelling processes, and informed management of different scientific languages can it be ensured that the sequence maintains its effectiveness beyond the experimental context. Accordingly, any future implementations should include ongoing, practice-oriented professional development, encompassing co-design sessions, participatory observation, mentoring, and reflective discussions. These conditions constitute fundamental prerequisites for ensuring the quality of the learning experience and the transferability of TLS outcomes to authentic school contexts.

8.3 Research perspectives

The findings and considerations emerging from this study, while confirming the validity and coherence of the designed TLS, highlight the partial nature of any empirical investigation conducted in experimental educational contexts. As previously discussed, the methodological choices adopted and the contextual constraints allowed for a focused examination of specific aspects of scientific learning, leaving others in the background.

From this perspective, future research should not be conceived merely as a quantitative extension of the present study, but as an opportunity to deepen, refine, and further problematise the interpretative framework that has emerged. Openness to new research questions responds to the need to more fully understand the processes of scientific knowledge construction, their evolution over time, and their dependence on the educational context in which they develop.

This section, therefore, positions itself in continuity with the work conducted, laying the foundations for subsequent developments that may contribute to consolidating and expanding the evidence obtained, while keeping at the centre the complexity of scientific learning and its instructional design.
Two main avenues for future research are identified. On the one hand, the extension of the analysis to observable aspects not explored in this study; on the other, the possibility of transferring the teaching sequence to different educational contexts, particularly at the university level. Collectively, these perspectives aim to strengthen the theoretical and empirical framework of the research, contributing to a deeper understanding of the conditions that foster meaningful, enduring, and modelling-oriented scientific learning.

8.3.1 Extension to the analysis of the other five observables

A significant perspective for future development concerns the extension of the TLS to the five observables not analysed in the present study, as identified in the framework on the promotion of scientific learning (see Chapter 4).

- Observable 1.3 – Long-term retention of concepts

  The current intervention focused primarily on conceptual acquisitions and the reorganisation of knowledge models observable over the short term. Although the results demonstrate significant progress in understanding surface phenomena and in the ability to construct coherent explanations, the issue of the stability of such knowledge over time remains open. Research in science learning emphasises that initial understanding, if not consolidated through repetition, reflection, and application in diverse contexts, may be subject to decay, even following well-structured instructional interventions (National Research Council, 2000).

  Monitoring the persistence of knowledge acquired through the TLS would allow an evaluation of whether the combination of macroscopic and mesoscopic experiences not only promotes the emergence of correct concepts in the short term but also supports the construction of robust and enduring mental models.

  Analysing long-term retention would require the administration of delayed tests several weeks or months after the conclusion of the TLS, in order to assess the persistence of scientific concepts and the potential autonomous reactivation of modelling strategies. This approach would also make it possible to investigate the efficacy of mesoscopic simulations not only as tools for immediate learning but also for cognitive consolidation and the internalisation of the rules and principles underlying the observed phenomena.

- Observable 2.3 – Generalization of what has been learned

  A central aspect of advanced scientific learning concerns students' ability to transfer knowledge, strategies, and reasoning models to new and diverse contexts. The generalisation of knowledge represents a key indicator of learning depth, as it goes beyond the mere acquisition of specific information to promote transferable cognitive skills.

  Within the TLS, assessing this observable would allow an understanding of whether the overall experience with the observed phenomena supports not only the comprehension of surface phenomena but also the

development of competencies transferable to analogous or interdisciplinary contexts. Literature indicates that knowledge transfer is facilitated by learning experiences that stimulate reflection, the construction of abstract conceptual frameworks, and the comparison of different levels of representation (National Research Council, 2000; Mestre, 2005). In this regard, interaction with concrete phenomena and the opportunity to model observed dynamics provide students with cognitive tools to extract general principles and apply knowledge to new situations.
Analysing students' ability to generalise knowledge would also allow the identification of which elements of the TLS (collaborative experiences, digital simulations, guided reflection) contribute most significantly to the development of transferable competencies, offering valuable guidance for the design of future teaching sequences.

- Observable 3.1 – Perception of self-efficacy

Perceived self-efficacy constitutes a crucial factor in scientific learning, influencing motivation, persistence in complex tasks, and engagement in STEM subjects (Bandura, 1997; Schunk & DiBenedetto, 2020). Through structured activities involving problem solving, experimentation, and guided reworking of errors, the TLS could positively impact this dimension, reinforcing students' confidence in their ability to understand and model complex scientific phenomena.
However, in the present study, self-efficacy was not measured. A systematic evaluation would allow a more rigorous assessment of the extent to which the learning experience contributes to enhancing perceived competence, and the identification of potential individual differences related to gender, socio-cultural background, or prior experiences.
Integrating this observable into future implementations of the TLS would not only confirm theoretical hypotheses regarding the role of motivation and self-efficacy in scientific learning but also enable the design of interventions aimed at strengthening students' confidence in their cognitive abilities, with positive effects on engagement, autonomy, and active participation in STEM contexts.

- Observable 3.5 – Understanding of the Nature of Science (NOS)

Understanding the nature of science (NOS) represents a central objective of contemporary science education, as it contributes to developing students capable of interpreting scientific processes, evaluating evidence, and distinguishing between observations and theoretical explanations (Lederman, 2007; McComas et al., 2002). Solid knowledge of NOS is associated not only with improved conceptual understanding of phenomena but also with the development of critical and reflective thinking, essential for addressing complex problems in scientific and societal contexts.

The implementation of the TLS provides a promising environment for promoting NOS understanding, as it integrates macroscopic experiences and mesoscopic simulations, allowing students to engage with multiple levels of representation and actively experience the scientific method. Through model construction and hypothesis testing, students can develop awareness of the role of evidence, the importance of coherence between data and explanations, and the provisional nature of scientific theories.

However, this dimension was not analysed in the current study. Including this observable in future research would contribute to evaluating not only students' conceptual and metacognitive gains but also their epistemic development, providing useful guidance for designing teaching sequences that foster deep and informed scientific learning.

- Observable 3.6 – Willingness to extend studies and research

Students' willingness to continue scientific inquiry and independently deepen their knowledge constitutes a key indicator of intrinsic motivation and interest in scientific disciplines (Ryan & Deci, 2000). This dimension reflects not only immediate engagement in the activities provided but also the capacity of the teaching sequence to stimulate curiosity, cognitive responsibility, and orientation towards self-directed learning.

The TLS establishes a favourable context for promoting intrinsic motivation. In particular, framing errors as learning opportunities, collaborative interaction, and guided construction of coherent explanations are elements that, according to the literature, increase students' propensity to undertake further investigative activities (Schunk & DiBenedetto, 2020; Ryan & Deci, 2017).

Despite these potential benefits, the current study did not assess this observable. Explicit monitoring of students' willingness to pursue further studies and research would allow measurement of the TLS's impact on long-term motivation, engagement in autonomous investigative activities, and future choices regarding scientific or technological pathways.

The integration of these observables in future analyses would provide a more comprehensive and multidimensional picture of the TLS's effectiveness. Moreover, it would enable the assessment of interactions and correlations between previously studied observables and those hitherto neglected, offering more robust evidence regarding the combined role of macroscopic and mesoscopic representational levels in promoting scientific learning.

8.3.2 Extension of the TLS to university contexts

A further research perspective concerns the transposition of the TLS into university settings, for example within first- or second-year courses in engineering, computer science, or related disciplines.

This extension represents an opportunity to examine the effectiveness of the teaching sequence on more mature students, possessing prior knowledge and more developed cognitive skills compared to secondary school students (Prince & Felder, 2006). Implementation at the university level would allow observation of how the TLS can support the construction of more complex conceptual models, enhancing students' abilities in abstraction, modelling, and autonomous management of scientific phenomena, while integrating theory and practice in contexts characterised by greater technical and cognitive complexity.

A particularly relevant aspect concerns the possibility of monitoring a more robust longitudinal dimension. The continuity of university students' participation in courses over one or two years provides the opportunity to observe the stability of acquired knowledge, the persistence of metacognitive skills, and the capacity to transfer reasoning strategies to new and more complex contexts (National Research Council, 2000; Mestre, 2005). This would enable verification not only of the long-term retention of scientific concepts but also of the development of advanced problem-solving skills, critical thinking, and modelling capabilities, all of which are essential for higher-level scientific learning.
Moreover, university students, due to their greater cognitive autonomy, prior laboratory experience, and familiarity with advanced digital tools, could be challenged with representational levels more sophisticated than those used with secondary school students. This includes the ability to navigate between macroscopic, mesoscopic, and theoretical–computational representations of phenomena, facilitating the integration of experimental concepts and formal models, and promoting multi-representational competencies considered central to contemporary scientific thinking (Gilbert & Treagust, 2009).

Adapting the TLS to university contexts also requires careful consideration of specific pedagogical and methodological aspects. Greater heterogeneity in prior knowledge, diverse disciplinary backgrounds, and differences in levels of motivation and self-efficacy necessitate the adoption of targeted scaffolding strategies, which modulate support according to individual needs and facilitate autonomous knowledge construction (Hmelo-Silver et al., 2007). At the same time, the TLS in university contexts allows investigation into how the sequence fosters the development of coherent explanations or critical reasoning, elements that the literature associates with deep and durable learning (National Research Council, 2000).

Finally, implementing the TLS at the university level would allow the collection of more diverse and detailed data, both quantitative and qualitative. This would enable evaluation of the extent to which the sequence supports not only the immediate acquisition of scientific knowledge but also its generalisation, intrinsic motivation, and students' preparation for advanced scientific or professional investigative pathways.

References

Abd-El-Khalick, F., & Lederman, N. G. (2000). Improving science teachers' conceptions of nature of science: A critical review of the literature. *International Journal of Science Education, 22*(7), 665–701. https://doi.org/10.1080/09500690050044044

Abell, S. K. (2007). Research on science teacher knowledge. In S. K. Abell & N. G. Lederman (Eds.), Handbook of research on science education (pp. 1105–1149). Routledge.

Adam, N. K. (1941). *The physics and chemistry of surfaces* (3rd ed.). Oxford University Press.

Adami, S., Hu, X. Y., & Adams, N. A. (2010). A new surface-tension formulation for multi-phase SPH using a reproducing divergence approximation. *Journal of Computational Physics, 229*(13), 5011–5021. https://doi.org/10.1016/j.jcp.2010.03.022

Adamson, A. W., & Gast, A. P. (1997). *Physical chemistry of surfaces* (6th ed.). Wiley.

Adorno, D. P., Pizzolato, N., & Fazio, C. (2018). Long-term stability of learning outcomes in undergraduates after an open-inquiry instruction on thermal science. *Physical Review Physics Education Research, 14*(1). https://doi.org/10.1103/PhysRevPhysEducRes.14.010108

Ainley, M. (2012). Students' interest and engagement in classroom activities. In S. L. Christenson, A. L. Reschly, & C. Wylie (Eds.), *Handbook of research on student engagement* (pp. 283–302). Springer Science + Business Media. https://doi.org/10.1007/978-1-4614-2018-7_13

Ainsworth, S. (1999). The functions of multiple representations. *Computers & Education, 33*(2–3), 131–152. https://doi.org/10.1016/s0360-1315(99)00029-9

Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations. *Learning and Instruction, 16*(3), 183–198. https://doi.org/10.1016/j.learninstruc.2006.03.001

Åkerlind, G. (2005). Variation and commonality in phenomenographic research methods. *Higher Education Research & Development, 24*(4), 321–334. https://doi.org/10.1080/07294360500284672

Åkerlind, G. S. (2008). A phenomenographic approach to developing academics' understanding of the nature of teaching and learning. *Teaching in Higher Education, 13*(6), 633–644. https://doi.org/10.1080/13562510802452350

Akinci, N., Akinci, G., & Teschner, M. (2013). Versatile surface tension and adhesion for SPH fluids. *ACM Transactions on Graphics, 32*(6), 1–8. https://doi.org/10.1145/2508363.2508395

Alamy. (n.d.). *Voce maschile paddling in wet jeans in mare pants containment* [Figure]. Alamy. https://www.alamy.it/voce-maschile-paddling-in-wet-jeans-in-mare-pantaloni-di-contenimento-image1138108.html

Alexander, R. (2008). *Towards dialogic teaching: Rethinking classroom talk*. Dialogos.

Alonazi, M., Beloff, N., & White, M. (2019). Exploring determinants of m-government services: A study from the citizens' perspective in Saudi Arabia. In M. Ganzha, L. Maciaszek, & M. Paprzycki (Eds.), *Proceedings of the 2019 Federated Conference on Computer Science and Information Systems (FedCSIS 2019)* (pp. 627–631). IEEE. https://doi.org/10.15439/2019F75

Arthur, W., Jr., Bennett, W., Jr., Stanush, P. L., & McNelly, T. L. (1998). Factors that influence skill decay and retention: A quantitative review and analysis. *Human Performance, 11*(1), 57–101. https://doi.org/10.1207/s15327043hup1101_3

Atkins, P. W., & De Paula, J. (2006). *Atkins' physical chemistry* (8th ed.). Oxford University Press.

Attride-Stirling, J. (2001). Thematic networks: An analytic tool for qualitative research. *Qualitative Research, 1*(3), 385–405. https://doi.org/10.1177/146879410100100307

Ausubel, D. P. (1968). *Educational psychology: A cognitive view*. Holt, Rinehart & Winston.

Bachelard, G. (1967). *La formation de l'esprit scientifique: Contribution à une psychanalyse de la connaissance objective* (5th ed.). Vrin. https://doi.org/10.1522/030331552

Bandura, A. (1985). *Social foundations of thought and action: A social cognitive theory.* Prentice-Hall.

Bandura, A. (1997). *Self-efficacy: The exercise of control*. Freeman.

Bangham, D. H., & Razouk, R. I. (1937). Adsorption and the wettability of solid surfaces. *Transactions of the Faraday Society, 33*, 1459–1463. https://doi.org/10.1039/TF9373301459

Barbe, W. B., Swassing, R. H., & Milone, M. N. (1979). *Teaching through modality strengths: Concepts and practices.* Zaner-Bloser.

Barrett, P., Davies, F., Zhang, Y., & Barrett, L. (2015). The impact of classroom design on pupils' learning: Final results of a holistic, multi-level analysis. *Building and Environment, 89,* 118–133. https://doi.org/10.1016/j.buildenv.2015.02.013

Barrows, H. S., & Tamblyn, R. M. (1980). *Problem-based learning: An approach to medical education* (Vol. 1). Springer Publishing Company.

Batchelor, G. K. (2000). *An introduction to fluid dynamics*. Cambridge University Press. https://doi.org/10.1017/CBO9780511800955

Battaglia, O. R., & Fazio, C. (2019). A mesoscopic mechanical model of the surface tension and some simulation results. *Journal of Physics: Conference Series, 1287*. https://doi.org/10.1088/1742-6596/1287/1/012037

Battaglia, O. R., Agliolo Gallitto, A., & Fazio, C. (2019). Computer simulations to approach surface tension by means of a simple mesoscopic mechanical model. *Computer Applications in Engineering Education, 27*(6), 1333–1342. https://doi.org/10.1002/cae.22154

Battaglia, O. R., Agliolo Gallitto, A., Termini, G., & Fazio, C. (2021). A study of capillarity phenomena by using a computer-based simulation approach. *European Journal of Physics, 42*(5), 055704. https://doi.org/10.1088/1361-6404/ac1531

Battaglia, O. R., Agliolo Gallitto, A., Termini, G., & Fazio, C. (2023). Outcomes of a teaching-learning sequence on modelling surface phenomena in liquids. *Education Sciences, 13*(4), 425. https://doi.org/10.3390/educsci13040425

Beichner, R. J. (2008). The SCALE-UP project: A student-centered active learning environment for undergraduate programs. *An invited white paper for the National Academy of Sciences*.

Bell, R. L., Smetana, L., & Binns, I. (2005). Simplifying inquiry instruction. *The Science Teacher, 72*(7), 30–33.

Benz, W. (1990). Smooth particle hydrodynamics: A review. In J. R. Buchler (Ed.), *The numerical modelling of nonlinear stellar pulsations* (NATO ASI Series, Vol. 302, pp. 269–303). Springer. https://doi.org/10.1007/978-94-009-0519-1_16

Berland, L. K., & Reiser, B. J. (2009). Making sense of argumentation and explanation. *Science Education, 93*(1), 26–55. https://doi.org/10.1002/sce.20286

Berry, M. V. (1971). The molecular mechanism of surface tension. *Physics Education*, *6*(2), 79. https://doi.org/10.1088/0031-9120/6/2/001

Berthier, J. (2012). *Micro-drops and digital microfluidics* (2nd ed.). William Andrew.

Besson, U. (2015). *Didattica della fisica*. Carocci Editore.

Besson, U., & Viennot, L. (2004). Using models at the mesoscopic scale in teaching physics: Two experimental interventions in solid friction and fluid statics. *International Journal of Science Education, 26*(9), 1083–1110. https://doi.org/10.1080/0950069042000205396

Bian, L., Leslie, S. J., & Cimpian, A. (2017). Gender stereotypes about intellectual ability emerge early and influence children's interests. *Science*, 355(6323), 389–391. https://doi.org/10.1126/science.aah6524

Biesta, G. (2020). *Educational research: An unorthodox introduction*. Bloomsbury Publishing.

Biggs, J., & Tang, C. (2011). *Teaching for quality learning at university: What the student does* (4th ed.). McGraw-Hill Education.

Birdi, K. S. (Ed.). (2015). *Handbook of surface and colloid chemistry* (4th ed.). CRC Press. https://doi.org/10.1201/b18633

Blackwell, L. S., Trzesniewski, K. H., & Dweck, C. S. (2007). Implicit theories of intelligence predict achievement across an adolescent transition: A longitudinal study and an intervention. *Child Development, 78*(1), 246–263. https://doi.org/10.1111/j.1467-8624.2007.00995.x

Blanchard, M. R., Southerland, S. A., Osborne, J. W., Sampson, V. D., Annetta, L. A., & Granger, E. M. (2010). Is inquiry possible in light of accountability? A quantitative comparison of the relative effectiveness of guided inquiry and verification laboratory instruction. *Science Education, 94*(4), 577–616. https://doi.org/10.1002/sce.20390

Bolger, N., Davis, A., & Rafaeli, E. (2003). Diary methods: Capturing life as it is lived. *Annual Review of Psychology, 54*(1), 579–616. https://doi.org/10.1146/annurev.psych.54.101601.145030

Bonn, D., Eggers, J., Indekeu, J., Meunier, J., & Rolley, E. (2009). Wetting and spreading. *Reviews of Modern Physics, 81*(2), 739–805. https://doi.org/10.1103/RevModPhys.81.739

Bonwell, C. C., & Eison, J. A. (1991). *Active learning: Creating excitement in the classroom* (ASHE-ERIC Higher Education Report No. 1). The George Washington University, School of Education and Human Development.

