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Pedagogical approaches to surface phenomena in liquids: Investigation-based laboratory and modelling activities to improve students' learning

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ABSTRACT

Paperclips can float on water, mercury drops do not spread on solid surfaces, and fluids can flow against gravity in capillary tubes. Surface tension can be used to explain these phenomena which are macroscopic manifestations of microscopic molecular interactions.
At both school and university levels, surface phenomena are introduced through traditional macroscopic or microscopic approaches. However, since explanations based on microscopic models are often in conflict with common macroscopic interpretations, the traditional teaching of the basic concepts related to surface phenomena can be unclear and can prevent students from an effective understanding of the topic. However, since surface phenomena applications are important in physics and other applied disciplines, it may be worth to reconstruct this content based on research results in Physics Education.

Research demonstrates that models constructed at an intermediate scale (i.e., mesoscopic scale) can be used effectively in science education. Particularly, the literature recognizes mesoscopic models as valuable for efficiently introducing topics such as solid friction and fluid statics. These models have the benefits of the microscopic model. Particularly, they foster understanding based on the recognition of a "mechanism of functioning", that is at the basis of the development of explicative lines or reasoning. Furthermore, these models do not require a significant amount of computer resources to execute simulations implementing the models.

On the basis of these observations, we asked ourselves how we could contribute to improve the teaching and learning of this topic. We hypothesised that choosing an appropriate modelling scale to introduce a given topic would appreciably enhance the teaching/learning processes at both school and university levels.

On the basis of our research hypothesis, we decided to study how and to what extent different didactical approaches based on macroscopic and mesoscopic description, respectively, can foster the teaching and learning of surface phenomena at the secondary school level. We designed two teaching-learning sequences (TLSs), one based on macroscopic modelling, and the other on mesoscopic modelling, which were trialled each with a group of upper secondary school students. Each TLS was based on an inquiry-based approach and was planned to involve students in active learning practices. The main goal of the trialling was not to identify which group highlights the best learning depending on the different modelling

approach, but to verify the aspects of each approach that can be considered truly relevant in promoting learning.

The planning and implementation of the two TLSs were guided by the general research question "Which aspects of each approach can be considered relevant in promoting students' scientific learning?".

The data collected during the trialling of the TLSs (student worksheets, interviews, students' answers to questionnaires etc.) were studied by means of qualitative and/or quantitative analysis methodologies. Resuming some results, after the instruction students who followed the macroscopic approach appear more capable than students who followed the mesoscopic approach in describing complex phenomena involving liquid-solid interaction, such as capillarity. However, a close analysis of their answers to questionnaires shows that they acquired quite superficial knowledge, as they simply memorized notions and information on the topic but did not reach a proper awareness of it. On the other hand, after the instruction, students who followed the mesoscopic approach seemed more capable of building explanation than students who followed the macroscopic approach. We can infer that mesoscopic modelling activities can support the development of explanation-oriented reasoning lines more than macroscopic traditional ones. We found that students who followed the mesoscopic approach to the analysed topics understood them more deeply than students who followed the macroscopic approach. This, however, often happens with respect to simple physical situations like the ones involving liquid-liquid interactions. These students found it difficult to understand more complex physical situations as those involved in liquid-solid interactions.

In general, both groups show comparable levels of well-being in learning. This indicates that the inquiry-type approach proposed through the two TLSs has been welcomed by most of the students. The mesoscopic approach promoted the development of the willingness to extend studies and research more than the macroscopic approach and this led students to reinforce beliefs and acquire behaviours characteristic of a growth mindset. On the other hand, students who followed the macroscopic approach developed the ability of generalization of what has been learned more than students who followed the mesoscopic approach.

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INTRODUCTION

Paperclips can float on water, mercury drops do not spread on solid surfaces, and fluids can flow against gravity in capillary tubes. Surface tension can be used to explain these phenomena which are macroscopic manifestations of microscopic molecular interactions.
At both school and university levels, surface phenomena are introduced through traditional macroscopic or microscopic approaches. However, since explanations based on microscopic models are often in conflict with common macroscopic interpretations, the traditional teaching of the basic concepts related to surface phenomena is often unclear and can prevent students from an effective understanding of the topic. Therefore, this topic often does not enjoy great popularity in teaching, not only at school but also at an undergraduate level.

However, surface phenomena applications are important in physics and other applied disciplines such as physical chemistry, engineering, and health sciences, so it may be worth to reconstruct this content based on research results in Physics Education.

Starting from these observations we asked ourselves how we could contribute to improve the teaching and learning of this topic. We hypothesised that choosing an appropriate modelling scale to introduce a given topic would appreciably enhance the teaching/learning processes at both school and university levels. Thus, from a teaching/learning perspective we think it is important to reflect on the explanatory power of the different scales that can be used to model surface phenomena, reflect on the aspects of each approach that may be useful in promoting effective learning and, at the same time, consider the aspects that could hinder students' understanding.