Boone, H. N., & Boone, D. A. (2012). Analyzing Likert data. *The Journal of Extension, 50*(2), Article 48. https://doi.org/10.34068/joe.50.02.48

Bormashenko, E. Y. (2019). *Wetting of real surfaces*. Berlin, Boston: De Gruyter. https://doi.org/10.1515/9783110583144

Bowden, J., & Walsh, E. (Eds.). (2000). *Phenomenography: Understanding qualitative research*. RMIT University Press. https://search.informit.org/doi/10.3316/informit.0864590199

Boyatzis, R. E. (1998). *Transforming qualitative information: Thematic analysis and code development*. SAGE Publications.

Brackbill, J. U., Kothe, D. B., & Zemach, C. (1992). A continuum method for modeling surface tension. *Journal of Computational Physics, 100*(2), 335–354. https://doi.org/10.1016/0021-9991(92)90240-Y

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Braun, V., & Clarke, V. (2021). *Thematic analysis: A practical guide*. SAGE Publications.

Breinlinger, T., Polfer, P., Hashibon, A., & Kraft, T. (2013). Surface tension and wetting effects with smoothed particle hydrodynamics. *Journal of Computational Physics, 243*, 14–27. https://doi.org/10.1016/j.jcp.2013.02.038

Brookes, D. T., Ektina, E., & Planinsic, G. (2020). Implementing an epistemologically authentic approach to student-centered inquiry learning. *Physical Review Physics Education Research, 16*(2), Article 020148. https://doi.org/10.1103/PhysRevPhysEducRes.16.020148

Brooks, J. G., & Brooks, M. G. (1999). *In search of understanding: The case for constructivist classrooms*. Association for Supervision and Curriculum Development.

Brousseau, G. (1976). Les obstacles épistémologiques et les problèmes en mathématiques. In J. Vanhamme & W. Vanhamme (Eds.), *La problématique et l'enseignement des mathématiques* (pp. 101–117). Louvain-la-Neuve. https://hal.science/hal-00516569v2

Brousseau, G. (2002). *Theory of didactical situations in mathematics*. Kluwer Academic Publishers. https://doi.org/10.1007/0-306-47211-2

Brown, J. S., Collins, A., & Duguid, P. (1988). Situated cognition and the culture of learning. BBN Systems and Technologies Corp. https://doi.org/10.21236/ada204690

Brownlee, R., Houston, P., Levesley, J., & Rosswog, S. (2007). Enhancing SPH using moving least-squares and radial basis functions. In A. Iske & J. Levesley (Eds.), *Algorithms for approximation* (pp. 87–106). Springer. https://doi.org/10.1007/978-3-540-46551-5_8

Bruner, J. S. (1960). *The process of education*. Harvard University Press.

Bruner, J. S. (1990). *Acts of meaning*. Harvard University Press.

Bruner, J. S. (1996). *The culture of education*. Harvard University Press. https://doi.org/10.4159/9780674251083

Bryman, A. (2016). *Social research methods* (5th ed.). Oxford University Press.

Butt, H. J., & Kappl, M. (2018). *Surface and interfacial forces* (2nd ed.). Wiley. https://doi.org/10.1002/9783527804351

Butt, H. J., Graf, K., & Kappl, M. (2023). *Physics and chemistry of interfaces* (4th ed.). Wiley.

Buty, C., Tiberghien, A., & Le Maréchal, J. (2004). Learning hypotheses and an associated tool to design and analyse teaching–learning sequences. *International Journal of Science Education, 26*(5), 579–604. https://doi.org/10.1080/0950069031000161473 5

Bybee, R. W. (2002). Scientific inquiry, student learning, and the science curriculum. In R. W. Bybee (Ed.), *Learning science and the science of learning*. NSTA Press.

Byers, T., Imms, W., & Hartnell-Young, E. (2018). Evaluating teacher and student spatial transition from a traditional classroom to an innovative learning environment. *Studies in Educational Evaluation, 58,* 156–166. https://doi.org/10.1016/j.stueduc.2018.07.004

Campbell, P. M. (1989). *Some new algorithms for boundary value problems in smooth particle hydrodynamics*. Technical Report.

Carey, S. (1985). *Conceptual change in childhood.* MIT Press.

Carifio, J., & Perla, R. (2008). Resolving the 50-year debate around using and misusing Likert scales. *Medical Education, 42*(12), 1150–1152. https://doi.org/10.1111/j.1365-2923.2008.03172.x

Carr, W., & Kemmis, S. (1986). *Becoming critical: Education knowledge and action research* (1st ed.). Routledge. https://doi.org/10.4324/9780203496626

Çengel, Y. A., & Cimbala, J. M. (2004). *Fluid mechanics: Fundamentals and applications*. McGraw-Hill.

Chapra, S. C., & Canale, R. P. (2021). *Numerical methods for engineers* (8th ed.). McGraw-Hill.

Charlesworth, T. E. S., & Banaji, M. R. (2019). Gender in science, technology, engineering, and mathematics: Issues, causes, solutions. *Journal of Neuroscience*, 39(37), 7228–7243. https://doi.org/10.1523/JNEUROSCI.0475-18.2019

Charmaz, K. (2006). *Constructing grounded theory: A practical guide through qualitative analysis*. SAGE Publications.

Chen, J. K., Beraun, J. E., & Carney, T. C. (1999). A corrective smoothed particle method for boundary value problems in heat conduction. *International Journal for Numerical Methods in Engineering, 46*(2), 231–252. https://doi.org/10.1002/(SICI)1097-0207(19990920)46:2<231::AID-NME672>3.0.CO;2-K

Cheryan, S., Ziegler, S. A., Montoya, A. K., & Jiang, L. (2017). Why are some STEM fields more gender balanced than others? *Psychological Bulletin*, 143(1), 1–35. https://doi.org/10.1037/bul0000052

Chi, M. T. H. (1992). Conceptual change within and across ontological categories: Examples from learning and discovery in science. In R. N. Giere (Ed.), *Cognitive models of science* (Vol. 15, pp. 129–186). University of Minnesota Press.

Chi, M. T. H. (1997). Quantifying qualitative analyses of verbal data: A practical guide. *Journal of the Learning Sciences, 6*(3), 271–315. https://doi.org/10.1207/s15327809jls0603_1

Chi, M. T. H. (2009). Active-Constructive-Interactive: A conceptual framework for differentiating learning activities. *Topics in Cognitive Science, 1*(1), 73–105. https://doi.org/10.1111/j.1756-8765.2008.01005.x

Chin, C., & Brown, D. E. (2000). Learning in science: A comparison of deep and surface approaches. *Journal of Research in Science Teaching, 37*(2), 109–138. https://doi.org/10.1002/(SICI)1098-2736(200002)37:2<109::AID-TEA3>3.0.CO;2-7

Chomsky, N. (1967). Review of Skinner's *Verbal Behaviour*. In L. A. Jakobovits & M. S. Miron (Eds.), *Readings in the psychology of language*. Prentice Hall.

Chorin, A. J., & Marsden, J. E. (2000). *A mathematical introduction to fluid mechanics* (4th ed.). Springer.

Chung, T. J. (2002). *Computational fluid dynamics*. Cambridge University Press.

Clarke, J. B., Hastie, J. W., Kihlborg, L. H. E., Metselaar, R., & Thackeray, M. M. (1994). Definitions of terms relating to phase transitions of the solid state (IUPAC Recommendations 1994). *Pure and Applied Chemistry, 66*(3), 577–594. https://doi.org/10.1351/pac199466030577

Claro, S., Paunesku, D., & Dweck, C. S. (2016). Growth mindset tempers the effects of poverty on academic achievement. *Proceedings of the National Academy of Sciences, 113*(31), 8664–8668. https://doi.org/10.1073/pnas.1608207113

Clement, J. (1982). Students' preconceptions in introductory mechanics. *American Journal of Physics, 50*(1), 66–71. https://doi.org/10.1119/1.12989

Clement, J. (2000). Model based learning as a key research area for science education. *International Journal of Science Education, 22*(9), 1041–1053. https://doi.org/10.1080/095006900416901

Cohen, L., Manion, L., & Morrison, K. (2018). *Research methods in education* (8th ed.). Routledge. https://doi.org/10.4324/9781315456539

Colagrossi, A., & Landrini, M. (2003). Numerical simulation of interfacial flows by smoothed particle hydrodynamics. *Journal of Computational Physics, 191*(2), 448–475. https://doi.org/10.1016/S0021-9991(03)00324-3

Colburn, A. (2000). An inquiry primer. *Science Scope, 23*(6), 42–44. https://www.jstor.org/stable/43180086

Cole, R. H. (1948). *Underwater explosions*. Princeton University Press. https://doi.org/10.5962/bhl.title.48411

Collaborative for Academic, Social, and Emotional Learning (CASEL). (2003). *Safe and sound: An educational leader's guide to evidence-based social and emotional learning (SEL) programs.* Collaborative for Academic, Social, and Emotional Learning.

Conosciamo Insieme. (2016, March 10). *Tensione superficiale* [Figure]. Conosciamo Insieme. https://conosciamoinsieme.wordpress.com/2016/03/10/tensione-superficiale/

Continuous Learning Institute. (2025). *The 5E learning cycle* [Figure]. Continuous Learning Institute. https://www.continuous-learning-institute.com/blog/the-5e-learning-cycle

Craik, F. I. M., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior, 11*(6), 671–684. https://doi.org/10.1016/s0022-5371(72)80001-x

Craik, K. J. W. (1948). Theory of the human operator in control systems. *British Journal of Psychology, General Section, 38*(3), 142–148. https://doi.org/10.1111/j.2044-8295.1948.tb01149.x

Crawford, B. A. (2014). From inquiry to scientific practices in the science classroom. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of research on science education* (Vol. II, 1st ed.). Routledge. https://doi.org/10.4324/9780203097267

Creswell, J. W., & Plano Clark, V. L. (2017). *Designing and conducting mixed methods research* (3rd ed.). SAGE Publications.

Creswell, J. W., & Poth, C. N. (2018). *Qualitative inquiry and research design: Choosing among five approaches* (4th ed.). SAGE Publications.

Cumming, G. (2013). The new statistics: Why and how. *Psychological Science, 25*(1), 7–29. https://doi.org/10.1177/0956797613504966

Danziger, K. (1990). *Constructing the subject: Historical origins of psychological research*. Cambridge University Press. https://doi.org/10.1017/CBO9780511524059

Das, A. K., & Das, P. K. (2010). Equilibrium shape and contact angle of sessile drops of different volumes – Computation by SPH and its further improvement by DI.

Chemical Engineering Science, 65(13), 4027–4037. https://doi.org/10.1016/j.ces.2010.03.043

De Gennes, P. G. (1985). Wetting: statics and dynamics. *Reviews of Modern Physics, 57*(3), 827–863. https://doi.org/10.1103/RevModPhys.57.827

De Gennes, P. G., Brochard-Wyart, F., & Quéré, D. (2004). *Capillarity and wetting phenomena: drops, bubbles, pearls, waves*. Springer New York. https://doi.org/10.1007/978-0-387-21656-0

Deci, E. L., & Ryan, R. M. (1985). *Intrinsic motivation and self-determination in human behavior*. Springer Science+Business Media. https://doi.org/10.1007/978-1-4899-2271-7

Deci, E. L., & Ryan, R. M. (2000). The "what" and "why" of goal pursuits: human needs and the self-determination of behavior. *Psychological Inquiry*, *11*(4), 227–268. https://doi.org/10.1207/S15327965PLI1104_01

Dehnen, W., & Aly, H. (2012). Improving convergence in smoothed particle hydrodynamics simulations without pairing instability. *Monthly Notices of the Royal Astronomical Society, 425*(2), 1068–1082. https://doi.org/10.1111/j.1365-2966.2012.21439.x

Del Barco, B. L., Castaño, E. F., Lázaro, S. M., & Gallego, D. I. (2015). Habilidades sociales en equipos de aprendizaje cooperativo en el contexto universitario. *Behavioral Psychology, 23*(2), 191–214.

Denzin, N. K., & Lincoln, Y. S. (Eds.). (2018). *The SAGE handbook of qualitative research* (5th ed.). SAGE Publications.

DeVellis, R. F. (2016). *Scale development: Theory and applications* (4th ed.). SAGE Publications.

Dewey, J. (1976). *Experience and education*. Macmillan.

Dillon, J. (2008). *A review of the research on practical work in school science*. King's College London.

DiPerna, J. C., & Elliott, S. N. (2000). *Academic Competence Evaluation Scales*. APA PsycTests. https://doi.org/10.1037/t14965-000

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10*(2–3), 105–225. https://doi.org/10.1080/07370008.1985.9649008

diSessa, A. A. (2004). Metarepresentation: Native competence and targets for instruction. *Cognition and Instruction, 22*(3), 293–331. https://doi.org/10.1207/s1532690xci2203_2 diSessa, A. A. (2014). A history of conceptual change research: Threads and fault lines. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (2nd ed.). Cambridge University Press.

Doran, R. L. (1972). Misconceptions of selected science concepts held by elementary school students. *Journal of Research in Science Teaching, 9*(2), 127–137. https://doi.org/10.1002/tea.3660090204

Driver, R. (1983). *The pupil as scientist?* Open University Press.

Driver, R., & Easley, J. (1978). Pupils and paradigms: A review of literature related to concept development in adolescent science students. *Studies in Science Education, 5*(1), 61–84. https://doi.org/10.1080/03057267808559857

Driver, R., Asoko, H., Leach, J., Scott, P., & Mortimer, E. (1994). Constructing scientific knowledge in the classroom. *Educational Researcher, 23*(7), 5–12. https://doi.org/10.3102/0013189X023007005

Driver, R., Guesne, E., & Tiberghien, A. (Eds.). (1985). *Children's ideas in science*. Open University Press.

Duan, R. Q., Koshizuka, S., & Oka, Y. (2003). Two-dimensional simulation of drop deformation and breakup around the critical Weber number. *Nuclear Engineering and Design, 225*(1), 37–48. https://doi.org/10.1016/S0029-5493(03)00137-7

Duit, R. (2007). Science education research internationally: Conceptions, research methods, domains of research. *Eurasia Journal of Mathematics, Science and Technology Education, 3*(1), 3–15. https://doi.org/10.12973/ejmste/75369

Duit, R., & Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning. *International Journal of Science Education, 25*(6), 671–688. https://doi.org/10.1080/09500690305016

Duit, R., Gropengießer, H., & Kattmann, U. (2005). Towards science education research that is relevant for improving practice: The model of educational reconstruction. In H. E. Fischer (Ed.), *Developing standards in research on science education*. CRC Press.

Dupré, A. (1869). *Théorie mécanique de la chaleur*. Gauthier-Villars.

Durand, M. (2021). Mechanical approach to surface tension and capillary phenomena. *American Journal of Physics, 89*(3), 261–266. https://doi.org/10.1119/10.0002411

Dweck, C. S. (2006). *Mindset: The new psychology of success*. Random House.

Dweck, C. S., & Yeager, D. S. (2019). Mindsets: A view from two eras. *Perspectives on Psychological Science, 14*(3). https://doi.org/10.1177/1745691618804166

Ebbinghaus, H. (1885). *Über das Gedächtnis: Untersuchungen zur experimentellen Psychologie*. Duncker & Humblot. Retrieved from Library of Congress: https://www.loc.gov/item/e11000616/

Elliott, J. (1991). *Action research for educational change*. Open University Press.

eMathHelp. (n.d.). *Conditions of concavity (convexity) of the function* [Figure]. https://www.emathhelp.net/notes/calculus-1/convex-and-concave-functions/conditions-of-concavity-convexity-of-the-function/

Engle, R. A., & Conant, F. R. (2002). Guiding principles for fostering productive disciplinary engagement: Explaining an emergent argument in a community of learners classroom. *Cognition and Instruction, 20*(4), 399–483. https://doi.org/10.1207/s1532690xci2004_1

Entwistle, N. (1997). Contrasting perspectives on learning. In F. Marton, D. Hounsell, & N. Entwistle (Eds.), *The experience of learning: Implications for teaching and studying in higher education* (3rd ed., Internet version). University of Edinburgh, Centre for Teaching, Learning and Assessment.

Erbil, H. Y. (2006). *Surface chemistry of solid and liquid interfaces*. Wiley-Blackwell. https://doi.org/10.1002/9781444305401

Erickson, F. (1986). Qualitative methods in research on teaching. In M. C. Wittrock (Ed.), *Handbook of research on teaching* (3rd ed., pp. 119–161). Macmillan.

Etkina, E., & Van Heuvelen, A. (2007). Investigative Science Learning Environment – A science process approach to learning physics. *Research-Based Reform of University Physics, 1*(1), 1–48.

Etkina, E., Brookes, D. T., & Planinšič, G. (2019). *Investigative Science Learning Environment: When learning physics mirrors doing physics*. Morgan & Claypool Publishers. https://doi.org/10.1088/2053-2571/ab3ebd

Eustathopoulos, N., Nicholas, M. G., & Drevet, B. (1999). *Wettability at high temperatures* (1st ed., Vol. 3). Elsevier.

Everett, D. H. (1972). Manual of symbols and terminology for physicochemical quantities and units, Appendix II: Definitions, terminology and symbols in colloid and surface chemistry. *Pure and Applied Chemistry, 31*(4), 577–638. https://doi.org/10.1351/pac197231040577

Fals-Borda, O., & Rahman, M. A. (1991). *Action and knowledge: Breaking the monopoly with participatory action research*. Apex Press.

Fereday, J., & Muir-Cochrane, E. (2006). Demonstrating rigor using thematic analysis: A hybrid approach of inductive and deductive coding and theme development. *International Journal of Qualitative Methods, 5*(1), 80–92. https://doi.org/10.1177/160940690600500107

Ferrand, M., Laurence, D. R., Rogers, B. D., Violeau, D., & Kassiotis, C. (2012). Unified semi-analytical wall boundary conditions for inviscid, laminar or turbulent flows in the meshless SPH method. *International Journal for Numerical Methods in Fluids, 71*(4), 446–472. https://doi.org/10.1002/fld.3666

Fetters, M. D., Curry, L. A., & Creswell, J. W. (2013). Achieving integration in mixed methods designs: Principles and practices. *Health Services Research, 48*(6 Pt 2), 2134–2156. https://doi.org/10.1111/1475-6773.12117

Fioravanti, G. (2018). *Tensione superficiale* [Figure]. Università degli Studi dell'Aquila. http://ing.univaq.it/fioravanti/chimica/Corso%20Chimica%20delle%20Superfici%20ed%20Interfasi/Lucidi%20Lezioni/04_Tensione_superficiale_2017_18.pdf

Fisher, K. (2005). Research into identifying effective learning environments. In *Evaluating quality in educational facilities*. OECD Publishing.

Flavell, J. H. (1976). Metacognitive aspects of problem solving. In L. B. Resnick (Ed.), *The nature of intelligence*. Routledge. https://doi.org/10.4324/9781032646527

Flavell, J. H. (1979). Metacognition and cognitive monitoring: A new area of cognitive–developmental inquiry. *American Psychologist, 34*(10), 906–911. https://doi.org/10.1037/0003-066x.34.10.906

Fleming, N. D., & Mills, C. (1992). Not another inventory, rather a catalyst for reflection. *To Improve the Academy, 11*(1), 137–155. https://doi.org/10.1002/j.2334-4822.1992.tb00213.x

Ford, M. (2008). Disciplinary authority and accountability in scientific practice and learning. *Science Education, 92*(3), 404–423. https://doi.org/10.1002/sce.20263

Fosnot, C. T. (Ed.). (2005). *Constructivism: Theory, perspectives, and practice* (2nd ed.). Teachers College Press.

Fraga Filho, C. A. D. (2019). *Smoothed particle hydrodynamics: Fundamentals and basic applications in continuum mechanics*. Springer. https://doi.org/10.1007/978-3-030-00773-7

Fraga Filho, C. A. D., & Aquije Chacaltana, J. T. (2016). Boundary treatment techniques in smoothed particle hydrodynamics: Implementations in fluid and thermal sciences and results analysis. In S. M. Ávila (Ed.), *Proceedings of the XXXVII Iberian Latin American Congress on Computational Methods in Engineering*.

Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H., & Wenderoth, M. P. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences, 111*(23), 8410–8415. https://doi.org/10.1073/pnas.1319030111

Freire, P. (1987). *Pedagogia do oprimido* (17a ed.). Paz e Terra.

Fulk, D. A. (1994). *A numerical analysis of smoothed particle hydrodynamics* (PhD thesis). Air Force Institute of Technology.

Furtak, E. M., Seidel, T., Iverson, H., & Briggs, D. C. (2012). Experimental and quasi-experimental studies of inquiry-based science teaching. *Review of Educational Research, 82*(3), 300–329. https://doi.org/10.3102/0034654312457206

Gao, L., & McCarthy, T. J. (2006). Contact angle hysteresis explained. *Langmuir, 22*(14), 6234–6237. https://doi.org/10.1021/la060254j

Geminard, L. (1987). Martinand (Jean-Louis): Connaître et transformer la matière. *Revue française de pédagogie, 81*, 113–115. https://www.persee.fr/doc/rfp_0556-7807_1987_num_81_1_2434_t1_0113_0000_1

Gentner, D., Loewenstein, J., & Thompson, L. (2003). Learning and transfer: A general role for analogical encoding. *Journal of Educational Psychology, 95*(2), 393–408. https://doi.org/10.1037/0022-0663.95.2.393

Gibbs, J. W. (1928). *The collected works of J. Willard Gibbs: Thermodynamics* (Vol. 1). Longmans, Green and Company.

Gilbert, J. K. (2008). Visualization: An emergent field of practice and enquiry in science education. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (Models and Modeling in Science Education, Vol. 3, pp. 3–24). Springer. https://doi.org/10.1007/978-1-4020-5267-5_1

Gilbert, J. K., & Justi, R. (2016). *Modelling-based teaching in science education*. Springer. https://doi.org/10.1007/978-3-319-29039-3

Gilbert, J. K., & Treagust, D. F. (Eds.). (2009). *Multiple representations in chemical education*. Springer. https://doi.org/10.1007/978-1-4020-8872-8

Gilbert, J. K., Reiner, M., & Nakhleh, M. (Eds.). (2008). *Visualization: theory and practice in science education*. Springer. https://doi.org/10.1007/978-1-4020-5267-5

Gingold, R. A., & Monaghan, J. J. (1977). Smoothed particle hydrodynamics: Theory and application to non-spherical stars. *Monthly Notices of the Royal Astronomical Society, 181*(3), 375–389. https://doi.org/10.1093/mnras/181.3.375

Glasheen, J. W., & McMahon, T. A. (1996). A hydrodynamic model of locomotion in the basilisk lizard. *Nature, 380*, 340–342. https://doi.org/10.1038/380340a0

Gray, V. R. (1965). Surface aspects of wetting and adhesion. *Chemistry & Industry, 23*, 969–978.

Greca, I. M., & Moreira, M. A. (2002). Mental, physical, and mathematical models in the teaching and learning of physics. *Science Education, 86*(1), 106–121. https://doi.org/10.1002/sce.10013

Greeno, J. G., Smith, D. R., & Moore, J. L. (1993). Transfer of situated learning. In D. Detterman & R. Sternberg (Eds.), *Transfer on trial: Intelligence, cognition, and instruction* (pp. 99–167). Ablex Publishing.

Grekov, E. V. (2021). On the cause of surface tension at a liquid–gas interface. *European Journal of Physics*, *42*(5), 055104. https://doi.org/10.1088/1361-6404/ac1443

Grosslight, L., Unger, C., Jay, E., & Smith, C. L. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching, 28*(9), 799–822. https://doi.org/10.1002/tea.3660280907

Guest, G., MacQueen, K. M., & Namey, E. E. (2012). *Applied thematic analysis*. SAGE Publications. https://doi.org/10.4135/9781483384436

Guggenheim, E. A. (1988). *Thermodynamics: An advanced treatment for chemists and physicists* (8th ed.). North-Holland.

Guggenheim, E. A., & Adam, N. K. (1933). The thermodynamics of adsorption at the surface of solutions. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, 139*(837), 218–236. https://doi.org/10.1098/rspa.1933.0015

Hadwin, A. F, Järvelä, S., & Miller, M. (2011). Self-regulated, co-regulated, and socially shared regulation of learning. In B. J. Zimmerman & D. H. Schunk (Eds.), *Handbook of self-regulation of learning and performance* (pp. 65–84). Routledge. https://doi.org/10.4324/9780203839010

Halliday, M. A. K., & Martin, J. R. (1993). *Writing science: Literacy and discursive power*. Falmer Press.

Harrison, A. G., & Treagust, D. F. (2000). A typology of school science models. *International Journal of Science Education, 22*(9), 1011–1026. https://doi.org/10.1080/095006900416884

He, L., Ban, X., Liu, X., & Wang, X. (2015). Individual time stepping for SPH fluids. *Eurographics short papers*, 41–44.

Hernquist, L., & Katz, N. (1989). TREESPH—A unification of SPH with the hierarchical tree method. *The Astrophysical Journal Supplement Series, 70*, 419–446. https://doi.org/10.1086/191344

Hewson, P. W. (1981). A conceptual change approach to learning science. *European Journal of Science Education, 3*(4), 383–396. https://doi.org/10.1080/0140528810304004

Hidi, S., & Renninger, K. A. (2006). The four-phase model of interest development. *Educational Psychologist, 41*(2), 111–127. https://doi.org/10.1207/s15326985ep4102_4

Hirt, C. W., Amsden, A. A., & Cook, J. L. (1974). An arbitrary Lagrangian–Eulerian computing method for all flow speeds. *Journal of Computational Physics, 14*(3), 227–253. https://doi.org/10.1016/0021-9991(74)90051-5

Hmelo-Silver, C. E. (2004). Problem-based learning: What and how do students learn? *Educational Psychology Review, 16*(3), 235–266. https://doi.org/10.1023/B:EDPR.0000034022.16470.F3

Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark (2006). *Educational Psychologist, 42*(2), 99–107. https://doi.org/10.1080/00461520701263368

Hu, D. L., Chan, B., & Bush, J. W. M. (2003). The hydrodynamics of water strider locomotion. *Nature, 424*, 663–666. https://doi.org/10.1038/nature01793

Hull, C. L. (1943). *Principles of behavior: An introduction to behavior theory*. Appleton-Century-Crofts.

Hutchins, E. (1995). *Cognition in the wild*. MIT Press.

Il Piacere di Scoprire. (2018, April 26). *Acqua misteriosamente sospesa nel vuoto..?* [Figure]. Il Piacere di Scoprire. https://www.ilpiacerediscoprire.it/acqua-misteriosamente-sospesa-nel-vuoto/

Immordino-Yang, M. H., & Damasio, A. (2007). We feel, therefore we learn: The relevance of affective and social neuroscience to education. *Mind, Brain, and Education, 1*(1), 3–10. https://doi.org/10.1111/j.1751-228X.2007.00004.x

Ip, S. W., & Toguri, J. M. (1994). The equivalency of surface tension, surface energy and surface free energy. *Journal of Materials Science, 29*(3), 688–692.

Israelachvili, J. N. (2011). *Intermolecular and surface forces* (3rd ed.). Academic Press.

Jamieson, S. (2004). Likert scales: How to (ab)use them. *Medical Education, 38*(12), 1217–1218. https://doi.org/10.1111/j.1365-2929.2004.02012.x

Jasper, J. J. (1972). The surface tension of pure liquid compounds. *Journal of Physical and Chemical Reference Data, 1*(4), 841–1010. https://doi.org/10.1063/1.3253106

Jiménez-Aleixandre, M. P., Bugallo Rodríguez, A., & Duschl, R. A. (2000). "Doing the lesson" or "doing science": Argument in high school genetics. *Science Education, 84*(6), 757–792. https://doi.org/10.1002/1098-237x(200011)84:6<757::aid-sce5>3.0.co;2-f

Johnson, B., & Christensen, L. (2019). *Educational research: Quantitative, qualitative, and mixed approaches* (7th ed.). SAGE Publications.

Johnson, D. W., & Johnson, R. T. (1998). *Learning together and alone: Cooperative, competitive, and individualistic learning* (5th ed.). Pearson.

Johnson, R. B., & Onwuegbuzie, A. J. (2004). Mixed methods research: A research paradigm whose time has come. *Educational Researcher, 33*(7), 14–26. https://doi.org/10.3102/0013189X033007014

Jonassen, D. (1999). Designing constructivist learning environments. In C. M. Reigeluth (Ed.), *Instructional-design theories and models: A new paradigm of instructional theory* (Vol. II). Routledge.

Jonassen, D. H. (1991). Objectivism versus constructivism: Do we need a new philosophical paradigm? *Educational Technology Research and Development, 39*(3), 5–14. https://doi.org/10.1007/BF02296434

Jurin, J. (1718). II. An account of some experiments shown before the Royal Society; with an enquiry into the cause of the ascent and suspension of water in capillary tubes. *Philosophical Transactions of the Royal Society of London*. 30(355), 739–747. http://doi.org/10.1098/rstl.1717.0026

Kahlweit, M. (1975). Ostwald ripening of precipitates. Advances in Colloid and Interface Science, 5(1), 1-35. https://doi.org/10.1016/0001-8686(75)85001-9

Kattmann, U., Duit, R., Gropengießer, H., & Komorek, M. (1996). Educational reconstruction – bringing together issues of scientific clarification and students' conceptions. In *Annual Meeting of the National Association for Research in Science Teaching (NARST)*, St. Louis, MO.

Kemmis, S., McTaggart, R., & Nixon, R. (2014). *The action research planner*. Springer. https://doi.org/10.1007/978-981-4560-67-2

Kernighan, B. W., & Plauger, P. J. (1976). *Software Tools*. Reading, MA: Addison-Wesley.

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39*(7), 551–578. https://doi.org/10.1002/tea.10036

Komorek, M., & Kattmann, U. (2009). The model of educational reconstruction. In S. Mikelskis-Seifert, U. Ringelband, & M. Brückmann (Eds.), *Four decades of research in science education: From curriculum development to quality improvement*. Waxmann.

Korthagen, F. A. J. (2004). In search of the essence of a good teacher: Towards a more holistic approach in teacher education. *Teaching and Teacher Education, 20*(1), 77–97. https://doi.org/10.1016/j.tate.2003.10.002

Koshizuka, S., Nobe, A., & Oka, Y. (1998). Numerical analysis of breaking waves using the moving particle semi-implicit method. *International Journal for Numerical Methods in Fluids, 26*(7), 751–769. https://doi.org/10.1002/(SICI)1097-0363(19980415)26:7<751::AID-FLD671>3.0.CO;2-C

Kreber, C. (2013). *Authenticity in and through teaching in higher education: The transformative potential of the scholarship of teaching*. Routledge.

Kuhn, T. S. (2012). *The structure of scientific revolutions* (4th ed.). University of Chicago Press.

Láng, G. G. (2015). Basic interfacial thermodynamics and related mathematical background. *ChemTexts*, *1*, 1-17. https://doi.org/10.1007/s40828-015-0015-z

Laplace, P. S. (1808). *Traité De Mécanique Céleste: Supplément au dixième livre du traité de méchanique céleste sur l'action capillaire* (Vol. 6). Duprat. BSB-ID 991098194979707356

Latour, B., & Woolgar, S. (1986). *Laboratory life: The construction of scientific facts*. Princeton University Press.

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge University Press. https://doi.org/10.1017/CBO9780511815355

Leach, J., & Scott, P. (2002). Designing and evaluating science teaching sequences: An approach drawing upon the concept of learning demand and a social constructivist perspective on learning. *Studies in Science Education, 38*(1), 115–142. https://doi.org/10.1080/03057260208560189

Lederman, N. G. (2007). Nature of Science: Past, present, and future. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of Research on Science Education*. Routledge. https://doi.org/10.4324/9780203824696

Leger, L., Erman, M., Guinet-Picard, A. M., Ausserre, D., & Strazielle, C. (1988). Precursor film profiles of spreading liquid drops. *Physical review letters, 60*(23), 2390-2393. https://doi.org/10.1103/PhysRevLett.60.2390

Lehrer, R., & Schauble, L. (2006). Scientific thinking and science literacy. In K. A. Renninger, I. E. Sigel, W. Damon, & R. M. Lerner (Eds.), *Handbook of Child Psychology: Child Psychology in Practice* (6th ed., Vol. 4). John Wiley & Sons, Inc. https://doi.org/10.1002/9780470147658

Lennard-Jones, J. E., & Dent, B. M. (1928). *Cohesion at a crystal surface. Transactions of the Faraday Society, 24,* 92-108. https://doi.org/10.1039/TF9282400092

Leroy, A., Violeau, D., Ferrand, M., & Kassiotis, C. (2014). Unified semi-analytical wall boundary conditions applied to 2-D incompressible SPH. *Journal of Computational Physics, 261*, 106–129. https://doi.org/10.1016/j.jcp.2013.12.035

LeVeque, R. J. (2007). *Finite difference methods for ordinary and partial differential equations: Steady-state and time-dependent problems*. Society for Industrial and Applied Mathematics. https://doi.org/10.1137/1.9780898717839

Levrini, O., Fantini, P., Tasquier, G., Pecori, B., & Levin, M. (2015). Defining and operationalizing appropriation for science learning. *The Journal of the Learning Sciences, 24*(1), 93–136. http://www.jstor.org/stable/43828552

Li, Z., Sun, A., & Zhao, X. (2013). Simulation of water and floating body with SPH method. In Z. Sun & Z. Deng (Eds.), *Proceedings of 2013 Chinese Intelligent Automation Conference* (Lecture Notes in Electrical Engineering, Vol. 255). Springer. https://doi.org/10.1007/978-3-642-38460-8_91

Likert, R. (1932). A technique for the measurement of attitudes. *Archives of Psychology, 22*(140), 1–55.

Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic inquiry*. SAGE Publications.

Linn, M. C. (2005). The knowledge integration perspective on learning and instruction. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 243–264). Cambridge University Press. https://doi.org/10.1017/CBO9780511816833.016

Linn, M. C., & Eylon, B.-S. (2011). *Science learning and instruction: Taking advantage of technology to promote knowledge integration* (1st ed.). Routledge. https://doi.org/10.4324/9780203806524

Liu, G. R., & Liu, M. B. (2003). *Smoothed particle hydrodynamics: A meshfree particle method*. World Scientific. https://doi.org/10.1142/5340

Liu, J., Koshizuka, S., & Oka, Y. (2005). A hybrid particle–mesh method for viscous, incompressible, multiphase flows. *Journal of Computational Physics, 202*(1), 65–93. https://doi.org/10.1016/j.jcp.2004.07.002

Liu, M. B., & Li, S. M. (2016). On the modeling of viscous incompressible flows with smoothed particle hydrodynamics. *Journal of Hydrodynamics, 28*(5), 731–745. https://doi.org/10.1016/S1001-6058(16)60676-5

Liu, M. B., & Liu, G. R. (2010). Smoothed particle hydrodynamics (SPH): An overview and recent developments. *Archives of Computational Methods in Engineering, 17*, 25–76. https://doi.org/10.1007/s11831-010-9040-7

Liu, M. B., Liu, G. R., & Lam, K. Y. (2002). Investigations into water mitigations using a meshless particle method. *Shock Waves, 12*(3), 181–195. https://doi.org/10.1007/s00193-002-0163-0

Liu, M., & Zhang, Z. (2019). Smoothed particle hydrodynamics (SPH) for modeling fluid–structure interactions. *Science China Physics, Mechanics & Astronomy, 62*(8), 1-38. https://doi.org/10.1007/s11433-018-9357-0

Liu, S., Li, S., & Liu, J. (2018). Jurin's law revisited: Exact meniscus shape and column height. *The European Physical Journal E, 41*(3), 1-7. https://doi.org/10.1140/epje/i2018-11648-1

Liu, W. K., Li, S., & Park, H. S. (2022). Eighty years of the finite element method: Birth, evolution, and future. *Archives of Computational Methods in Engineering, 29*, 4431–4453. https://doi.org/10.1007/s11831-022-09740-9

Logan, D. L. (2022). *A first course in the finite element method* (6th ed., Enhanced SI Version). Cengage Learning.

Lombardi, M. M. (2007). Authentic learning for the 21st century: An overview. *EDUCAUSE Learning Initiative*, pp. 1–12.

Loucks-Horsley, S., Stiles, K. E., Mundry, S., Love, N., & Hewson, P. W. (2010). *Designing professional development for teachers of science and mathematics*. Corwin Press. https://doi.org/10.4135/9781452219103

Loughran, J. (2010). *What expert teachers do: Enhancing professional knowledge for classroom practice* (1st ed.). Routledge. https://doi.org/10.4324/9780203851470

Loughran, J. J. (2002). Effective reflective practice: In search of meaning in learning about teaching. *Journal of Teacher Education, 53*(1), 33–43. https://doi.org/10.1177/0022487102053001004

Lucy, L. B. (1977). A numerical approach to the testing of the fission hypothesis. *The Astronomical Journal, 82*(12), 1013–1024. https://doi.org/10.1086/112164

Lyklema, J. (2000). *Fundamentals of interfacial and colloid science Vol III: Liquid-fluid interfaces*. Academic Press.