In a treatment of surface phenomena based on a purely macroscopic approach, surface tension is usually understood as a force per unit of length acting along with the interface, or as the work required to increase a liquid-free surface. Even if this approach can allow students to obtain quantitatively correct results, it may not be effective in promoting an authentic understanding, mainly because it does not provide students with a functioning mechanism that can help them to make sense of the phenomena they observe and study. On the other hand, an explanation of surface phenomena at the microscopic scale can help students to understand concepts like surface tension in terms of interactions among molecules. This approach can help students to understand relevant liquid properties as the coexistence in a stable equilibrium of the vapour and liquid phases, and to better understand the nature of forces acting among liquid molecules. It is well-known that forces acting between two generic molecules are both attractive and repulsive, and are anisotropic and isotropic, respectively. Thus, a microscopic model of liquid seems to be more effective than a macroscopic one for educational purposes. However, this approach is also affected by some critical issues. In fact, it often proves to be too tricky, also from a mathematical point of view, for both high school and undergraduate students. It may also not be suitable when simulating the behaviour of large portions of liquid, since it requires computational resources not available in commonly used computers such as those found in didactic laboratories. Thus, to address these drawbacks, the introduction of alternative approaches is needed. Approaches to teaching/learning surface phenomena alternative to purely macroscopic and microscopic ones, have been proposed in the literature. They imply the introduction of models based on a mesoscopic scale, that is, an intermediate scale between the macroscopic and microscopic ones. Mesoscopic models are used quite commonly in physics research, especially in electrodynamics and hydrodynamics. However, because of the simplifications they introduce, these models are sometimes considered less precise than microscopic ones. Nevertheless, from the pedagogic perspective, the introduction of mesoscopic models represents a good compromise to present surface phenomena at an elementary level. Mesoscopic models, especially when implemented in computer simulations that allow students to easily control the model parameters, can be effectively used to help students to understand basic concepts related to surface phenomena at the level of functioning mechanisms. In the literature, the forces introduced to describe the interaction between mesoscopic particles (i.e., clusters of molecules) have the same form as the forces acting between molecules at the microscopic level. In this way, a satisfying description of real physical systems can be obtained. The mesoscopic approach has the advantages of the microscopic one, and at the same time, allows students and teachers to simulate large portions of liquids overcoming the issues concerning the computational efficiency of common-use computers.

On the basis of our research hypothesis, we decided to study how and to what extent different didactical approaches based on macroscopic and mesoscopic description, respectively, can foster the teaching and learning of surface phenomena at the secondary school level. We designed two teaching-learning sequences (TLSs), one based on macroscopic modelling, and the other on mesoscopic modelling, which were trialled each with a group of upper secondary school students. Each TLS was based on an inquiry-based approach and was planned to involve the students in active learning practice, by means of constructing questions, gathering information (through experiments, simulations, books, internet etc.), discussing and contrasting results, and sharing knowledge. The main goal of the trialling was not to identify which group highlights the best learning depending on the different modelling approach, but to verify the aspects of each approach that can be considered truly relevant in promoting learning.

Data collection instruments to evaluate student learning, such as questionnaires and student worksheets, were designed by us and validated according to methods well-known in the literature. Qualitative, quantitative, and simulated experiments proposed during the trialling were also designed by us and adapted to the TLSs' needs.

The qualitative experiments were designed to introduce students to the situations to be analysed. We also proposed to the students quantitative experiments aimed at studying improving the understanding of surface phenomena and obtaining estimations of surface tension values and contact angles in different liquids. In some cases, starting from well-known experimental set-ups, we reconstructed them with a very low budget, using materials available in ordinary didactic laboratories.

In the simulation activities, the mesoscopic model of liquids was implemented by the SPH method. Students were introduced to the model without discussing its mathematical details. Students were only required to understand the types of interactions between particles by reflecting on the pressure force and the molecular-like force. Particularly, they focused on the different role played by forces over small and large distances and on different interaction between two “liquid” particles and “solid” and “liquid” particles. By using numerical simulations based on the SPH method, students were able to control relevant model parameters, visualize the simulation results and compare them with the experimental ones.

The planning and implementation of the two TLSs on surface phenomena based on macroscopic and mesoscopic approaches, respectively, were guided by the general research question “Which aspects of each approach can be considered relevant in promoting students' scientific learning?”.

In trying to answer this question we came across another question: “What does ‘promoting learning’ actually mean?”. To address this issue, we conducted preliminary literature research on all the features of learning the researchers and the teachers focus on when they investigate issues related to the concept of learning, finding that “promotion of student learning” is quite a complex concept to study. Thus, the reflection on this general idea, and a subsequent extensive literature review on the topic, led us to build a conceptual map highlighting three main aspects of learning that can be considered relevant in the light of the research literature.

According to the literature, the aspects useful to characterize the promotion of learning, with specific reference to scientific learning, are:

1) “Acquisition of conceptual knowledge”,
2) “Intellectual growth”,
3) “Development of a mindset fitted to learning Science”.

According to the literature, each of these three aspects can be described at a finer grain level. In particular, we finally identified 13 variables that can be studied to inspect the effectiveness of our TLSs with respect to the ‘promotion of learning’.

Each variable was studied by means of qualitative and/or quantitative analysis of data coming from the TLSs’ trialling. Particularly, we used phenomenographic and content analyses on data coming from pre-instruction and post-instruction administration of questionnaires, and from the re-administration of one of the questionnaires three month after the end of the trialling. We used thematic analysis on data coming from student worksheets, audio recordings of small group and large group discussions, interviews, and researchers’ notes.

In Chapter 1, we introduce the physics of surface phenomena through an overview of the main literature results about this topic. In particular, we trace back the most common approaches used to introduce surface phenomena at both school and university level.

In Chapter 2, we focus on the treatment of surface phenomena through the mesoscopic approach. In this Chapter, we also describe the main feature of the model used to implement the mesoscopic approach e make some examples of computer-based simulation which allow us to reproduce some well-known surface phenomena.

In Chapter 3, we describe the pedagogical approaches on which this work is based. In this chapter, after introducing teaching/learning sequences and after discussing student’s conceptions, we give an overview of the main features of Constructivism, Educational Reconstruction, Active Learning and, finally, ISLE approach.

Chapter 4 is dedicated to the presentation of our research problem. In this chapter we discuss the results of the bibliographic research that guided us in the study of the aspects of learning we want to analyse to address our research problem.

In Chapter 5, after describing the design of our research, we introduce the activities carried out in the context of the trialling of the TLSs.

In Chapter 6, we describe the instruments used to collect data and the methodologies we used to analyse each specific database. Moreover, we give an overview of the main features of qualitative and quantitative data analysis methodologies.

In Chapter 7, we describe the results of our analysis. In this chapter we report the results obtained for each group to highlight the differences emerging from the introduction of a macroscopic and mesoscopic approach, respectively.

In Chapter 8, we resume the results of the entire work and give some insights on the implications for teaching and the limitation of our study.

CHAPTER 1

INTRODUCTION TO SURFACE PHENOMENA

Objects with a density greater than water (for example, paperclips or pins) can float on its surface. Mercury does not spread on solid surfaces. These are only two of the most common examples of surface phenomena. These phenomena are macroscopic manifestations of microscopic molecular interactions and can be explained in terms of surface tension.

Surface phenomena is a fascinating topic whose understanding involves thermodynamics, statistical mechanics, and fluid mechanics. Moreover, the understanding of these phenomena is relevant not only in physics but also in engineering, biology, and other applied sciences.

At a macroscopic level, surface tension is described as a force at the interface between separate domains, or as energy per unit area, while its microscopic origin is deeply related to intermolecular electrochemical interactions and thermal effects.

Since microscopic intuition is often in conflict with common macroscopic interpretations, the traditional teaching of the basic concepts related to surface phenomena is often unclear and sometimes affected by errors that prevent students from an effective understanding of the topic. Therefore, it often does not enjoy great popularity in teaching, even at an undergraduate level (Marchand et al., 2011; Berry, 1971). From the teaching/learning perspective, it can be relevant to take into account the explanatory power of the different scales that be used to model surface tension (Millar et al., 1990), and plan pedagogical approaches (e.g., Teaching Learning Sequences (Psillos and Kariotoglou, 2016; Meheut, and Psillos, 2004) recognizing the relevance of these modelling scales in fostering student understanding of the physical contents.

Macroscopic models are usually used to introduce surface phenomena, especially at the school level. The macroscopic analysis is based on experimental evidence of the presence of a restoring surface force. This quantity emerges when an infinitesimal contact area between two immiscible fluids is created. The force is tangent to the surface and no a priori knowledge at the microscopic level is required for its formulation.

In this section, standard issues, addressed by both students and researchers, related to surface tension understanding are discussed. The imprecise understanding of this topic is often caused by an improper and/or incomplete definition of the system on which the forces act. Although Marchand et al. (2011) propose a reconciliation between macroscopic and microscopic models for didactical purposes, in our research we also focus on an alternative approach based on a mesoscopic description of fluids. This allows us to simulate physical phenomena by exploiting computational resources available in most of the computers present in didactic laboratories. In the following paragraphs, an overview of the main models through which surface phenomena are presented and their pros and cons are discussed.

1.1 Surface tension: state of the art

1.1.1 Physical units and methods of measurement

In most textbooks, surface tension (usually indicated by the symbol γ), is defined as a force per unit length or as an energy per unit surface. Its physical units in the SI and CGS are reported below:

$$\gamma = 1\,\frac{dyn}{cm} = 1\,\frac{erg}{cm^2} = 10^{-3}\,\frac{N}{m} = 10^{-3}\,\frac{J}{m^2}\,. \qquad (1)$$

The instrument for measuring this quantity is called tensiometer. There are various methods for estimating surface tension, depending on the nature of the liquid and the conditions in which the measurements are made. Among the widespread measurement procedures, there are for instance the du Noüy ring method (du Noüy, 1925), the Wilhelmy plate method (Wu, Dai and Micale, 1999), the capillary rise method (Richards and Carver, 1921), sessile drop method (Staicopolus, 1962). In Tab. 1 surface tension values of a sample of common liquids are reported.

Tab. 1: Surface tension values of a sample of common liquids. Values at different temperatures are reported for water (Butt, Graf and Kappl, 2006).

Liquid	**Surface tension (mN/m)**
Water (10 °C)	74.2
Water (25 °C)	72.0
Water (50 °C)	67.9
Mercury (25 °C)	485.5
Acetone (25 °C)	23.5
Ethanol (25 °C)	23.2
Formamide (25 °C)	57.0
Nitrogen (77 °C)	8.85

1.1.2 Surface tension as a force per unit length

To clarify why γ is defined as a force per unit length, we can consider the system in Fig. 1. In a fluid at rest, two portions of the bulk exert on each other a repulsive effect, i.e., a pressure. At the intersection between the liquid-vapour interface and the surface separating the two portions of the liquid, a new force, attractive and tangent to the liquid-vapour interface, arises in the system. This force is the surface tension (Marchand et al., 2011). The total force acting on the contour (the dashed line in Fig. 1) is proportional to its width b.

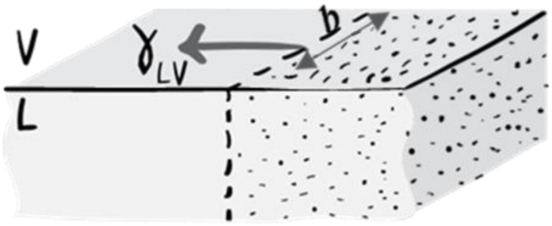


Fig. 1: Representation of surface tension as a force per unit length exerted by one portion of fluid on the other one. Surface tension is parallel to the interface and perpendicular to the separating dashed line (Marchand et al., 2011).

We can use the virtual work principle to link mechanics and thermodynamics points of view. The shift of the contour of width b by a quantity dl, leads to an increase by $b\ dl$ of the area of the interface in the considered portion. This results in an increment of the free energy by an amount $\gamma_{LV}\ b\ dl$. The change in free energy should equate the work done by the surface tension force. This force has to be parallel to the interface, normal to the contour, and have an intensity $\gamma_{LV}\ b$. Thus, the surface tension γ_{LV} is a force per unit length.