Lyman, F. T. (1981). The responsive classroom discussion: The inclusion of all students. In A. S. Anderson (Ed.), *Mainstreaming Digest*. University of Maryland Press.

Macià, F., Antuono, M., & Colagrossi, A. (2011). Benefits of using a Wendland kernel for free-surface flows. In *6th ERCOFTAC SPHERIC Workshop on SPH Applications* (Hamburg, Germany, pp. 30–37). Available at: https://core.ac.uk/download/pdf/148662105.pdf

Macià, F., González, L. M., Cercos-Pita, J. L., & Souto-Iglesias, A. (2012). A boundary integral SPH formulation: consistency and applications to ISPH and WCSPH. *Progress of Theoretical Physics, 128*(3), 439–462. https://doi.org/10.1143/PTP.128.439

Magnani, L., & Bertolotti, T. (Eds.). (2017). *Springer handbook of model-based science*. Springer. https://doi.org/10.1007/978-3-319-30526-4

Manikantan, H., & Squires, T. M. (2020). Surfactant dynamics: hidden variables controlling fluid flows. *Journal of Fluid Mechanics*, *892*, P1. doi:10.1017/jfm.2020.170

Marchand, A., Weijs, J. H., Snoeijer, J. H., & Andreotti, B. (2011). Why is surface tension a force parallel to the interface? *American Journal of Physics*, *79*(10), 999-1008. https://doi.org/10.1119/1.3619866

Marmur, A. (1994). Thermodynamic aspects of contact angle hysteresis. *Advances in colloid and interface science, 50*, 121-141. https://doi.org/10.1016/0001-8686(94)80028-6

Marton, F. (1981). Phenomenography—Describing conceptions of the world around us. *Instructional Science, 10*, 177–200. https://doi.org/10.1007/BF00132516

Marton, F. (2015). *Necessary conditions of learning*. Routledge. https://doi.org/10.4324/9781315816876

Marton, F., & Booth, S. (1997). *Learning and awareness* (1st ed.). Routledge. https://doi.org/10.4324/9780203053690

Marton, F., & Säljö, R. (1976). On qualitative differences in learning: I—Outcome and process. *British Journal of Educational Psychology, 46*(1), 4–11. https://doi.org/10.1111/j.2044-8279.1976.tb02980.x

Marton, F., & Tsui, A. B. M. (2004). *Classroom discourse and the space of learning*. Lawrence Erlbaum Associates. https://doi.org/10.4324/9781410609762

Marzano, R. J. (1992). *A different kind of classroom: Teaching with dimensions of learning*. Association for Supervision and Curriculum Development.

Maxwell, J. A. (2013). *Qualitative research design: An interactive approach* (3rd ed.). SAGE Publications.

Mazur, E. (1997). *Peer instruction: A user's manual*. Prentice Hall.

McCaughan, J. B. T. (1987). Capillarity-a lesson in the epistemology of physics. *Physics Education*, *22*(2), 100-106. https://doi.org/10.1088/0031-9120/22/2/005

McCaughan, J. B. T. (1988). Capillarity reply. *Physics Education, 23*(4), 205–206. https://doi.org/10.1088/0031-9120/23/4/105

McCloskey, M. (1983). Naïve theories of motion. In D. Gentner & A. L. Stevens (Eds.), *Mental models*. Erlbaum.

McComas, W. F., Clough, M. P., & Almazroa, H. (2002). The role and character of the nature of science in science education. In W. F. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 3–39). Springer.

Méheut, M., & Psillos, D. (2004). Teaching–learning sequences: Aims and tools for science education research. *International Journal of Science Education, 26*(5), 515–535. https://doi.org/10.1080/0950069032000070306

Mercer, N. (2000). *Words and minds: How we use language to think together* (1st ed.). Routledge. https://doi.org/10.4324/9780203464984

Merrill, M. D. (2002). First principles of instruction. *Educational Technology Research and Development, 50*(3), 43–59. https://doi.org/10.1007/BF02505024

Messick, S. (1995). Validity of psychological assessment: Validation of inferences from persons' responses and performances as scientific inquiry into score meaning. *American Psychologist, 50*(9), 741–749. https://doi.org/10.1037/0003-066X.50.9.741

Mestre, J. P. (Ed.). (2005). *Transfer of learning from a modern multidisciplinary perspective*. Information Age Publishing.

Mezirow, J. (1991). *Transformative dimensions of adult learning*. Jossey-Bass.

Michael, J. (2006). Where's the evidence that active learning works? *Advances in Physiology Education, 30*(4), 159–167. https://doi.org/10.1152/advan.00053.2006

Miles, M. B., Huberman, A. M., & Saldaña, J. (2014). *Qualitative data analysis: A methods sourcebook* (3rd ed.). SAGE Publications.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review, 63*(2), 81–97. https://doi.org/10.1037/h0043158

MIUR – Ministero dell'Istruzione, dell'Università e della Ricerca. (2019). *Linee guida sui percorsi per le competenze trasversali e per l'orientamento*. Roma: MIUR. https://www.mim.gov.it/-/linee-guida-dei-percorsi-per-le-competenze-trasversali-e-per-l-orientamento

Monaghan, J. J. (1982). Why particle methods work. *SIAM Journal on Scientific and Statistical Computing, 3*(4), 422–433. https://doi.org/10.1137/0903027

Monaghan, J. J. (1985). Particle methods for hydrodynamics. *Computer Physics Reports, 3*(2), 71–124. https://doi.org/10.1016/0167-7977(85)90010-3

Monaghan, J. J. (1992). Smoothed particle hydrodynamics. *Annual Review of Astronomy and Astrophysics, 30*, 543–574. https://doi.org/10.1146/annurev.aa.30.090192.002551

Monaghan, J. J. (1994). Simulating free surface flows with SPH. *Journal of Computational Physics, 110*(2), 399–406. https://doi.org/10.1006/jcph.1994.1034

Monaghan, J. J. (2005). Smoothed particle hydrodynamics. *Reports on Progress in Physics, 68*(8), 1703–1759. https://doi.org/10.1088/0034-4885/68/8/R01

Monaghan, J. J., & Lattanzio, J. C. (1985). A refined particle method for astrophysical problems. *Astronomy and Astrophysics, 149*, 135–143. https://ui.adsabs.harvard.edu/abs/1985A&A...149..135M/abstract

Morris, J. P., Fox, P. J., & Zhu, Y. (1997). Modeling low Reynolds number incompressible flows using SPH. *Journal of Computational Physics, 136*(1), 214–226. https://doi.org/10.1006/jcph.1997.5776

Mortari, L., & Ghirotto, L. (2019). *Metodi per la ricerca educativa*. Carocci.

Mortimer, E. F., & Scott, P. H. (2003). *Meaning making in secondary science classrooms*. Open University Press.

Myers, D. (2005). *Surfactant science and technology*. (3rd ed.). John Wiley & Sons. https://doi.org/10.1002/047174607X

NASA. (2015, October 9). *4K Video of Colorful Liquid in Space* [Figure]. YouTube. https://www.youtube.com/watch?v=bKk_7NIKY3Y

National Research Council. (1996). *National science education standards*. The National Academies Press. https://doi.org/10.17226/4962

National Research Council. (2000). *How people learn: Brain, mind, experience, and school* (Expanded ed.). The National Academies Press. https://doi.org/10.17226/9853

National Research Council. (2007). *Taking science to school: Learning and teaching science in grades K–8*. The National Academies Press. https://doi.org/10.17226/11625

Neisser, U. (2014). *Cognitive psychology: Classic edition* (1st ed.). Psychology Press. https://doi.org/10.4324/9781315736174

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. National Academies Press.

Noddings, N. (2005). *The challenge to care in schools: An alternative approach to education*. Teachers College Press.

Nowell, L. S., Norris, J. M., White, D. E., & Moules, N. J. (2017). Thematic analysis: Striving to meet the trustworthiness criteria. *International Journal of Qualitative Methods, 16*(1). https://doi.org/10.1177/1609406917733847

OECD. (2019). *OECD future of education and skills 2030: OECD learning compass 2030. A series of concept notes*. OECD.

Oppenheim, A. N. (1992). *Questionnaire design, interviewing and attitude measurement*. Continuum.

Osborne, J. (2014). Teaching scientific practices: Meeting the challenge of change. *Journal of Science Teacher Education, 25*(2), 177–196. https://doi.org/10.1007/s10972-014-9384-1

Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What "ideas-about-science" should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching, 40*(7), 692–720. https://doi.org/10.1002/tea.10105

Osborne, J., Erduran, S., & Simon, S. (2004). Enhancing the quality of argumentation in school science. *Journal of Research in Science Teaching, 41*(10), 994–1020. https://doi.org/10.1002/tea.20035

Pajares, F. (1996). Self-efficacy beliefs in academic settings. *Review of Educational Research, 66*(4), 543–578. https://doi.org/10.3102/00346543066004543

Pashler, H., McDaniel, M., Rohrer, D., & Bjork, R. (2008). Learning styles: Concepts and evidence. *Psychological Science in the Public Interest, 9*(3), 105–119. https://doi.org/10.1111/j.1539-6053.2009.01038.x

Patton, M. Q. (1999). Enhancing the quality and credibility of qualitative analysis. *Health Services Research, 34*(5 Pt 2), 1189–1208.

Patton, M. Q. (2015). *Qualitative research & evaluation methods: Integrating theory and practice* (4th ed.). SAGE Publications.

Pavlov, P. I. (2010). Conditioned reflexes: An investigation of the physiological activity of the cerebral cortex. *Annals of Neurosciences, 17*(3), 136–141. https://doi.org/10.5214/ans.0972-7531.1017309

Pekrun, R. (2006). The control-value theory of achievement emotions: assumptions, corollaries, and implications for educational research and practice. *Educational Psychology Review*, *18*(4), 315–341. https://doi.org/10.1007/s10648-006-9029-9

Petrucci, R. H., Herring, F. G., Madura, J. D., & Bissonnette, C. (2011). *General chemistry: principles and modern applications* (10th ed.). Pearson Canada.

Piaget, J. (1952). *The origins of intelligence in children*. W. W. Norton & Company. https://doi.org/10.1037/11494-000

Piaget, J. (1959). *The language and thought of the child*. Routledge & Kegan Paul.

Piaget, J. (1971). *The child's conception of the world*. Routledge & Kegan Paul.

Piaget, J. (1977). *Psychology and epistemology: Towards a theory of knowledge*. Penguin Books.

Pintrich, P. R., Marx, R. W., & Boyle, R. A. (1993). Beyond Cold Conceptual Change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change. *Review of Educational Research, 63*(2), 167–199. https://doi.org/10.3102/00346543063002167

Podolefsky, N. S., Moore, E. B., & Perkins, K. K. (2013). Implicit scaffolding in interactive simulations: Design strategies to support multiple educational goals. *arXiv*. https://doi.org/10.48550/arXiv.1306.6544

Pope, S. B. (2000). *Turbulent flows*. Cambridge University Press. https://doi.org/10.1017/CBO9780511840531

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*(2), 211–227. https://doi.org/10.1002/sce.3730660207

Prausnitz, J.M., Lichtenthaler, R.N., & Azevedo E.G. (1999) *Molecular thermodynamics of fluid-phase equilibria* (3rd ed). Prentice Hall Inc.

Price, J. F. (2006). Lagrangian and Eulerian representations of fluid flow: Kinematics and the equations of motion. *MIT OpenCourseWare*. (pp. 1–99).

Prince, M. (2004). Does active learning work? A review of the research. *Journal of Engineering Education, 93*(3), 223–231. https://doi.org/10.1002/j.2168-9830.2004.tb00809.x

Prince, M. J., & Felder, R. M. (2006). Inductive teaching and learning methods: Definitions, comparisons, and research bases. *Journal of Engineering Education*, 95(2), 123–138. https://doi.org/10.1002/j.2168-9830.2006.tb00884.x

ProblemDestroyer. (2022, February 25). *What's the fault in the logic I am thinking for not balancing of a needle and any blade etc. on water?* [Figure]. Physics Stack Exchange. https://physics.stackexchange.com/questions/696528/whats-the-fault-in-the-logic-i-am-thinking-for-not-balancing-of-a-needle-and-any

Prosser, M., & Trigwell, K. (1999). *Understanding learning and teaching: The experience in higher education*. SRHE & Open University Press.

Punch, K. F., & Oancea, A. (2014). *Introduction to research methods in education* (2nd ed.). SAGE Publications.

Quéré, D. (2008). Wetting and roughness. *Annu. Rev. Mater. Res.*, *38*(1), 71-99. https://doi.org/10.1146/annurev.matsci.38.060407.132434

Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., … Soloway, E. (2004). A scaffolding design framework for software to support science inquiry. *Journal of the Learning Sciences*, 13(3), 337–386. https://doi.org/10.1207/s15327809jls1303_4

Radke, C. J. (2015). Gibbs adsorption equation for planar fluid–fluid interfaces: Invariant formalism. *Advances in colloid and interface science, 222*, 600-614. https://doi.org/10.1016/j.cis.2014.01.001

Randles, P. W., & Libersky, L. D. (1996). Smoothed particle hydrodynamics: Some recent improvements and applications. *Computer Methods in Applied Mechanics and Engineering, 139*(1–4), 375–408. https://doi.org/10.1016/S0045-7825(96)01090-0

Rapp, B. E. (2016). *Microfluidics: modeling, mechanics and mathematics*. William Andrew.

Rayleigh. (1899). *XXXVI. Investigations in Capillarity:—The size of drops.—The liberation of gas from supersaturated solutions.—Colliding jets.—The tension of contaminated water-surfaces. The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 48*(293), 321–337. https://doi.org/10.1080/14786449908621342

Reddy, J. N. (2006). *An introduction to the finite element method* (3rd ed.). McGraw-Hill.

Redish, E. F., & Smith, K. A. (2008). Looking beyond content: Skill development for engineers. *Journal of Engineering Education, 97*(3), 295–307. https://doi.org/10.1002/j.2168-9830.2008.tb00980.x

Reif, F. (1965). *Fundamentals of statistical and thermal physics*. Waveland Press.

Reiser, B. J. (2004). Scaffolding complex learning: The mechanisms of structuring and problematizing student work. *Journal of the Learning Sciences*, 13(3), 273–304. https://doi.org/10.1207/s15327809jls1303_2

Renninger, K. A., & Hidi, S. (2015). *The power of interest for motivation and engagement*. Routledge. https://doi.org/10.4324/9781315771045

Ritchhart, R. (2002). *Intellectual character: What it is, why it matters, and how to get it*. Jossey-Bass.

Rocard, M., Csermely, P., Jorde, D., Lenzen, D., Walberg-Henriksson, H., & Hemmo, V. (2007). *Science education now: A renewed pedagogy for the future of Europe*. Office for Official Publications of the European Communities.

Rodríguez-Valverde, M. Á., & Tirado Miranda, M. (2011). *Derivation of Jurin's law revisited. European Journal of Physics, 32*(1), 49–54. https://doi.org/10.1088/0143-0807/32/1/005

Rogers, C. R., & Freiberg, H. J. (1994). *Freedom to learn* (3rd ed.). Merrill Publishing.

Rosen, M. J., & Kunjappu, J. T. (2012). *Surfactants and interfacial phenomena*. John Wiley & Sons. (4th ed.). https://doi.org/10.1002/9781118228920

Rosenshine, B. (1987). Explicit teaching and teacher training. *Journal of Teacher Education, 38*(3), 34–36. https://doi.org/10.1177/002248718703800308

Rowlinson, J. S., & Widom, B. (2003). *Molecular Theory of Capillarity*. Dover Publications; Reprint edition.

Rusanov, A. I. (1996). Thermodynamics of solid surfaces. *Surface Science Reports*, *23*(6-8), 173-247. https://doi.org/10.1016/0167-5729(95)00007-0

Ryan, R. M., & Deci, E. L. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *American Psychologist*, 55(1), 68–78. https://doi.org/10.1037/0003-066X.55.1.68

Ryan, R. M., & Deci, E. L. (2017). *Self-determination theory: Basic psychological needs in motivation, development, and wellness*. Guilford Press. https://doi.org/10.1521/978.14625/28806

Saldaña, J. (2015). *The coding manual for qualitative researchers* (3rd ed.). SAGE Publications.

Schön, D. A. (1992). *The reflective practitioner: How professionals think in action*. Routledge. https://doi.org/10.4324/9781315237473

Schrader, M. E. (1995). Young-Dupre revisited. *Langmuir, 11*(9), 3585-3589. https://doi.org/10.1021/la00009a049

Schraw, G., & Dennison, R. S. (1994). Assessing metacognitive awareness. *Contemporary Educational Psychology, 19*(4), 460–475. https://doi.org/10.1006/ceps.1994.1033

Schunk, D. H. (2012). *Learning theories: An educational perspective* (6th ed.). Pearson.

Schunk, D. H., & DiBenedetto, M. K. (2020). Motivation and social cognitive theory. *Contemporary Educational Psychology*, 60, Article 101832. https://doi.org/10.1016/j.cedpsych.2019.101832

Schwandt, T. A. (2000). Three epistemological stances for qualitative inquiry. In N. K. Denzin & Y. S. Lincoln (Eds.), *Handbook of qualitative research* (2nd ed., pp. 189–213). SAGE Publications.

Schwartz, D. L., Bransford, J. D., & Sears, D. (2005). Efficiency and innovation in transfer. In J. Mestre (Ed.), *Transfer of learning from a modern multidisciplinary perspective* (pp. 1–51). IAP.

Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Achér, A., Fortus, D., … Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching, 46*(6), 632–654. https://doi.org/10.1002/tea.20311

Scott, P. H., Asoko, H. M., & Driver, R. H. (1991). Teaching for conceptual change: A review of strategies. In A. Tiberghien, E. L. Jossem, & J. Barojas (Eds.), *Connecting research in physics education with teacher education* (Vol. 1). Zenodo. https://doi.org/10.5281/zenodo.6463545

Sechenov, I. M. (1965). *Reflexes of the brain: An attempt to establish the physiological basis of psychological processes* (S. Belsky, Trans.). MIT Press.

Sfard, A. (1998). On two metaphors for learning and the dangers of choosing just one. *Educational Researcher, 27*(2), 4–13. https://doi.org/10.3102/0013189X027002004

Shadloo, M. S. (2013). *Improved multiphase smoothed particle hydrodynamics* (PhD thesis). Sabanci University.

Shen, H., Brousseau, E., & Kulasegaram, S. (2023). Assessment and validation of SPH modeling for nano-indentation. *Computational Particle Mechanics, 10*, 603–613. https://doi.org/10.1007/s40571-022-00514-5

Shen, Y., Couzis, A., Koplik, J., Maldarelli, C., & Tomassone, M. S. (2005). Molecular dynamics study of the influence of surfactant structure on surfactant-facilitated spreading of droplets on solid surfaces. *Langmuir: the ACS journal of surfaces and colloids*, *21*(26), 12160–12170. https://doi.org/10.1021/la051354c

Sherin, B. L. (2001). How students understand physics equations. *Cognition and Instruction, 19*(4), 479–541. https://doi.org/10.1207/s1532690xci1904_3

Shi, X. D., Brenner, M. P., & Nagel, S. R. (1994). A cascade of structure in a drop falling from a faucet. *Science, 265*(5169), 219–222. https://doi.org/10.1126/science.265.5169.219

Shibata, K., Koshizuka, S., Matsunaga, T., & Masaie, I. (2017). The overlapping particle technique for multi-resolution simulation of particle methods. *Computer Methods in Applied Mechanics and Engineering, 325*, 434–462. https://doi.org/10.1016/j.cma.2017.06.030

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15*(2), 4–14. https://doi.org/10.3102/0013189X015002004

Siqveland, L. M., & Skjæveland, S. M. (2021). Derivations of the Young-Laplace equation. *Capillarity*, *4*(2), 23-30.

Skinner, B. F. (1965). *Science and human behavior*. Free Press.

Skinner, B. F. (1991). *The behavior of organisms: An experimental analysis*. B. F. Skinner Foundation.

Slavin, R. E. (2018). *Educational psychology: Theory and practice* (12th ed.). Pearson Education.

Smith III, J. P., diSessa, A. A., & Roschelle, J. (1994). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *Journal of the Learning Sciences, 3*(2), 115–163. https://doi.org/10.1207/s15327809jls0302_1

Smolianski, A. (2001). *Numerical modeling of two-fluid interfacial flows* (PhD thesis). University of Jyväskylä.

Sophocleous, M. (2010). Understanding and explaining surface tension and capillarity: an introduction to fundamental physics for water professionals. *Hydrogeology journal*, *18*, 811-821. https://doi.org/10.1007/s10040-009-0565-5

Speight, J. G. (2018). *Natural gas: a basic handbook*. Gulf Professional Publishing. (2nd ed.) https://doi.org/10.1016/C2015-0-02190-6

Sperandeo-Mineo, R. M., Fazio, C., & Tarantino, G. (2006). Pedagogical content knowledge development and pre-service physics teacher education: A case study. *Research in Science Education, 36*, 235–268. https://doi.org/10.1007/s11165-005-9004-3

Springel, V. (2005). The cosmological simulation code GADGET-2. *Monthly Notices of the Royal Astronomical Society, 364*(4), 1105–1134. https://doi.org/10.1111/j.1365-2966.2005.09655.x

Stone, A. (2013). *The theory of intermolecular forces*. (2nd ed.). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199672394.001.0001

Strike, K. A., & Posner, G. J. (1992). A revisionist theory of conceptual change. In R. A. Duschl & R. J. Hamilton (Eds.), *Philosophy of science, cognitive psychology, and educational theory and practice*. SUNY Press.

Strikwerda, J. C. (2004). *Finite difference schemes and partial differential equations* (2nd ed.). Society for Industrial and Applied Mathematics. https://doi.org/10.1137/1.9780898717938

Tabak, I. (2004). Synergy: A complement to emerging patterns of distributed scaffolding. *Journal of the Learning Sciences*, 13(3), 305–335. https://doi.org/10.1207/s15327809jls1303_3

Taber, K. S. (2009). *Progressing science education: Constructing the scientific research programme into the contingent nature of learning science*. Springer. https://doi.org/10.1007/978-90-481-2431-2

Takeda, H., Miyama, S. M., & Sekiya, M. (1994). Numerical simulation of viscous flow by smoothed particle hydrodynamics. *Progress of Theoretical Physics, 92*(5), 939–960. https://doi.org/10.1143/ptp/92.5.939

Tam, M. (2000). Constructivism, instructional design, and technology: Implications for transforming distance learning. *Journal of Educational Technology & Society, 3*(2), 50–60. Retrieved from http://www.jstor.org/stable/jeductechsoci.3.2.50

Tartakovsky, A. M., & Meakin, P. (2006). Pore-scale modeling of immiscible and miscible fluid flows using smoothed particle hydrodynamics. *Advances in Water Resources, 29*(10), 1464–1478. https://doi.org/10.1016/j.advwatres.2005.11.014

Tartakovsky, A., & Meakin, P. (2005). Modeling of surface tension and contact angles with smoothed particle hydrodynamics. *Physical Review E, 72*(2), 026301. https://doi.org/10.1103/PhysRevE.72.026301

Tashakkori, A., & Teddlie, C. (2010). *SAGE handbook of mixed methods in social & behavioral research*. SAGE Publications. https://doi.org/10.4135/9781506335193

Termini, G. (2023). *Pedagogical approaches to surface phenomena in liquids: Investigation-based laboratory and modelling activities to improve students' learning* [Unpublished doctoral dissertation]. University of Palermo, Palermo, Italy.

Textile Today. (2018, July 30). *Covestro unveils waterproof and breathable coating* [Figure]. Textile Today. https://textiletoday.com.bd/covestro-unveils-waterproof-breathable-coating

Thoburn, W. C. (1977). The origin of surface tension in liquids. *The Physics Teacher*, *15*(4), 234-236. https://doi.org/10.1119/1.2339608

Thorndike, E. L. (1898). Animal intelligence: An experimental study of the associative processes in animals. *Psychological Review: Monograph Supplements, 2*(4), i–109. https://doi.org/10.1037/h0092987

Thorndike, E. L. (1927). The law of effect. *The American Journal of Psychology, 39*(1–4), 212–222. https://doi.org/10.2307/1415413

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review, 55*(4), 189–208. https://doi.org/10.1037/h0061626

Toulmin, S. (1972). *Human understanding. Volume 1: General introduction and part 1. The collective use and evolution of concepts*. Clarendon Press: Oxford University Press.

Trasatti, S., & Parsons, R. (1986). Interphases in systems of conducting phases (Recommendations 1985). *Pure and Applied Chemistry*, *58*(3), 437-454. http://dx.doi.org/10.1351/pac198658030437

Treagust, D. F. (2006). Diagnostic assessment in science as a means to improving teaching, learning, and retention. In *Proceedings of the Australian Conference on Science and Mathematics Education (ACSME)*.

Treagust, D. F., Chittleborough, G., & Mamiala, T. L. (2002). Students' understanding of the role of scientific models in learning science. *International Journal of Science Education, 24*(4), 357–368. https://doi.org/10.1080/09500690110066485

Tropea, C., Yarin, A. L., & Foss, J. F. (Eds.). (2007). *Springer handbook of experimental fluid mechanics*. Springer. https://doi.org/10.1007/978-3-540-30299-5

Tulczyjew, W. M. (1977). The legendre transformation. In *Annales de l'institut Henri Poincaré. Section A, Physique Théorique*, 27(1), 101-114.

Vafaei, S., & Podowski, M. Z. (2005). Analysis of the relationship between liquid droplet size and contact angle. *Advances in Colloid and Interface Science, 113*(2–3), 133–146. https://doi.org/10.1016/j.cis.2005.03.001

Van Liedekerke, P., Smeets, B., Odenthal, T., Tijskens, E., & Ramon, H. (2013). Solving microscopic flow problems using Stokes equations in SPH. *Computer Physics Communications, 184*(7), 1686–1696. https://doi.org/10.1016/j.cpc.2013.02.013

Veenman, M. V. J., Van Hout-Wolters, B. H. A. M., & Afflerbach, P. (2006). Metacognition and learning: Conceptual and methodological considerations. *Metacognition and Learning, 1*(1), 3–14. https://doi.org/10.1007/s11409-006-6893-0

Vermunt, J. D., & Verloop, N. (1999). Congruence and friction between learning and teaching. *Learning and Instruction, 9*(3), 257–280. https://doi.org/10.1016/s0959-4752(98)00028-0

Viennot, L. (1979). Spontaneous reasoning in elementary dynamics. *European Journal of Science Education, 1*(2), 205–221. https://doi.org/10.1080/0140528790010209

Viennot, L. (2001). *Reasoning in physics: The part of common sense*. Springer. https://doi.org/10.1007/0-306-47636-3

von Glasersfeld, E. (1995). *Radical constructivism: A way of knowing and learning*. Falmer Press.

VonNeumann, J., & Richtmyer, R. D. (1950). A method for the numerical calculation of hydrodynamic shocks. *Journal of Applied Physics, 21*(3), 232–237. https://doi.org/10.1063/1.1699639

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. *Learning and Instruction, 4*(1), 45–69. https://doi.org/10.1016/0959-4752(94)90018-3

Vosniadou, S. (Ed.). (2008). *International handbook of research on conceptual change* (1st ed.). Routledge. https://doi.org/10.4324/9780203874813

Vosniadou, S., & Brewer, W. F. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology, 24*(4), 535–585. https://doi.org/10.1016/0010-0285(92)90018-w

Vosniadou, S., Vamvakoussi, X., & Skopeliti, I. (2008). The framework theory approach to the problem of conceptual change. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (1st ed.). Routledge.

Vygotsky, L. S. (1978). *Mind in society: Development of higher psychological processes* (M. Cole, V. John-Steiner, S. Scribner, & E. Souberman, Eds.). Harvard University Press.

Wang, B., Zhang, Y., Shi, L., Li, J., & Guo, Z. (2012). Advances in the theory of superhydrophobic surfaces. *Journal of Materials Chemistry*, *22*(38), 20112-20127.

Wang, M. T., & Degol, J. L. (2017). Gender gap in science, technology, engineering, and mathematics (STEM): Current knowledge, implications for practice, policy, and future directions. *Educational Psychology Review*, 29(1), 119–140. https://doi.org/10.1007/s10648-015-9355-x

Watson, J. B. (1913). Psychology as the behaviorist views it. *Psychological Review, 20*(2), 158–177. https://doi.org/10.1037/h0074428

Wellington, J. (2015). *Educational research: Contemporary issues and practical approaches* (2nd ed.). Bloomsbury Academic.

Wendland, H. (1995). Piecewise polynomial, positive definite and compactly supported radial functions of minimal degree. *Advances in Computational Mathematics, 4*, 389–396. https://doi.org/10.1007/BF02123482

Wendt, J. F. (Ed.). (2008). *Computational fluid dynamics: An introduction*. Springer. https://doi.org/10.1007/978-3-540-85056-4

Wenger, E. (1998). *Communities of practice: Learning, meaning, and identity*. Cambridge University Press. https://doi.org/10.1017/CBO9780511803932

Wenger, E., McDermott, R., & Snyder, W. M. (2002). *Cultivating communities of practice: A guide to managing knowledge*. Harvard Business Press.

White, B. Y., & Frederiksen, J. R. (1998). Inquiry, modeling, and metacognition: Making science accessible to all students. *Cognition and Instruction, 16*(1), 3–118. https://doi.org/10.1207/s1532690xci1601_2

Wilson, C. D., Taylor, J. A., Kowalski, S. M., & Carlson, J. (2009). The relative effects and equity of inquiry-based and commonplace science teaching on students' knowledge, reasoning, and argumentation. *Journal of Research in Science Teaching, 47*(3), 276–301. https://doi.org/10.1002/tea.20329

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, 92(5), 941–967. https://doi.org/10.1002/sce.20259

Wohlfarth, C., & Lechner, M. D. (2016). *Surface Tension of Pure Liquids and Binary Liquid Mixtures: Supplement to Volume IV/24*. Springer. https://doi.org/10.1007/978-3-662-48336-7

Xu, H., Shirvanyants, D., Beers, K., Matyjaszewski, K., Rubinstein, F. M., & Sheiko, S. S. (2004). Molecular motion in a spreading precursor film. *Physical review letters, 93*(20), 206103. https://doi.org/10.1103/PhysRevLett.93.206103

Yeganehdoust, F., Yaghoubi, M., Emdad, H., & Ordoubadi, M. (2016). Numerical study of multiphase droplet dynamics and contact angles by smoothed particle hydrodynamics. *Applied Mathematical Modelling, 40*(19–20), 8493–8512. https://doi.org/10.1016/j.apm.2016.05.021

Yoo, H. S., Choi, H. Y., Kim, T. H., & Kim, E. S. (2022). Effect of wettability on the water entry of spherical projectiles: Numerical analysis using smoothed particle hydrodynamics. *AIP Advances, 12*(3), 035327. https://doi.org/10.1063/5.0072710

Young, T. (1805). III. An essay on the cohesion of fluids. *Philosophical transactions of the royal society of London*, (95), 65-87. https://doi.org/10.1098/rstl.1805.0005

Zeichner, K. M., & Liston, D. P. (2013). *Reflective teaching: An introduction* (2nd ed.). Routledge. https://doi.org/10.4324/9780203771136

Zhang, M. (2010). Simulation of surface tension in 2D and 3D with smoothed particle hydrodynamics method. *Journal of Computational Physics, 229*(19), 7238–7259. https://doi.org/10.1016/j.jcp.2010.06.010

Zhang, M., Zhang, S., Zhang, H., & Zheng, L. (2012). Simulation of surface-tension-driven interfacial flow with smoothed particle hydrodynamics method. *Computers & Fluids, 59*, 61–71. https://doi.org/10.1016/j.compfluid.2012.02.017

Zimmerman, B. J. (2000a). Self-efficacy: An essential motive to learn. *Contemporary Educational Psychology, 25*(1), 82–91. https://doi.org/10.1006/ceps.1999.1016

Zimmerman, B. J. (2000b). Attaining self-regulation: A social cognitive perspective. In M. Boekaerts, P. R. Pintrich, & M. Zeidner (Eds.), *Handbook of self-regulation* (pp. 13–39). Academic Press. https://doi.org/10.1016/B978-0-12-109890-2.X5027-6

Zimmerman, B. J. (2002). Becoming a self-regulated learner: An overview. *Theory Into Practice, 41*(2), 64–70. https://doi.org/10.1207/s15430421tip4102_2

Appendix A

Questionnaire Q.1

1. Imagine dipping a small portion of a biscuit into milk or tea. What happens to the liquid level? Try to provide an explanation for what you think might occur.

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2. What do you think happens to the biscuit? Justify your response.

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3. What do we observe when we place a dry sponge on the surface with a small amount of water? Provide an explanation for your observation.

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4. Why is detergent added to water when washing clothes?

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5. Why is it preferable to use hot water to remove stains from clothes?

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6. Imagine fastening a piece of tulle (a mesh fabric often used in gift wrappings), figure A1, over the top of a glass and securing it with a rubber band. If we gently pour water into the glass through the tulle and then place a piece of cardboard on top, sealing the glass, we can invert the glass and remove the cardboard without the water falling out. Why does this happen?

Figure A.1: Surface tension keeps water inside the inverted glass, even with a mesh covering the opening (Il Piacere di Scoprire, 2018).

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7. On a rainy day, you might wear clothing (jackets, shoes, etc.) made of different materials. As you may have noticed, water behaves differently when in contact with various materials (figure A2).


Figure A.2: Illustrates how water interacts differently with various materials (Textile Today, 2018; Alamy, n.d.).

Do you think there is a difference in the water's behaviour in the two cases shown in the previous pictures? Explain what you think causes these differences.

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8. Why, when oil is poured into a non-stick pan, does it not form droplets as water does? Specifically, how does the oil behave? What do you think causes this behaviour?

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9. Why is the insect shown in the figure A3 able to walk on water without sinking?

Figure A.3: The figure shows an insect walking on water, a phenomenon made possible by surface tension (Conosciamo Insieme, 2016).

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10. How does water travel from the roots to the leaves of a tree?

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Appendix B

Questionnaire Q.2

1. The meniscus of a liquid inside a glass capillary tube has a concave shape. Explain why this occurs in terms of forces.

2. A liquid does not wet the glass with which it is in contact. Explain why this happens in terms of forces.

3. A small boat is floating on the surface of the water in a container. After adding a few drops of soap to the water using a dropper, the boat begins to move. Explain why this happens in terms of the forces acting on the boat.

4. What are the units of surface tension? Do you know how these units can be derived?

5. The number of water droplets needed to completely cover the surface of a coin is greater than the number of vegetable oil droplets required to cover the surface of an identical coin. Explain what might cause this phenomenon.

6. Consider three capillary tubes made of the same material and with the same diameter (figure B1), each immersed in containers holding water, mercury, and oil, respectively. Indicate which of the liquids will behave as shown in the figure.

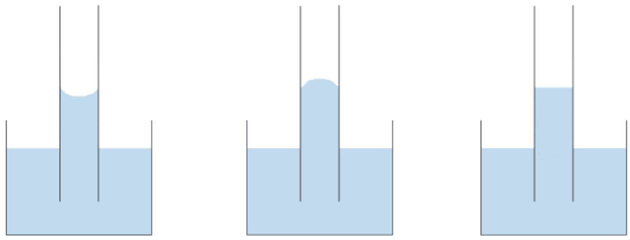

Figure B.1: Capillary tubes made of the same material and with the same diameter.

□ Water	□ Water	□ Water
□ Mercury	□ Mercury	□ Mercury
□ Oil	□ Oil	□ Oil
□ No liquid	□ No liquid	□ No liquid

Now provide an explanation in terms of forces.

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7. What do you think "adhesive forces" and "cohesive forces" are? Provide some examples where you think these forces are present.

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8. What do you think is the difference between these two types of forces?

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9. Explain which quantities influence the rise of a liquid inside a capillary.

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10. Do you think soap changes the properties of water? If so, which ones?

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11. When soap is added to water and a drop of this mixture is placed on a horizontal surface, it spreads evenly across the surface instead of forming a distinct droplet. Explain this phenomenon.

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Appendix C

Qualitative experiment No. 1

You will be shown a video featuring an insect placed on the surface of water.

Individual Student Prediction

Do you think it will be able to move across the surface? What factors do you believe might enable this movement?

Small Group Prediction

Discuss within your group what you think will happen to the insect and write down your shared prediction.

VIDEO LINK: https://www.youtube.com/watch?v=4CU8gYYkwSw

Individual Observation

Report what aspect of the video struck you the most. How did this contribute to your understanding of the phenomenon?

Small Group Observation

After discussing within your group, report how your understanding of the phenomenon has changed or remained the same. Did you adopt any specific strategy to make the physical phenomenon more comprehensible?

LARGE GROUP DISCUSSION

Comparison between large group, small group, and individual observations

Are the conclusions reached through the whole-class discussion consistent with your initial prediction? And with your small group's?

Individual Student's Opinion

At the end of this activity, you will have had the opportunity to engage with your peers. Do you truly agree with what was established in the whole-class discussion? Explain your viewpoint as clearly as possible.