The experimental apparatus represented in Fig. 2 can be used to clarify why the surface tension is related to a force parallel to the interface (Durand, 2021). This apparatus is composed of a U-shaped wire frame on which a wire can slide with negligible friction. After soaking the wire frame in a soap solution, a thin film will be supported by the frame and the sliding wire. Surface tension causes a contraction of the liquid surface, thus for the slider to occupy a fixed distance l from the opposite edge, a force F has to act.

As mentioned above, an infinitesimal displacement $\delta \boldsymbol{l} = \delta l\ \boldsymbol{t}$ of the slider (where $\boldsymbol{t}$ is the unit vector tangent to the film) corresponds to a work $\delta W = \boldsymbol{F} \cdot \delta \boldsymbol{l} = F\ \delta l$ done by the operator. In this way the surface energy will be incremented by the exact same amount $\delta W =$

$2\gamma_{LV}\ \delta A$, with $\delta A = h\ \delta l$. The factor 2 is due to the two liquid-vapour interfaces, above and below the film. By equating the two expressions of δW we obtain $F = 2\ \gamma_{LV}\ h\ t$. Therefore, from Newton’s third law of motion, the value of the restoring force per unit length and per interface is γ_{LV}.

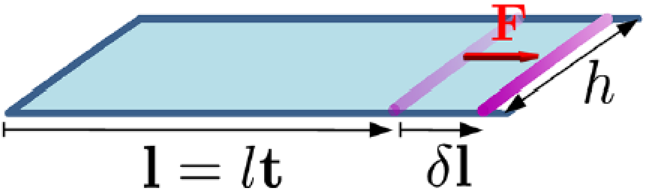
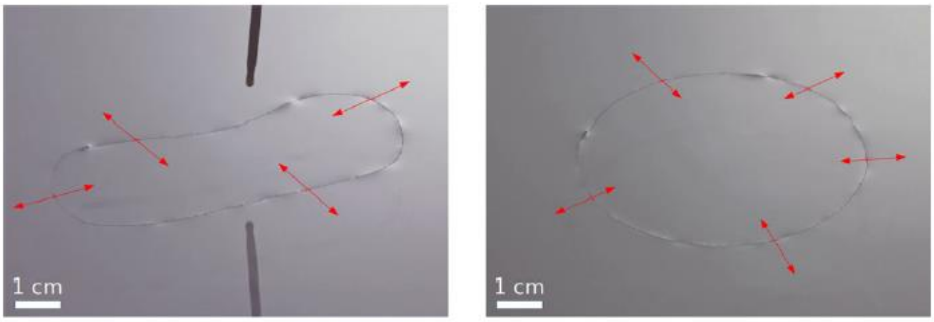


Fig. 2: Sketch of the experimental apparatus used to show the presence of a parallel restoring force which hinds an increase of the liquid-vapour interface (Durand, 2021). However, the experiment described above is not completely satisfactory in explaining the tangential feature of the surface tension. In fact, this setup does not take into account that for any general orientation of the external forces applied at the interface, the resultant of the forces F acting on the two liquid-vapour interfaces has to lie by symmetry along the film.

The experiment shown in Fig. 3 provides further and clearer evidence of the tangential orientation of the surface tension. The experiment consists in laying carefully a loop of thread in a random shape on the surface of the water (Fig. 3a) and subsequently, dropping a small quantity of soap on the surface embedded by the thread (Fig. 3b). In this second phase of the experiment, the loop acquires a circular shape due to a force acting orthogonally to the circumference and tangential to the surface of the water.



(a) (b)

Fig. 3: Experiment highlighting the tangential orientation of surface tension: (a) a loop of thread in a generic shape, is placed over the surface of the water. The red arrows, represent the forces acting on both sides of the thread perimeter. These forces cancel each other, by symmetry. (b) By adding a small quantity of soap on the liquid area embedded by the thread, the latter forms a circular loop, since the inner and outer forces are not balanced. (Durand, 2021).

Moreover, through the experiment described in Fig. 3, it emerges that the surface tension, being an interfacial property, strongly depends on the nature of the two fluids in contact. In particular, forces from both the inner and outer regions, characterized by the same magnitude and opposite in direction, act on each point of the thread when suspended over the liquid (Fig. 3a). On the other hand, as it is shown in Fig. 3b, after dropping the soap, on each point of the thread a net force perpendicular to it and pointing outward acts. This force is due to the decrease in the magnitude of the inner tensile force after the introduction of the soap.

1.1.3 Surface tension as an energy per unit area

From the thermodynamics perspective, surface tension can be seen as the excess free energy due to the presence of an interface between bulk phases (Gibbs, 1948). The environment of a molecule near interphase (for instance, the liquid-vapour interphase) differs from that of a molecule in bulk. As it is possible to note in Fig. 4, a molecule on the surface establishes fewer bonds with the surrounding molecules than a molecule in the bulk, and it causes an increase in free energy.

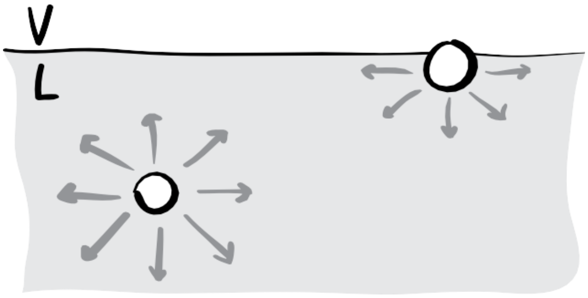


Fig. 4: Representation of the forces acting on a molecule near the liquid-vapour interphase and in bulk. The ‘missing’ intermolecular bonds near the interface lead to an increment of the free energy per unit area, i.e., the surface tension (Marchand et al., 2011).