Activity 1: Objects on the surface of water

You have the following materials at your disposal:

- A container
- Water
- Objects such as paperclips and needles

Individual Activity

1. How would you use the available materials to further investigate the phenomenon previously observed? The aim is to describe a behaviour of water like what was shown in the video.

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2. Can you think of a different experiment that might demonstrate the same behaviour of water, even using materials other than those currently available?

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Small Group Activity

3. After searching for information (e.g., online), agree together on which experiment to carry out using the materials provided here. Describe the experiment.

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4. Report the results you observed during the experiment.

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5. Discuss whether the outcomes observed in the previous point correspond with what you had predicted individually and as a group.

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LARGE GROUP DISCUSSION

Comparison between large group, small group, and individual observations

6. Are the conclusions reached during the whole-class discussion consistent with your individual predictions? And with your small group's?

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Individual Student's Opinion

7. At the end of this activity, you will have had the opportunity to exchange ideas with your peers. Do you truly agree with what was established during the whole-class discussion? Explain your position as clearly as possible.

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Qualitative experiment No. 2

You will be shown a video that displays the following phenomenon: water is placed in a glass, on top of which a mesh is positioned. Finally, a piece of card is placed over the top of the glass to seal it.

Individual Student Prediction

What do you think will happen to the water once the glass is turned upside down and the card is removed?

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____

Small Group Prediction

Discuss within your group what you believe will happen to the water when the glass is turned upside down and write down your shared prediction.

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VIDEO LINK: https://www.youtube.com/watch?v=WsksFbFZeeU [minutes 1:12 – 1:53]

Individual Student Observation

Report what in the video struck you the most. How did this contribute to your understanding of the phenomenon?

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Small Group Observation

After discussing with your group, explain how your understanding of the phenomenon has changed or remained the same. Did you use any strategy to make the physical phenomenon more understandable?

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LARGE GROUP DISCUSSION

Comparison between large group, small group, and individual observations

Are the conclusions reached during the whole-class discussion consistent with your initial prediction? And with your small group's?

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Individual Student's Opinion

At the end of this activity, you will have had the opportunity to compare your ideas with those of your classmates. Do you truly agree with what was established during the whole-class discussion? Explain your position as clearly as possible.

Activity 2: Films of soapy water on metal structures

You have the following materials at your disposal:

- A container
- Water
- Soap
- Rigid metal frame
- Flexible metal frame

Individual Activity

1. How would you use the available materials to further investigate the phenomenon previously observed? The aim is to describe a behaviour of water like what was shown in the video.

   ____

   ____

2. Can you think of different experiment that might demonstrate the same behaviour of water, even using materials or frames of a different shape than those currently available?

   ____

   ____

Small Group Activity

3. After searching for information (e.g., online), agree together on which experiment to carry out using the materials provided here. Describe the experiment.

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   ____

4. Report the results you observed during the experiment.

   ____

   ____

5. Discuss whether the outcomes observed in the previous point correspond with what you had predicted individually and as a group.

   ____

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LARGE GROUP DISCUSSION

Comparison between large group, small group, and individual observations

6. Are the conclusions reached during the whole-class discussion consistent with your own predictions? And with your small group's?

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Individual Student's Opinion

7. At the end of this activity, you will have had the opportunity to exchange ideas with your peers. Do you truly agree with what was established during the whole-class discussion? Explain your position as clearly as possible.

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Qualitative experiment No. 3

You will watch a video showing a celery stalk immersed in a glass of coloured water.

Individual Student Prediction

What do you think will happen to the celery stalk? And to the water?

Small Group Prediction

Discuss in your group what you think will happen to the celery and the water and report your shared prediction.

VIDEO LINK: https://www.youtube.com/watch?v=11n5g1QE-Nk

Individual Observation

Report what aspect of the video struck you the most. How did this contribute to your understanding of the phenomenon?

Small Group Observation

After discussing within your group, report how your understanding of the phenomenon has changed or remained the same. Did you adopt any specific strategy to make the physical phenomenon more comprehensible?

LARGE GROUP DISCUSSION

Comparison between large group, small group, and individual observations

Are the conclusions reached through the whole-class discussion consistent with your initial prediction? And with your small group's?

Individual Student Opinion

At the end of this activity, you will have had the opportunity to engage with your peers. Do you truly agree with what was established in the whole-class discussion? Explain your viewpoint as clearly as possible.

Activity 3a: Capillary rise with absorbent paper

You have the following materials at your disposal:

- 2 plastic cups
- Water
- Food colouring
- Absorbent paper
- Scissors

Individual Activity

1. How would you use the available materials to further investigate the phenomenon previously observed? The aim is to describe a behaviour of water like what was shown in the video.

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2. Can you think of a different experiment that might demonstrate the same behaviour of water, even using materials other than those currently available?

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____

Small Group Activity

3. After searching for information (e.g., online), agree together on which experiment to carry out using the materials provided here. Describe the experiment.

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4. Report the results you observed during the experiment.

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5. Discuss whether the outcomes observed in the previous point correspond with what you had predicted individually and as a group.

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LARGE GROUP DISCUSSION

Comparison between large group, small group, and individual observations

6. Are the conclusions reached during the whole-class discussion consistent with your individual predictions? And with your small group's?

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Individual Student's Opinion

7. At the end of this activity, you will have had the opportunity to exchange ideas with your peers. Do you truly agree with what was established during the whole-class discussion? Explain your position as clearly as possible.

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Activity 3b: Capillary rise in pipes

You have the following materials at your disposal:

- A set of capillary tubes
- Water
- Food colouring

Individual Activity

1. How would you use the available materials to further investigate the phenomenon previously observed? The aim is to describe a behaviour of water like what was shown in the video.

   ____

   ____

2. Can you think of a different experiment that might demonstrate the same behaviour of water, even using materials other than those currently available?

   ____

   ____

Small Group Activity

3. After searching for information (e.g., online), agree together on which experiment to carry out using the materials provided here. Describe the experiment.

   ____

   ____

4. Report the results you observed during the experiment.

   ____

   ____

5. Discuss whether the outcomes observed in the previous point correspond with what you had predicted individually and as a group.

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LARGE GROUP DISCUSSION

Comparison between large group, small group, and individual observations

6. Are the conclusions reached during the whole-class discussion consistent with your individual predictions? And with your small group's?

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Individual Student's Opinion

7. At the end of this activity, you will have had the opportunity to exchange ideas with your peers. Do you truly agree with what was established during the whole-class discussion? Explain your position as clearly as possible.

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Qualitative experiment No. 4

You will be shown a video displaying a small paper boat placed on the surface of the water. At a certain point, a drop of soap is added behind the boat.

Individual Student Prediction

What do you think will happen to the boat? And to the water?

Small Group Prediction

Discuss in your group what you think will happen to the boat and the water and write down your shared prediction.

VIDEO LINK: https://www.youtube.com/watch?v=miWlDVOhrSE

Individual Student Observation

Report what in the video struck you the most. How did this contribute to your understanding of the phenomenon?

Small Group Observation

After discussing with your group, explain how your understanding of the phenomenon has changed or remained the same. Did you use any strategy to make the physical phenomenon more understandable?

LARGE GROUP DISCUSSION

Comparison between large group, small group, and individual observations

Are the conclusions reached during the whole-class discussion consistent with your initial prediction? And with your small group's?

Individual Student's Opinion

At the end of this activity, you will have had the opportunity to compare your ideas with those of your classmates. Do you truly agree with what was established during the whole-class discussion? Explain your position as clearly as possible.

Activity 4: The effect of soap on surface tension

You have the following materials at your disposal:

- A container
- Water
- Soap
- Objects such as talcum powder, pepper, turmeric, toothpicks

Individual Activity

1. How would you use the available materials to further investigate the phenomenon previously observed? The aim is to describe a behaviour of water like what was shown in the video.

   ____

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2. Can you think of a different experiment that might demonstrate the same behaviour of water, even using materials other than those currently available?

   ____

   ____

Small Group Activity

3. After searching for information (e.g., online), agree together on which experiment to carry out using the materials provided here. Describe the experiment.

   ____

   ____

4. Report the results you observed during the experiment.

   ____

   ____

5. Discuss whether the outcomes observed in the previous point correspond with what you had predicted individually and as a group.

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LARGE GROUP DISCUSSION

Comparison between large group, small group, and individual observations

6. Are the conclusions reached during the whole-class discussion consistent with your individual predictions? And with your small group's?

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Individual Student's Opinion

7. At the end of this activity, you will have had the opportunity to exchange ideas with your peers. Do you truly agree with what was established during the whole-class discussion? Explain your position as clearly as possible.

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Appendix D

Simulation-based activity No. 1: Simulation of a two-dimensional droplet in microgravity

Note: The two screenshots below were generated in MATLAB using output obtained by running a script based on the SPH (Smoothed Particle Hydrodynamics) algorithm. In these images, pressure forces are shown in yellow, while liquid-liquid interaction forces are represented in red. These combined simulate molecular interactions in liquids, acting as attractive forces over longer distances and as repulsive forces at shorter distances.

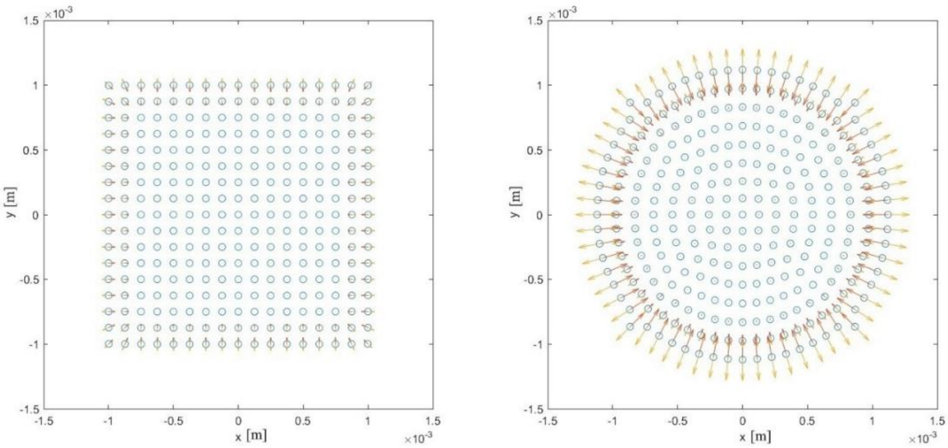

Figure D.1: Configurations of a droplet in microgravity conditions, represented with both square and circular particle arrangements (Battaglia et al. 2019).

Analyse the behaviour of the simulated liquid for a liquid-liquid interaction value of 3.0.

Individual Student Observation

1. After becoming familiar with the simulated system, try pausing the simulation shortly after it starts and, using the MATLAB function plot (…), create a graph of it. The resulting image will depict a square distribution of particles. How do you think pressure force and interaction forces (or interparticle forces) affect the system?

2. Which aspects of the mesoscopic model did you find most useful for understanding the forces acting on the drop?

____

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Small Group Discussion

3. After discussing with your group, describe if your understanding of the phenomenon has changed or remained the same.

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4. Did any different interpretations arise in your group discussion regarding the effect of the two forces (pressure force and liquid-liquid interaction force)?

____

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5. How did discussing with your classmates help you improve your understanding of the simulated system?

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Large Group Discussion

Now, choose a representative within your small group to present your conclusions to the large group. After listening to the representatives of all the small groups, start a large group discussion to compare your different positions.

6. Are the conclusions reached by the large group discussions compatible with your predictions? And with those of the small group?

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7. At the end of this activity, do you really agree with what was agreed by the large group? Explain your position as best you can.

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Simulation-based activity No. 2: Simulation of a two-dimensional droplet in the presence of gravity

Note: The screenshot below was generated in MATLAB using output obtained by running a script based on the SPH (Smoothed Particle Hydrodynamics) algorithm. In this image, pressure forces are shown in yellow, while liquid-liquid interaction forces are represented in red. These combined simulate molecular interactions in liquids, acting as attractive forces over longer distances and as repulsive forces at shorter distances.

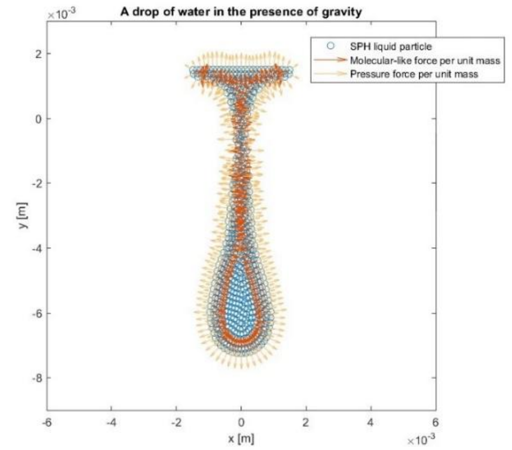

Figure D.2: Simulation of a droplet under the influence of gravity. Fixed particles at the top constrain the liquid, simulating the presence of a solid surface and resembling the behaviour of a dripping tap (Battaglia et al. 2019).

Analyse the behaviour of the simulated liquid for a liquid-liquid interaction value of 3.0.

Individual Student Observation

1. After familiarising yourself with the simulated system, use the MATLAB function plot(...) to generate a graph. The resulting image will display a pendant droplet. What role do you think intermolecular forces, in combination with gravitational and pressure forces, have played in shaping this configuration?

   ____

   ____

2. Which aspects of the mesoscopic model did you find most useful for understanding the forces acting on the drop?

   ____

   ____

Small Group Discussion

3. After discussing with your group, describe if your understanding of the phenomenon has changed or remained the same.

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4. Did any different interpretations arise in your group discussion regarding the effect of the three forces (gravity force, pressure force and liquid-liquid interaction force)?

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5. How did discussing with your classmates help you improve your understanding of the simulated system?

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Large Group Discussion

Now, choose a representative within your small group to present your conclusions to the large group. After listening to the representatives of all the small groups, start a large group discussion to compare your different positions.

6. Are the conclusions reached by the large group discussions compatible with your predictions? And with those of the small group?

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7. At the end of this activity, do you really agree with what was agreed by the large group? Explain your position as best you can.

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Simulation-based activity No. 3: Formation of liquid menisci

Note: The two screenshots below were generated in MATLAB using output obtained by running a script based on the SPH (Smoothed Particle Hydrodynamics) algorithm. In these images, pressure forces are shown in yellow, while liquid-liquid interaction forces are represented in red. These combined simulate molecular interactions in liquids, acting as attractive forces over longer distances and as repulsive forces at shorter distances.

Analyse the behaviour of the simulated liquid for a fixed liquid-liquid interaction value of 3.0 in the following cases:

- Case a: solid-liquid interaction equal to 2.6
- Case b: solid-liquid interaction equal to 1.85

After familiarising yourself with the simulated system and setting the values as indicated above, generate the resulting graph for each case using the MATLAB function plot(...).

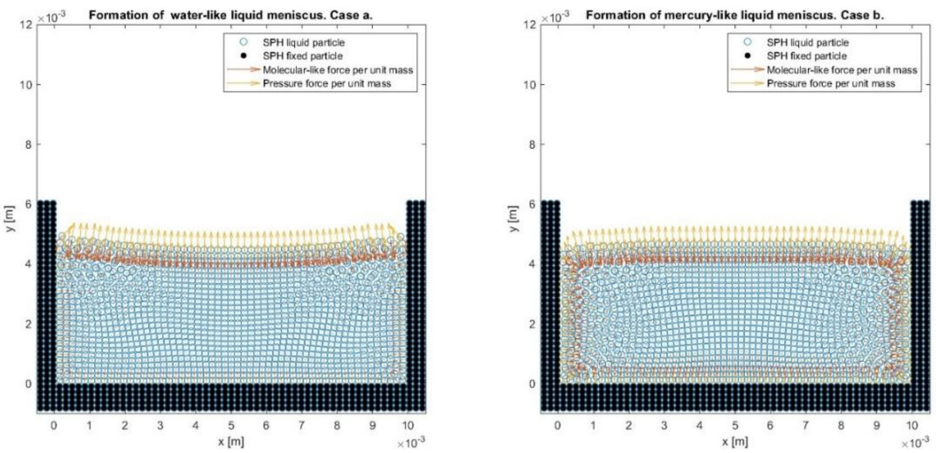

Figure D.3: Simulation setup illustrating meniscus formation under gravity. In case a, the liquid forms a concave meniscus, simulating the behaviour of water. In case b, the liquid forms a convex meniscus, simulating the behaviour of mercury (Battaglia et al. 2019).

The graphs will allow you to visualise the distribution of liquid particles within a container, whose walls are simulated by introducing fixed particles.

Individual Student Observation

1. Which forces come into play between the liquid particles and those constituting the wall? How do these forces influence the shape of the liquid?

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2. In what way does the differing intensity of solid–liquid and liquid-liquid interactions affect the distribution of liquid particles? Provide some examples of real-life situations in which similar behaviours can be observed.

Small Group Discussion

3. After discussing with your group, describe if your understanding of the phenomenon has changed or remained the same.

4. How did discussing with your classmates help you improve your understanding of the simulated system?

Large Group Discussion

Now, choose a representative within your small group to present your conclusions to the large group. After listening to the representatives of all the small groups, start a large group discussion to compare your different positions.

5. Are the conclusions reached by the large group discussions compatible with your predictions? And with those of the small group?

6. At the end of this activity, do you really agree with what was agreed by the large group? Explain your position as best you can.

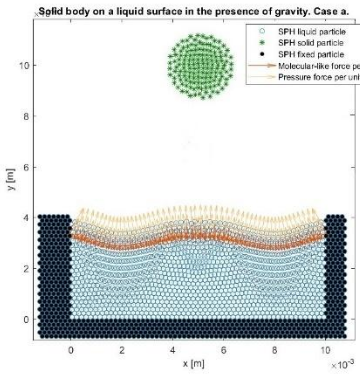
Simulation-based activity No. 4: Interaction between a solid body and a fluid

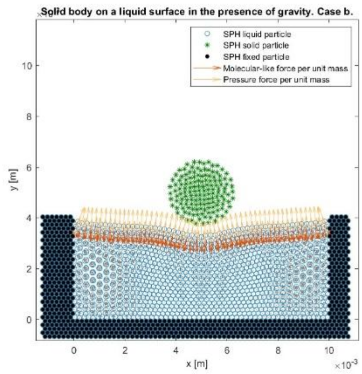
Note: The three screenshots below were generated in MATLAB using output obtained by running a script based on the SPH (Smoothed Particle Hydrodynamics) algorithm. In these images, pressure forces are shown in yellow, while liquid-liquid interaction forces are represented in red. These combined simulate molecular interactions in liquids, acting as attractive forces over longer distances and as repulsive forces at shorter distances.