If we take into account a system of volume V containing n molecules at temperature T, the surface tension can be expressed as a function of the free energy G per unit area as:

$$\gamma_{LV} = \left(\frac{\partial G}{\partial A}\right)_{T,V,n} \tag{2}$$

Thus, γ_{LV} is the energy necessary to increase the area of the interface by one unit and it is usually expressed in $\frac{J}{m^2}$.

1.1.4 Traditional interpretations of the Young- Dupré equation in the thermodynamic and mechanical perspective

Liquid-vapour surface tension can be experimentally determined by measuring the force necessary to pull a metallic plate out of a liquid contained in a tank. The setup used to carry out this measurement is sketched in Fig. 5a.
Let's consider a vertical shift of the plate by a quantity dl. Since the plate's displacement does not affect the area of the liquid-vapour interface, the interfacial energy does not vary. Conversely, the plate's motion causes a decrease of the immersed solid-liquid interface area, and an increase of the solid-vapour interface, by the same quantity $b\,dl$.

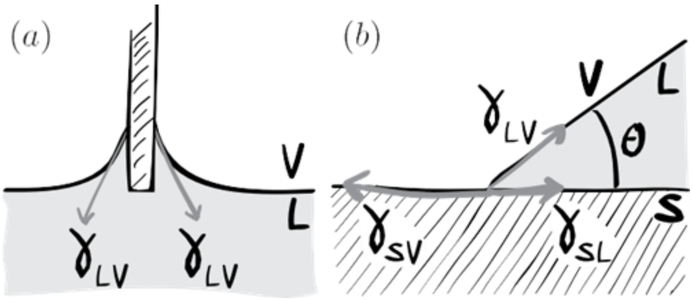


Fig. 5: (a) Sketch of the experimental apparatus used to measure the liquid-vapour surface tension γ_{LV}. The force per unit length necessary to pull the metallic plate out of the liquid is $\gamma_{LV}\,cos\,\vartheta$, where ϑ is the contact angle at the equilibrium. (b) The Young-Dupré law can be interpreted as a condition of force balance for surface tensions (Marchand et al., 2011).

That implies a variation of the free energy $dG = (\gamma_{SV} - \gamma_{SL})b\,dl$ in which γ_{SV} and γ_{SL} represent the solid-vapour and solid-liquid surface tensions. This is the energy provided through the work done by the operator who carries out the experiment, due to the force necessary to displace the plate by a quantity dl. Therefore, this force must have a modulus equal to $(\gamma_{SV} - \gamma_{SL})b$. The relation between this quantity and the liquid-vapour surface tension γ_{LV}, can be found by introducing the Young-Dupré law for the contact angle ϑ. We define the contact line as the ideal boundary at which all the interfaces (liquid-solid, liquid-vapour, solid-vapour interfaces) meet each other. Then, the liquid forms an angle ϑ with the solid at the contact line (Young, 1805). This quantity is called contact angle and its value is given by the well-known Young-Dupré equation

$$\gamma_{LV}\, cos\,\vartheta\ = \gamma_{SV} - \gamma_{SL}. \tag{3}$$

Thus, the force exerted on the plate can be expressed as $\gamma_{LV}\, cos\,\vartheta\ b$, and can be used to design a tensiometer.

From a mechanical perspective, this force can be interpreted as due to the surface tension that acts parallel to the liquid-vapour interface. The total force exerted on the solid is vertical since, by symmetry, the horizontal components cancel each other. By taking the vertical component of the surface tension times b, one indeed gets $b\,\gamma_{LV}\, cos\,\vartheta$. By analogous reasoning, the forces balance condition at the contact line gives Young-Dupré's law for ϑ. The equilibrium condition along the vertical direction i.e., along the solid substrate, gives $\gamma_{SL} + \gamma_{LV}\, cos\,\vartheta\ = \gamma_{SV}$ which is the result shown in Eq. 3.

This interpretation is a common source of confusion for students, who seem to struggle in comprehending the situations proposed up to now.

1.1.5 Young-Dupré equation: a new perspective

In most textbooks surface phenomena are usually addressed through a thermodynamic approach rather than a mechanical one since this latter is considered unclear and misleading to introduce this topic.

Durand (2021), starting from the consideration that a mechanical approach is more intuitive for students, shows that capillary phenomena can be correctly described by using this approach, when the region of the system on which the forces act is properly defined.

In Durand (2021) it is possible to find an interesting derivation of the Young-Dupré equation, showing as this relation can be interpreted as an interface condition at the contact line, rather than a force balance equation. Thanks to this, mistakes in the identification of capillary forces acting on the system of interest can be avoided.

The geometry of a system composed of a liquid and a vapour in contact with a solid can be described by using the already cited Young-Dupré equation (Eq. 3).

However, since physical forces act on material systems and not on mathematical lines, the introduction of this equation in terms of the balance of forces acting on the contact line, which is a mathematical line, can be misleading for students.

In addition, many textbooks present the Young-Dupré equation by introducing arguments based on free energy minimization that, failing to mention the support reaction R, come to an unbalance of forces along the vertical direction.

To correctly identify the capillary forces acting on the system of interest, Durand (2021) suggests considering the meniscus formed by the liquid close to a vertical wall (Fig. 6). Thus, to explain why in Fig. 6 four forces act on the contact line, which is at the end of the liquid-vapour interface, while only one must be considered to answer the question “what is the force exerted on the liquid-vapour interface at the contact line?”, Durand (2021) derives the Young–Dupré equation (Eq. 3) by introducing a new mechanical approach.

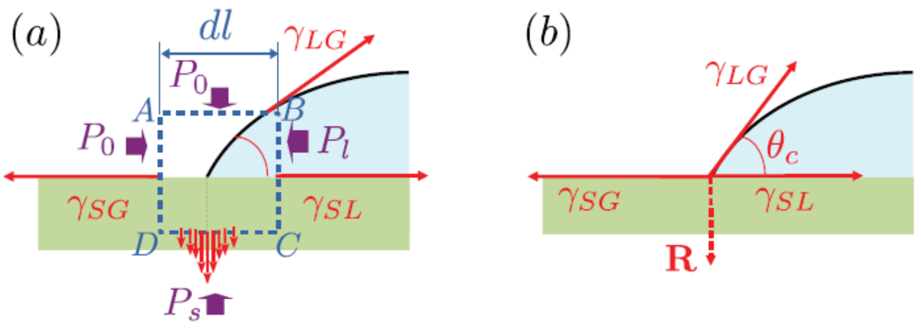


Fig. 6: (a) Representation of the forces acting on a control volume enclosing the contact line, when the Young-Dupré equation is derived from Newton’s second principle. (b) Young-Dupré equation can be interpreted as an interface condition at the contact line, relating the contact angle θ_c to the surface tensions $\gamma_{SG}, \gamma_{LG}, \gamma_{SL}$ (Durand, 2021).

A control volume with square section $dl \times dl$ which encloses the contact line is defined (see Fig. 6a). The geometry is supposed invariant by translation in the direction perpendicular to the figure. Among the forces per unit length acting on this control volume, there are:

- Forces acting on the volume, as the weight $\rho_{eff} dl^2 \boldsymbol{g}$. These forces scale as dl^2 and are expressed in the general form $\rho_{eff}\, \boldsymbol{f}_v dl^2$. The quantity ρ_{eff} represents the effective density of the system enclosed by the volume.
- Forces acting on the four faces. Pressure is uniform in both vapour and liquid, and its values are indicated as P_0 and P_l, respectively. The pressure acting within the solid is given by two components. The first component, indicated with P_s, equilibrates the pressure acting in the two fluids above. Its value continuously increases from P_0 in the region under the vapour, to P_l in the region under the liquid-vapour, and P_l under the liquid. The associated pressure forces acting on the contour can be expressed as $\sum_i \boldsymbol{P}_i dl$ and scale as dl. The second component of the pressure acting within the solid originates from the elastic response to the normal force $\gamma_{LG}\, sin\theta_c\, \boldsymbol{n}$ pulling on its surface. Usually, surface tensions' force is much weaker than the cohesive forces in the solid, and the deformations of the solid are not significative. Nevertheless, components of stress are finite: they spread through the solid material from the source point (Landau et al., 1986). Conversely, when approaching the contact line, the stress is concentrated in a very localized zone, so its integration over segment DC tends to a constant $\boldsymbol{R}$ independent of dl.
- Capillary forces $\boldsymbol{\Gamma}_{LG}, \boldsymbol{\Gamma}_{SL}, \boldsymbol{\Gamma}_{SG}$, tangential to the interfaces between liquid, vapour, and solid. These forces scale as dl^0.

From Newton's second principle:

$$\sum_i \boldsymbol{P}_i dl + \rho_{eff} \boldsymbol{f}_v dl^2 + (\boldsymbol{\Gamma}_{LG} + \boldsymbol{\Gamma}_{SL} + \boldsymbol{\Gamma}_{SG} + \boldsymbol{R}) = \rho_{eff} \boldsymbol{a}_{cm} dl^2, \qquad (4)$$

Where the term $\rho_{eff} \boldsymbol{a}_{cm} dl^2$ is the inertia of the system inside the control volume, and $\boldsymbol{a}_{cm}$ represents the acceleration of its centre of mass. For $dl \rightarrow 0$ one obtains

$$\boldsymbol{\Gamma}_{LG} + \boldsymbol{\Gamma}_{SL} + \boldsymbol{\Gamma}_{SG} + \boldsymbol{R} = 0. \qquad (5)$$

The vertical projection of the Eq. (5), $R + \gamma_{LG} sin\vartheta_c = 0$ reflects Newton's third law, while its horizontal projection yields the Young–Dupré equation (Eq. 3).

According to this procedure it is then clear how the Young-Dupré equation must be considered as an interface condition at the boundary between three media, rather than a balance of forces on an immaterial line. In this perspective, the Young-Dupré equation defines the geometry around the contact line by relating the contact angle to the three surface tensions. Moreover, in this framework, Durand (2021) shows that theoretically speaking, the Young-Dupré equation does not apply only to the static case, but also to a contact line with a non-uniform motion. Nevertheless, this introduces a "discrepancy" since it is known that, due to surface defects, the contact angle on real substrates, is different for an advancing or receding contact line (de Gennes, 2004).

Another aspect to consider is that Young-Dupré equation validity is restricted to a contact line on a non-deformable solid substrate, even if recently, several authors (Andreotti and Snoeijer, 2020; Dervaux et al., 2020; Zhao, 2018; Karpitschka et al., 2016) have studied the Young-Dupré equation and wetting phenomena also in the case of a deformable substrate.

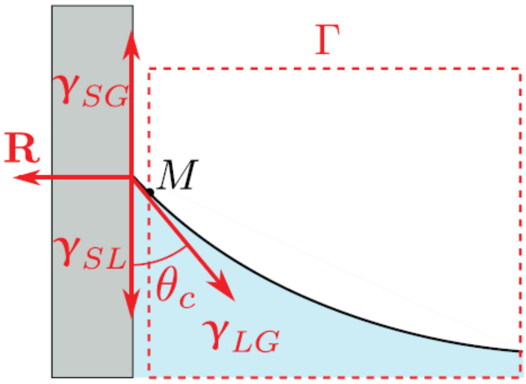


Fig. 7: Illustration of quantities at play in the Young–Dupré equation, clarifying which is the force acting on the liquid-vapour interface at the contact line (Durand, 2021).