Analyse the behaviour of the simulated liquid for a fixed liquid-liquid interaction value of 3.0 in the following cases:

- Case a: solid-liquid interaction equal to 2.5
- Case b: solid-liquid interaction equal to 1.85
- Case c: solid-liquid interaction equal to 0.1

After familiarising yourself with the simulated system and setting the values as indicated above, generate the resulting graph for each case using the MATLAB function plot(...).





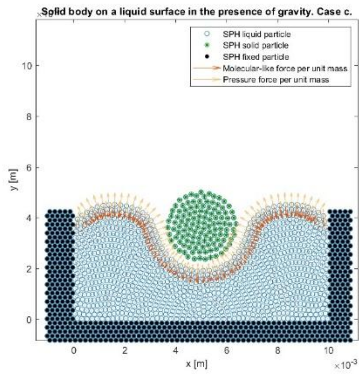


Figure D.4: Screenshots of the three configurations describing the interaction between a solid body and a liquid surface: the solid is positioned away from the liquid surface, strong interaction between solid and liquid, weak interaction between solid and liquid (Battaglia et al. 2019).

These graphs illustrate how a solid body positions itself with respect to the surface of a liquid contained within a tray. The container walls and the solid body are represented by fixed particles.

Individual Student Observation

1. Which forces come into play between the liquid particles and those of the solid body? Provide an explanation, in terms of these forces, for each of the three cases considered.

   ____

   ____

2. In what way does the differing intensity of solid–liquid and liquid-liquid interactions affect the distribution of liquid particles?

   ____

   ____

Small Group Discussion

3. After discussing with your group, describe if your understanding of the phenomenon has changed or remained the same.

   ____

   ____

4. How did discussing with your classmates help you improve your understanding of the simulated system?

   ____

   ____

Large Group Discussion

Now, choose a representative within your small group to present your conclusions to the large group. After listening to the representatives of all the small groups, start a large group discussion to compare your different positions.

5. Are the conclusions reached by the large group discussions compatible with your predictions? And with those of the small group?

   ____

   ____

6. At the end of this activity, do you really agree with what was agreed by the large group? Explain your position as best you can.

   ____

   ____

Simulation-based activity No. 5: Formation of a sessile droplet with static contact angle

Note: The two screenshots below were generated in MATLAB using output obtained by running a script based on the SPH (Smoothed Particle Hydrodynamics) algorithm. In these images, pressure forces are shown in yellow, while liquid-liquid interaction forces are represented in red. These combined simulate molecular interactions in liquids, acting as attractive forces over longer distances and as repulsive forces at shorter distances.

Analyse the behaviour of the simulated liquid for a fixed liquid-liquid interaction value of 3.0 in the following cases:

- Case a: solid-liquid interaction equal to 1.85
- Case b: solid-liquid interaction equal to 2.7

After familiarising yourself with the simulated system and setting the values as indicated above, generate the resulting graph for each case using the MATLAB function plot(...).

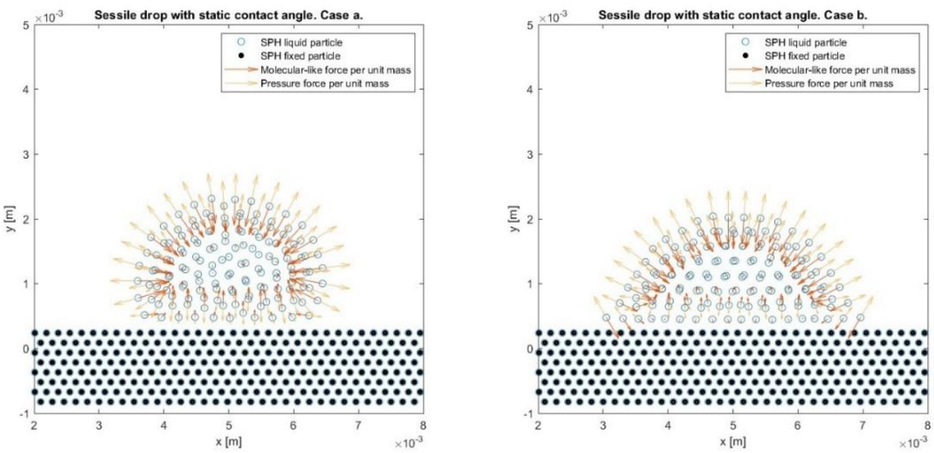


Figure D.5: Screenshots of a sessile droplet on a solid surface under the effect of gravity. The first image shows a non-wetting configuration, while the second depicts a wetting configuration (Battaglia et al. 2019).

These graphs will display a set of liquid particles simulating a two-dimensional droplet in contact with a solid surface, composed of fixed particles, under the influence of gravity.

Individual Student Observation

1. Which forces act between the liquid particles and those of the solid surface? How do these forces influence the position assumed by the liquid on the surface of the solid?

2. In what way does the differing intensity of solid–liquid and liquid-liquid interactions affect the distribution of liquid particles? Provide some examples of real-life situations in which similar behaviours can be observed.

3. If the interaction between the liquid and the solid surface were very weak, how do you think the liquid particles would behave? What shape would they take?

Small Group Discussion

4. After discussing with your group, describe if your understanding of the phenomenon has changed or remained the same.

5. How did discussing with your classmates help you improve your understanding of the simulated system?

Large Group Discussion

Now, choose a representative within your small group to present your conclusions to the large group. After listening to the representatives of all the small groups, start a large group discussion to compare your different positions.

6. Are the conclusions reached by the large group discussions compatible with your predictions? And with those of the small group?

7. At the end of this activity, do you really agree with what was agreed by the large group? Explain your position as best you can.

Appendix E

Satisfaction questionnaire Q.3

Gender: □ Male □ Female □ Prefer not to disclose

PART I: EXPECTATIONS AND PRIOR KNOWLEDGE

1.1 Compared to your expectations before attending the course, to what extent did you find it interesting and/or useful?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

1.2 To what extent was your prior knowledge useful in completing the course activities?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

PART II: ORGANISATION

2.1 Do you consider the overall duration of the course (total hours) to have been appropriate?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

2.2 Were you able to balance the commitment required by the project with your regular schoolwork?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

2.3 Were the learning environments provided (classrooms, laboratories, etc.) comfortable and suitable?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

PART III: SELF-ASSESSMENT AND IMPACT ON CURRICULAR LEARNING

3.1 Through participation in this project, to what extent do you feel you have acquired:

New knowledge:

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

A new working method:

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

New practical skills:

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

3.2 Have the things you learned during the project been useful for the subjects you study at school, or do you think they could be in the future?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

PART IV: EVALUATION OF TEACHING STRATEGIES

4.1 How positively do you evaluate the materials and tools used (equipment, computers, etc.)?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

4.2 Were the activities carried out during the course (experiments, simulations, exercises, discussions, etc.) interesting?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

4.3 Did you encounter difficulties in completing the proposed activities?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

4.4 Do you consider moments of individual reflection prior to group work to be useful?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

4.5 Do you consider the group work approach to be effective?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

4.6 After completing the course, to what extent do you feel capable of describing a studied phenomenon?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

4.7 After completing the course, to what extent do you feel capable of explaining a studied phenomenon?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

4.8 Do you think it is useful to use sources other than the textbook (internet, other books, scientific articles, videos, etc.) when researching a topic?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

4.9 Do you think it is beneficial to build explanations and descriptions collaboratively, through experiments and discussions, rather than immediately receiving a complete explanation from the teacher (traditional lesson)?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

PART V: RELATIONAL CLIMATE AND MOTIVATION

5.1 Did a positive and participatory atmosphere develop within your group?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

5.2 After attending the course, do you feel more confident when dealing with physics-related topics?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

5.3 After attending the course, do you believe you are well-suited to subjects like physics?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

PART VI: OVERALL SATISFACTION

6.1 How demanding did you find the course?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

6.2 Overall, how satisfied are you with the course?

□ Not at all □ Slightly □ Moderately □ Very □ Extremely

PART VII: FINAL COMMENTS

Please add any additional comments below.

____

____

Appendix F

To ensure transparency and traceability in the qualitative analysis process, the following provisional codebooks, developed during the initial coding phase of the various collected materials (worksheets and interviews, researchers' logbooks, and feedback via Questionnaire Q.3), are presented. These tables document the construction and evolution of the coding system, illustrating how the data were organised and interpreted in relation to the research objectives.
The provisional codebooks were compiled individually by the three researchers involved in data collection and analysis: each table corresponds to the work of a single researcher and reflects their initial approach to coding the material.

Provisional Codebook – Worksheets / Interviews

Table F.1: Coding matrix derived from students' responses in the worksheets and interview transcripts, compiled by Researcher A.

Code	Operational definition
Specialist terminology	Refers to the use of technical vocabulary and discipline-specific concepts, denoting a more formal and structured command of scientific language. The appropriate use of terminology indicates an advanced level of understanding and the ability to situate observations within a recognised theoretical framework.
Discussion and negotiation	Indicates moments when students compare differing ideas, arguing and evaluating alternative hypotheses. Meaning negotiation processes emerge from collaborative dialogue, in which individual positions are transformed through engagement with the group.
Connection with prior experiences	Refers to students' tendency to draw upon personal experiences, everyday knowledge, or previously acquired school-based learning to interpret the observed phenomenon.
Hypothetical reflection	Emerges when students formulate scenarios, hypotheses, or predictions that have not yet been

Code	Operational definition
	verified, demonstrating a willingness to reason beyond immediate data.
Spontaneous interpretation	Includes intuitive and immediate responses that are not based on in-depth elaboration but reveal initial conceptions or implicit prior knowledge.
Integration of perspectives	Describes instances in which students demonstrate the ability to combine multiple viewpoints, their own or others', into a more coherent and articulated understanding. It reflects a process of cognitive synthesis that supports the co-construction of knowledge.
Critical reflection	Manifests when students argue their own ideas and/or question previous explanations, revealing an epistemic stance of inquiry and analysis aimed at improving their understanding.
Models of understanding	Refers to the development of conceptual or interpretative representations that explain the observed phenomenon, highlighting students' capacity to construct more or less sophisticated models that serve as interpretative tools.
Proactive attitude	Concerns students' ability to take an active role by proposing ideas, suggestions, or alternative solutions to guide the activity. It reflects a constructive, forward-looking disposition aimed at influencing task development.
Exploratory growth	Describes openness to new learning opportunities, a desire to deepen understanding, and the adoption of an exploratory mindset. It reflects a process of expanding competencies and intellectual curiosity.
Experiential/Graphical deepening	Refers to situations in which students explicitly indicate that recourse to experiential or simulated tools facilitated the comprehension of complex concepts. It highlights awareness of the role of concrete and visual supports as cognitive mediators, capable of making

Code	Operational definition
	abstract notions more accessible and promoting a more solid consolidation of knowledge.
Wellbeing/Support	Indicates the relational and emotional dimension emerging in responses, such as expressions of trust, mutual encouragement, or perceived support within the working context.
Procedural description	Concerns the ability to illustrate the operational steps followed or to be followed, reflecting a sequential understanding of necessary actions. This description reveals attention to methodology and awareness of experimental or analytical phases.

Table F.2: Coding matrix derived from students' responses in the worksheets and interview transcripts, compiled by Researcher B.

Code	Operational definition
Technical language	Refers to students' use of domain-specific terminology. The use of technical language indicates a more structured level of understanding and the ability to situate explanations within a formal framework.
Mathematical formalism	Pertains to the use of mathematical tools, such as formulas or quantitative relationships, to describe or explain a phenomenon.
Comparison	Encompasses instances in which students relate different explanations, hypotheses, or observations, evaluating their coherence or validity.
Knowledge integration	Occurs when students connect information from diverse sources to construct a more elaborated explanation. It reflects the capacity to build a

Code	Operational definition
	complex interpretative framework through the synthesis of heterogeneous knowledge.
Alternative perspective	Describes students' willingness to adopt a viewpoint different from their own or from prior explanations. It expresses an open and flexible attitude, oriented towards reconsidering the phenomenon from new angles.
Negotiation	Highlights process in which students discuss and refine differing positions, reaching a shared understanding. It reflects the social and cooperative dimension of learning, wherein meaning is collectively constructed.
Interpersonal relations	Refers to expressions of support, collaboration, or relational dynamics emerging in group work, emphasising the role of a positive social climate and interactions in facilitating learning.
Projection ability	Pertains to students' propensity to formulate predictions or envisage future scenarios based on available knowledge. It indicates a forward-looking competence that allows students to go beyond immediate observation.
Common knowledge	Refers to the use of everyday knowledge, personal experiences, or shared intuitive explanations, signalling the employment of informal understanding as a starting point for interpreting a phenomenon.
Self-efficacy	Manifests through expressions of confidence in one's own capacity to comprehend and tackle the task.
Metacognition	Concerns instances in which students explicitly reflect on their own thinking processes, indicating awareness of cognitive functioning that supports self-regulated learning.

Code	Operational definition
Tools	Refers to explicit mention by students of the use of material or conceptual tools employed to observe, analyse, or understand a phenomenon.
Further exploration	Denotes students' interest in pursuing beyond provided instructions, proposing additional questions or new lines of inquiry. It signals intellectual curiosity and openness to autonomous learning pathways.
Representation/Visualisation mode	Encompasses the use of graphs or other visual forms to support concept explanation, highlighting the role of graphical representations as mediators that make understanding more immediate and accessible.
Scaffolding	Occurs when students acknowledge the role of support received, whether explicit or implicit, affective or practical, during the learning process.
Procedure description	Refers to the orderly articulation of the phases or actions undertaken in a task, reflecting students' attention to operational sequencing and methodological clarity.

Table F.3: Coding matrix derived from students' responses in the worksheets and interview transcripts, compiled by Researcher C.

Code	Operational definition
Scientific language	This concerns the use of terms, expressions, and concepts specific to scientific discourse. It highlights students' ability to describe and interpret observed phenomena by adopting a linguistic register appropriate to the disciplinary context.
Debate	This refers to situations in which students openly engage with one another, expressing opinions, objections, or differing interpretations. It underscores the value of

Code	Operational definition
	dialogue as a tool for developing and clarifying complex concepts.
Structured reasoning	This indicates the construction of coherent and well-founded arguments. It highlights students' capacity to support their ideas through clearly articulated logic and relevant justifications.
Connection with prior knowledge	This refers to moments when students draw on previous experiences, whether from school or everyday life, to interpret a phenomenon or support an explanation.
Openness to alternative perspectives	This emerges when students consider viewpoints different from their own, demonstrating cognitive flexibility and a willingness to revise their ideas considering new interpretations.
Self-awareness	This indicates students' reflection on their own cognitive processes, emotions, or limitations, as well as their awareness of the strategies they employ.
Use of analogies	This consists in drawing comparisons with familiar phenomena, situations, or concepts to explain what is being observed. It highlights the role of analogies as a cognitive resource to facilitate understanding.
Curiosity to go beyond	This refers to students' tendency to formulate new questions or to investigate aspects not explicitly required by the activity. It reveals a disposition towards curiosity and a desire to deepen knowledge.
Use of different communication styles	This code concerns students' ability to recognise and select the communicative or representational style most functional to the understanding of a phenomenon. This may involve, for instance, a preference for a visual rather than a textual mode, or for a kinaesthetic rather than an auditory approach.
Reference to tools and resources	This relates to the conscious use of technical or conceptual tools that support the analysis and comprehension of phenomena. It underscores students'

Code	Operational definition
	capacity to identify and effectively employ the resources available.
Comfort	This gathers expressions that denote confidence, trust, or perceived support within the working context. It highlights the importance of the emotional and relational dimension in fostering a calm and effective learning environment.
Understanding of content	This highlights responses in which students demonstrate comprehension of key concepts or of the fundamental mechanisms needed to describe a phenomenon.

Provisional Codebook – Researchers' logbooks

Table F.4: Provisional coding system developed from the analysis of the logbooks, compiled by Researcher A.

Code	Operational definition
Resistance to change	This refers to observed situations in which students display difficulties in adopting new strategies, concepts, or operational modes compared to those already consolidated.
Mutual support	This indicates behaviours in which students provide help, clarification, or encouragement to their peers during activities.
Active discovery	This encompasses observations relating to moments when students autonomously interact with materials or simulations, exploring, experimenting, and formulating hypotheses.
Critical awareness	This emerges when students demonstrate the ability to analyse, evaluate, or question information, procedures, or explanations, recognising both limitations and strengths.

Code	Operational definition
Development of technical-scientific lexical mastery	This concerns the increasing and correct use of terms and concepts specific to scientific language.
Construction of a group identity	This refers to the evolution of collaborative work, which, from an initial phase characterised by students' preference for working autonomously, progressively develops into a process of sharing. Such a trajectory leads not only to the creation of a collective identity linked to the task, but also to the intertwining of personal and affective bonds among members, thereby strengthening the sense of belonging and cohesion.
Integration of common/scientific knowledge	This encompasses situations in which students combine and/or replace concepts derived from common sense with more structured scientific explanations, seeking to elaborate coherent and well-founded interpretations.

Table F.5: Provisional coding system developed from the analysis of the logbooks, compiled by Researcher B.

Code	Operational definition
Well-being	This refers to observations concerning positive or negative emotional states perceived by students during the activities. It highlights how the emotional climate influences participation and engagement in learning.
Engagement	This refers to signs of active participation, interest, and motivation observed during the activities. It underscores students' energy, attention, and commitment within the learning process.
Tools	This indicates the use and relevance of material, conceptual, or digital tools employed by students to observe, analyse, represent, and understand phenomena.

Code	Operational definition
Peer debate	This refers to interactions in which students compare ideas, opinions, or explanations, emphasising the value of confrontation as a driver of shared knowledge construction.
Modelling	This encompasses situations in which students elaborate conceptual representations of observed phenomena to explain and predict behaviours.
Common knowledge/Scientific knowledge	This refers to moments in which students integrate or replace ideas derived from common sense with more structured scientific explanations, seeking to construct coherent interpretations.

Table F.6: Provisional coding system developed from the analysis of the logbooks, compiled by Researcher C.

Code	Operational definition
Reluctance/Support	This refers to situations in which students display resistance or difficulties in approaching new activities or concepts, counterbalanced by moments in which they receive or provide mutual support, including support from the teacher or researcher.
Exploration	This indicates student behaviours characterised by curiosity and a willingness to interact actively with materials, tools, or simulations, formulating hypotheses and experimenting autonomously.
Lexicon	This highlights the process of acquiring and consolidating terminological competence and expressive precision in the use of specific languages and concepts.
Collaboration	This refers to interactive dynamics among students, in which the sharing of ideas, strategies, and explanations

Code	Operational definition
	contributes to the construction of shared meanings and the advancement of activities.
Interest	This refers to signs of engagement, curiosity, and attention expressed by students towards observed phenomena or proposed activities. It underscores intrinsic motivation and cognitive effort as key factors for effective learning.