Summing up, to correctly identify the force exerted on the liquid-vapour interface at the contact line, Durand (2021) suggests the introduction of a control volume Γ which encloses liquid and vapour phases except for a thin layer at the vicinity of the wall (Fig. 7). The capillary force exerted by this thin layer on the system at point M tends to $-\gamma_{LG}$ as the layer thickness decreases to 0.

1.1.6 Why is surface tension a force parallel to the interface?

One of the most interesting questions one can ask when dealing with surface phenomena is "Why is surface tension a force parallel to the interface?" This question was addressed through different approaches (Grekov, 2021; Marchand et al., 2011; Berry; 1971). In particular, Marchand et al. (2011) starting from Berry's results, tried to clarify this point by analysing the behaviour of the liquid-vapour interface in a microscopic perspective.

In Fig. 8a the liquid-vapour interface obtained through a Molecular Dynamics simulation is represented. The simulated molecules interact through a Lennard-Jones potential (Weijs et al., 2011; Indekeu, 1992). In Fig. 8b the corresponding time-averaged density profile is plotted. As can be seen, the transition from the region of high density of the liquid, to the region of low density of the vapour, involves a narrow region of molecules.

The red dotted line in Fig. 8a divides the system into two parts. This can facilitate the identification of the capillary forces acting on the system.

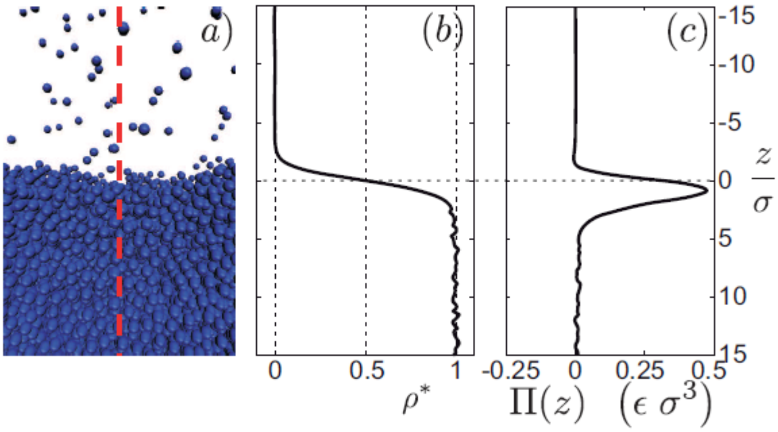


Fig.8: Representation of the liquid-vapour interface. The vertical axis is in unit of the molecular scale σ. (a) liquid-vapour interface simulated by introducing Lennard-Jones potential. (b) Time-averaged normalized density profile $\rho^*(z)$ across the liquid-vapour interface. (c) Tangential force per unit area exerted by the left part on the right part of the system. In the plot the difference $\Pi = p_{NN} - p_{TT}$ between the normal and tangential components of the stress tensor are represented.

The force per unit surface, which the left part of the system exerts on the right one as a function of the vertical position z can be defined as stress. This stress is given by two components. The first is the pressure P, which we assume has the same value in the vapour and the liquid bulk, the second one is an extra stress $\Pi(z)$ acting along the direction parallel to the interface (see Fig. 8c).

By analysing the profile of this stress anisotropy, it can be noted that there is a force at the interface, parallel to it. The range of action of this force is comparable with the thickness (few molecular scales) of the density jump across the interface. Thus, since the integrated contribution of this force is equal to γ_{LV} per unit length, i.e., the surface tension, it is evident that surface tension is a mechanical force. At this point, starting from the result that there is a parallel force at the interface, it is possible to answer the initial question.

While in Fig. 4 only the attraction between molecules is represented, in Fig. 9 the repulsive forces (dashed arrows) in the internal pressure are also included.

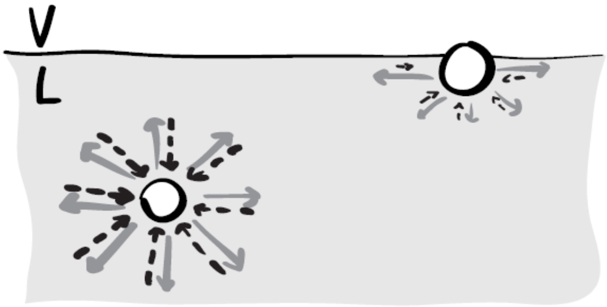


Fig. 9: Repulsive (dashed black arrows) and attractive (solid grey arrows) forces acting in the bulk and at the surface.

The net average force on a molecule far from the surface is zero due to the up-down symmetry in the bulk. On the other hand, around the interface, the symmetry is broken and to restore the force balance in the vertical direction, the upward repulsive arrow (dashed arrow) has to equate the downward attractive one (solid arrow). Parallel to the interface the symmetry is intact, meaning that a force balance is present on the surface. Thus, there is no reason why the attractive forces should have the same magnitude as the repulsive ones along the interface. The attractive forces are stronger than the repulsive ones, resulting in a positive surface tension force (Marchand et al., 2011).