Provisional Codebook – Feedback (Questionnaire Q.3)

Table F.7: Preliminary coding scheme developed from students' responses to the feedback question in Questionnaire Q.3, compiled by Researcher A.

Code	Operational definition
New perspectives	This refers to students' ability to develop a renewed vision not only of the phenomenon under study but also of the methods of investigation typical of experimental research. In addition, it highlights how students have gained greater self-awareness, including their cognitive preferences and the ways in which they prefer to receive and process information.
Intrinsic motivation	This indicates the expression of interest, curiosity, or enjoyment related to the learning activity itself, regardless of external rewards. It highlights authentic engagement that fosters personal commitment and persistence in study.
Cognitive fatigue	This gathers the signs through which students display difficulties arising from task overload or from demands perceived as excessive. It reflects conditions in which learning is hindered by the limited availability of cognitive and emotional resources.
Peer collaboration	This refers to the dynamics emerging in group activities, where cooperation among students extended beyond the achievement of cognitive goals and the understanding of

Code	Operational definition
	the phenomenon, also fostering the construction of meaningful interpersonal relationships.
Qualified support	This describes moments in which the intervention of an expert figure, such as a teacher or researcher, provides clarifications, explanations, or guidance that promote the advancement of understanding. It underscores the role of expert guidance as an essential support to the learning process.
Interactive resources	This concerns the use and recognition of the value of digital tools, simulations, or practical activities that allow direct interaction with the content. It highlights how interactivity serves as a significant mediator in making complex concepts more accessible and engaging.

Table F.8: Preliminary coding scheme developed from students' responses to the feedback question in Questionnaire Q.3, compiled by Researcher B.

Code	Operational definition
Future perspectives	This refers to students' ability to project themselves beyond the activity carried out, formulating reflections on potential personal, academic, or professional developments. It highlights a future-oriented attitude in which the educational experience becomes an opportunity to envision trajectories of growth and applications of the knowledge acquired.
Metacognition	This indicates how students consciously reflect on their own thinking and learning processes, recognising effective strategies, difficulties encountered, or progress made.
Well-being	This gathers the expressions of satisfaction, confidence, and a sense of calm experienced by students within the context of the activity. It underscores the importance of

Code	Operational definition
	the emotional and relational dimension as a factor that sustains motivation and facilitates learning.
In-depth exploration	This refers to instances in which students display the desire or ability to go beyond the requirements of the activity, examining in greater detail concepts, procedures, or theoretical connections.
Constructive feedback	This describes situations in which students provide constructive observations, suggestions, or indications aimed at improving understanding and the design of the activities undertaken.
Interpersonal relationships	This concerns the social dynamics that emerge within the group, including mutual support, collaboration, and the establishment of positive bonds. It highlights how relationships among peers and with teachers contribute to creating a favourable environment for learning and personal development.

Table F.9: Preliminary coding scheme developed from students' responses to the feedback question in Questionnaire Q.3, compiled by Researcher C.

Code	Operational definition
Learning horizons	This concerns students' ability to broaden their vision not only with respect to the phenomena observed, but also regarding strategies and methods of inquiry. It includes awareness of new approaches to learning, reflection on what proves most effective for oneself, and the possibility that such experiences may inform future choices or personal and academic development.
Self-awareness	This indicates moments in which students explicitly recognise their own learning styles, strengths, and difficulties. It highlights the presence of conscious reflection that supports self-regulation and sustains intrinsic motivation.

Code	Operational definition
Comfort	This gathers students' expressions that denote a sense of security, calmness, and confidence within the educational context. It underscores the significance of emotional well-being as a favourable condition for engagement and participation.
Feedback	This refers to observations, comments, or suggestions made during the activities. It represents not only a tool for guidance but also a stimulus for critical reflection.
Social interaction	This describes the relational dynamics that emerge in collaboration among students, within discussions, or during shared activities. It emphasises the value of dialogue and social exchange as fundamental resources for the construction of shared meanings.
Educational innovation	This concerns students' references to practices, tools, or methodologies perceived as new or different from traditional ones. It highlights the recognition of the value of innovative educational approaches capable of stimulating curiosity, engagement, and new modes of learning.

Appendix G

This appendix presents the tables related to the triangulation and negotiation of codes among the researchers. While, in the previous phase, the researchers independently coded the same subset of data, in this phase, through peer debriefing sessions, discrepancies were discussed and correspondences between similar codes were identified. The tables show the final compromise, that is, the convergence of codes that were initially distinct but considered analogous. This process allowed the consolidation of code definitions, ensuring conceptual coherence, operational reliability, and an interpretative enrichment derived from the integration of different perspectives.

Code Triangulation – Worksheets / Interviews

Table G.1: Table showing the intersection between the codes assigned by different researchers to the worksheets and the interviews.

Researcher A	Researcher B	Researcher C
Specialist terminology	Technical language Mathematical formalism	Scientific language
Discussion and negotiation	Comparison Knowledge integration Alternative perspective Negotiation Interpersonal relations	Debate Structured reasoning
Connection with prior experiences	-	Connection with prior knowledge
Hypothetical reflection	Projection ability	-

Researcher A	Researcher B	Researcher C
Spontaneous interpretation	Common knowledge	-
Integration of perspectives	Knowledge integration Alternative perspective	Openness to alternative perspectives
Critical reflection	Self-efficacy Metacognition	Self-awareness Structured reasoning
Models of understanding	Tools	Use of analogies
Proactive attitude	-	-
Exploratory growth	Further exploration	Curiosity to go beyond
-	-	Use of different communication styles
Experiential/Graphical deepening	Tools Representation/Visualisation mode	Reference to tools and resources
Wellbeing/Support	Scaffolding	Comfort
Procedural description	Procedure description	Understanding of content

Code Triangulation – Researchers' logbooks

Table G.2: Table illustrating the convergence of the codes that emerged from the researchers' logbooks.

Researcher A	Researcher B	Researcher C
Resistance to change Mutual support	Well-being	Reluctance/Support
Active discovery	Tools	Exploration
Critical awareness	Modelling	-
Development of technical-scientific lexical mastery	-	Lexicon
Construction of a group identity	Peer debate	Collaboration
-	Engagement	Interest
Integration of common/scientific knowledge	Common knowledge/Scientific knowledge	-

Code Triangulation – Feedback (Questionnaire Q.3)

Table G.3: Table summarising the compromise reached by the researchers regarding the codes derived from students' feedback on Questionnaire Q.3.

Researcher A	Researcher B	Researcher C
New perspectives	Future perspectives	Learning horizons
Intrinsic motivation	Metacognition	Self-awareness

Researcher A	Researcher B	Researcher C
	Well-being In-depth exploration	Comfort
Cognitive fatigue	Well-being Constructive feedback	Feedback
Peer collaboration	Interpersonal relationships	Social interaction
Qualified support	Well-being	-
Interactive resources	-	Educational innovation

Appendix H

This appendix contains the final codebooks developed for each data collection method (worksheets/interviews, researchers' logbooks, feedback from Questionnaire Q.3). These codebooks represent the subsequent stage of the coding process, directly derived from the triangulation and negotiation of codes among the researchers. The tables document the final labels and their corresponding detailed descriptions, showing how the information was organised in a coherent and shared manner to ensure reliability and clarity in the qualitative analysis.

Final Codebook – Worksheets / Interviews

Table H.1: Matrix presenting the final codes and their corresponding descriptions, developed following triangulation and negotiation among the researchers for the worksheets and interview transcripts.

Code	Operational definition
Scientific language	This refers to the deliberate use of specialised terminology and formal structures typical of mathematical and scientific discourse. It is applied to instances in which students adopt a technical register appropriate to the discipline, thereby demonstrating mastery of terminology and the expressive conventions specific to the scientific context.
Discussion and negotiation	This concerns collaborative interactions among students, in which the comparison of ideas, the discussion of different perspectives, and the negotiation of shared meanings emerge. It is applied to cases where students integrate knowledge, argue their positions, and construct common solutions through debate.
Recall of previous knowledge	This refers to knowledge already acquired or to students' previous experiences, which are employed as a starting point for interpreting a phenomenon or supporting an explanation. It highlights how students attempt to make sense of what they observe or discuss by activating their

Code	Operational definition
	personal repertoire of ideas, everyday experiences, or school-based knowledge.
Projection	This refers to the ability to elaborate hypotheses or imagine situations that are not directly observable, projecting into alternative or future conditions. It applies when students formulate possibilities, explore "what if…" scenarios, and expand the conceptual space beyond the immediate situation.
Common-sense reasoning	This indicates the use of immediate interpretations or explanations based on personal intuitions and widespread beliefs, rather than on formalised scientific concepts. It is applied when students explain phenomena by drawing on simple and familiar cognitive frameworks, anchored in everyday language and common sense.
Shared construction	This concerns the ability to relate different perspectives or knowledge from diverse contexts to construct a broader and more articulated framework. This process entails recognising the partiality of each perspective and the willingness to combine them into a richer, shared understanding.
Critical awareness	This refers to the student's ability to construct, present, and defend reasoning through evidence, explanations, and logical connections. It also includes reflection on one's own thinking processes and on the strategies adopted.
Interpretative models	This refers to the strategies employed by students to construct and organise their knowledge, drawing on models, conceptual tools, or analogies to simplify and understand a phenomenon. Such elements make complex concepts more accessible and enable connections with prior experiences or knowledge.
Proactive attitude	This concerns the student's ability to assume an active role in the learning process by advancing ideas, suggesting strategies, proposing solutions, and orienting group work. It includes autonomous initiative, an

Code	Operational definition
	enterprising approach, the willingness to contribute to collective progress, and a readiness to experiment with different approaches.
Exploratory drive	This refers to the student's tendency to go beyond the boundaries of the assigned task, exploring connections, variables, and scenarios not explicitly required. It encompasses intellectual curiosity, the ability to ask autonomous questions, and the pursuit of further inquiry.
Plurality of languages	This refers to the student's ability to identify and adopt the communicative or representational style most effective for understanding a phenomenon. It may include a preference for visual rather than textual modes, kinaesthetic rather than auditory approaches, or other strategies that facilitate the processing and integration of information.
Comprehension tools	This refers to the conscious use of practical tools, graphical representations, or modes of visualisation to support the comprehension of complex concepts or phenomena that would otherwise remain abstract or not immediately observable.
Well-being	This refers to the creation of a context in which students experience trust, security, and emotional support, both from facilitators and peers. It includes collaborative dynamics and positive interactions that promote learning, active engagement, and the development of constructive relationships within the group.
Operational description	This concerns students' ability to illustrate the operational steps followed or to be followed, highlighting a sequential understanding of the necessary actions. The description underscores attention to method and awareness of experimental or analytical phases, without implying interpretations of scientific content.

Final Codebook – Researchers' logbooks

Table H.2: System presenting the final codes and their corresponding descriptions, developed following triangulation and negotiation among the researchers for the logbooks they compiled.

Code	Operational definition
Managing change	Refers to the dynamic in which students initially encounter difficulties or resistance in adapting to new methodologies, environments, or activities. It highlights how peer support and the presence of a safe and positive context can foster the overcoming of such resistance, promoting well-being, trust, and greater openness to collaborative learning.
Active inquiry	Refers to students' propensity to explore phenomena, tools, or concepts autonomously, actively seeking new knowledge. It emphasises the conscious use of resources and tools to investigate and understand, stimulating curiosity, personal initiative, and deeper, more meaningful learning.
Analytical reflection	Refers to students' ability to analyse phenomena, construct interpretative representations, and critically evaluate hypotheses and explanations. It highlights a reflective and autonomous attitude towards the comprehension of content, which includes the capacity to reorganise information and arrive at reasoned conclusions.
Scientific language competence	Refers to students' ability to use technical-scientific terms, expressions, and concepts correctly. It highlights the progressive acquisition of an appropriate vocabulary for describing phenomena, interpreting data, and communicating in a coherent and scientifically sound manner.
Collaborative cohesion	Refers to the processes through which students work together, discuss, share ideas, and build interpersonal bonds. It highlights how collaboration not only fosters content understanding but also contributes to the construction of group identity and the development of

Code	Operational definition
	positive and supportive relationships within the learning context.
Engagement	Refers to the degree of attention, motivation, and participation demonstrated by students in the proposed activities. It highlights how engagement with content fosters greater concentration, a proactive attitude, and more meaningful interaction with the learning experience.
Evolution of knowledge	Indicates the process through which students move from a spontaneous and unstructured use of common knowledge to a more conscious, rigorous, and formalised application of scientific knowledge. This progression emerges both in the understanding of phenomena and in peer interactions, revealing an increasing capacity to select, organise, and apply disciplinary knowledge in an appropriate and targeted manner.

Final Codebook – Feedback (Questionnaire Q.3)

Table H.3: Framework presenting the final codes and their corresponding descriptions, developed following triangulation and negotiation among the researchers for the feedback question in Questionnaire Q.3.

Code	Operational definition
Broadening perspectives	Refers to students' ability to reorient their learning perspectives when encountering new environments and methodologies. It indicates an awareness that enables them to move beyond a traditional school-centred vision towards a more autonomous and flexible approach, capable of valuing alternative strategies and tools.
Awareness and motivation	Refers to the engagement experienced by students throughout the learning pathway, characterised by curiosity, a sense of novelty, and discovery. It points to a progressive self-awareness and understanding of one's

Code	Operational definition
	own cognitive processes, leading to a more mature form of learning.
Cognitive-emotional balance	Indicates the conditions that either facilitate or hinder learning, encompassing aspects related to emotional well-being, the management of cognitive effort, and the perception of a calm study environment. It includes both signs of fatigue and manifestations of comfort and security, underlining how the quality of the context directly affects participation and the effectiveness of cognitive processes.
Collaborative dynamics	Concerns the dynamics that emerge from relationships among students, in which comparison and collaboration become central tools for constructing shared meanings. It highlights how working together fosters not only cognitive elaboration but also the creation of a supportive climate and collective growth.
Expert support	Refers to the combination of support provided by expert figures and the positive social climate that promotes students' well-being. It highlights how students recognise the opportunity to interact with such figures, receiving clarifications, guidance, or suggestions that help them orient their learning within a safe, collaborative, and scaffolded environment.
Interactive learning	Refers to the use of digital tools, simulations, practical activities, or innovative methodological approaches that stimulate active interaction with content. It emphasises how interactive resources can facilitate understanding, foster curiosity, encourage autonomous exploration, and promote more engaging and meaningful learning.

Appendix I

This appendix presents the intersection between the final codebook codes and the observables identified as the reference framework for the analysis. The observables considered are:

1.1 Appropriation of concepts and forms of representation

1.2 Evolutions of common-sense conceptions into scientific ones

2.1 Enhancement of interpersonal and social skills

2.2 Development of reasoning lines

2.4 Recognition and evolution of personal cognitive/learning styles

3.2 Growth mindset

3.3 Metacognition

3.4 Well-being in learning

The codes are associated with one or more observables, thus spanning different dimensions. This reflects the complex and intertwined nature of learning processes, in which the same empirical evidence can be read and interpreted through different perspectives.
To ensure transparency, it was deemed appropriate to make explicit the criteria by which each observable was assigned to the codes, namely:

- Conceptual coherence: the definition of the code was compared with the formulations of the observables, verifying conceptual alignment.
- Empirical evidence: the association between codes and observables was guided by concrete traces collected during the activities (written outputs, oral interactions, observed behaviours). In this way, the choices reflected the recurrence and significance of manifestations that were effectively documented in the data.
- Multiple relevance: in cases of overlap among several observables, preference was given to those that best reflected the core of the observed behaviour.
- Collegial discussion: the attributions were discussed and negotiated by the research team until shared consensus was reached.

These criteria consider both the conceptual content of the codes and the ways in which students manifested behaviours, reflections, or attitudes in relation to specific observable dimensions. In this sense, the proposed tables do not have prescriptive or exclusive value, but represent an interpretative map shared by the research team.

The following tables illustrate the intersections between codes and observables, distinguished according to the different sources of data considered: the worksheets and student interviews, the logbooks compiled by the researchers, and the feedback gathered through Questionnaire Q.3.

Table I.1: Intersection between codes and observables emerging from the analysis of worksheets and student interviews.

Code	Obs. 1.1	Obs. 1.2	Obs. 2.1	Obs. 2.2	Obs. 2.4	Obs. 3.2	Obs. 3.3	Obs. 3.4
Scientific language	✓	✓						
Discussion and negotiation			✓			✓		✓
Recall of previous knowledge		✓						
Projection				✓			✓	
Common-sense reasoning	✓	✓						
Shared construction		✓	✓			✓	✓	
Critical awareness	✓			✓			✓	
Interpretive models	✓			✓			✓	
Proactive attitude				✓		✓		
Exploratory drive						✓		
Plurality of languages					✓		✓	
Comprehension tools		✓			✓		✓	
Well-being			✓					✓
Operational description		✓						

Table I.2: Intersection between codes and observables emerging from the analysis of the researchers' logbooks.

Code	Obs. 1.1	Obs. 1.2	Obs. 2.1	Obs. 2.2	Obs. 2.4	Obs. 3.2	Obs. 3.3	Obs. 3.4
Managing change			✓					✓
Active inquiry				✓		✓		
Analytical reflection							✓	
Scientific language competence	✓	✓						
Collaborative cohesion			✓					✓
Engagement						✓		✓
Evolution of knowledge		✓						

Table I.3: Intersection between codes and observables derived from the feedback collected through Questionnaire Q.3.

Code	Obs. 1.1	Obs. 1.2	Obs. 2.1	Obs. 2.2	Obs. 2.4	Obs. 3.2	Obs. 3.3	Obs. 3.4
Broadening perspectives						✓		
Awareness and motivation						✓	✓	
Cognitive-emotional balance							✓	✓
Collaborative dynamics			✓					✓
Expert support				✓				✓
Interactive learning					✓			✓

To clarify the process of assignment, two illustrative examples are drawn from Table I.1, showing how the identified codes were related to the corresponding observables.

The code *scientific language* was associated with observables 1.1 (Appropriation of concepts and forms of representation) and 1.2 (Evolutions of common-sense conceptions into scientific ones), as students' outputs progressively demonstrated conscious re-elaboration of knowledge. A gradual shift was observed from the use of everyday expressions and colloquial formulations to a more formalised language capable of reflecting a scientific understanding of the phenomena under study.

Similarly, the code *well-being* was linked to observables 2.1 (Enhancement of interpersonal and social skills) and 3.4 (Well-being in learning). The dynamics observed showed how active involvement in collaborative activities and peer interaction contributed to strengthening relational and social competences, while simultaneously promoting mutual listening and the construction of an inclusive climate. At the same time, the learning experience was perceived as rewarding and sustainable: this fostered a reduction in anxiety or resistance and, in parallel, an increase in motivation and confidence, making well-being a structural element of the educational process.