To explain why the intermolecular forces give rise to such a strong tension along the surface, Marchand et al. (2011) use Berry (1971)'s arguments. As noted by Berry (1971), to a good approximation, the repulsive contribution to the pressure is isotropic while attraction is strongly anisotropic. Due to the hard core of the molecules, the range of action of the repulsive force is short and can be considered as "contact force". Given its short-range nature, the repulsive force is not very sensitive to the changes in the molecular structure around the interface and can be assumed equally strong in all directions (Weijs et al., 2011). On the other hand, the attractive forces act at long range and are particularly affected by variations in the molecular structure. Thus, that gives rise to the pressure anisotropy around the interface from which the surface tension force originates.

Marchand et al. (2011) study the problem in more detail, analysing the horizontal and vertical directions separately. He first divides the liquid into two regions using control surfaces parallel to the liquid-vapour interface (see Fig. 10a). As can be seen in Fig. 10a the liquid exerts on the dotted region a force resulting from both the attractive and repulsive interactions. Given that the region is at equilibrium, there must be a balance between these components. Since the density increases from the vapour towards the liquid phase, the attractive force becomes more intense as the size of the attracting region increases. The magnitude of the attractive forces saturates to the bulk value when the control surface is close to the interface.

Along the vertical direction, Marchand et al. (2011) divide the liquid into two regions using a control surface perpendicular to the liquid-vapour interface (Fig. 10b). The magnitude of repulsive forces exerted by the left side of the liquid on the dotted region, given their isotropic nature, increases departing from the vapour toward the liquid bulk, in a way analogous to that in Fig. 10a. On the other hand, the intensity of attraction depends very weakly on the vertical direction. This results in a net attraction of the dotted region by the rest of the liquid (dark grey arrow in Fig. 10c), which grows stronger near the interface.

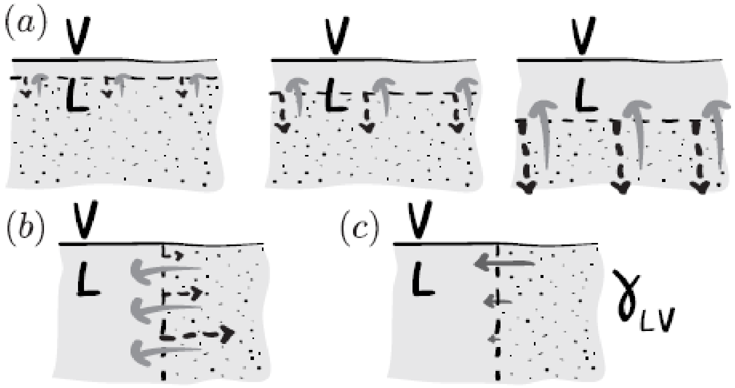


Fig.10: Representation of the forces exerted on a region of liquid (dotted region) by the rest of the liquid. (a) A line parallel to the liquid-vapour interface divides the dotted region from the interfacial region. The dotted region is submitted to an attractive force (grey arrows) and repulsive force (dashed black arrows) exerted by the rest of the liquid. These forces balance each other. (b) A line perpendicular to the liquid-vapour interface divides the liquid in two regions. The dotted region on the right is submitted to an attractive force (grey arrows) and to a repulsive force (dashed arrows) exerted by the rest of the liquid. As the repulsive force is isotropic, it has the same magnitude as in (a) and hence decays near the surface. On the contrary, the attractive force is almost constant, also close to the surface. (c) This leads to a net attractive force from one side on the other.

CHAPTER 2

SURFACE TENSION IN THE MESOSCOPIC PERSPECTIVE

As previously anticipated, choosing the scale at which a given topic is introduced, is crucial from the didactic point of view. Therefore, it is important to analyse the aspects of each approach, potentially useful in promoting effective learning and also consider those aspects that could hinder student understanding. In a treatment of surface phenomena based on a purely macroscopic approach, surface tension is usually understood as a force per unit of length acting along the interface, or as the work required to increase a liquid free surface. Even if this approach can allow students to obtain quantitatively correct results, it may not be effective in promoting an authentic understanding, mainly because it does not provide students with a functioning mechanism (Dieks, 2019; De Regt and Dieks, 2005).

On the other hand, an explanation of surface phenomena at the microscopic scale can help students to understand concepts like surface tension in terms of molecular interactions and thermal effects. This approach can help them to deepen their knowledge on relevant liquid properties like the coexistence of the vapour and liquid phases in a stable equilibrium, and also to better understand the nature of forces acting among liquid molecules. It is well-known that the forces acting between two generic molecules are both attractive and repulsive and are respectively anisotropic and isotropic (Marchand et al., 2011; Roura, 2005; Berry, 1971, see Chapter 1). Thus, a microscopic model for the liquid seems to be more effective than a macroscopic one for educational purposes. However, this approach is also affected by some critical issues. In fact, it often proves to be too tricky for both high school and undergraduate students and it is not suitable when simulating the behaviour of large portions of liquid, since it requires computational resources not available in commonly used computers (as those present in didactic laboratories). To address this kind of drawback, the introduction of alternative approaches is needed.

Approaches to teaching/learning of surface phenomena alternative to purely macroscopic and microscopic ones have been proposed in the literature (Battaglia et al. 2021; Battaglia et al., 2019; Besson and Viennot, 2004). They imply the introduction of models based on a mesoscopic scale, that is at an intermediate level between the macroscopic and microscopic descriptions. Mesoscopic models are quite commonly used in physics research (e.g., Jaiswal et al., 2023; Mortensen, 2021; Manghia et al., 2014). However, because of the simplifications they introduce, these models are sometimes considered less precise than microscopic ones.

Nevertheless, in the pedagogic perspective, the introduction of mesoscopic models represents a good compromise in presenting surface phenomena at an elementary level. These models, especially when implemented in computer simulations, can be effectively used to help students to understand basic concepts related to surface phenomena at the level of functional mechanisms, allowing them to easily control the parameters of the system. In the mesoscopic model we focus on in our research, liquid is made of particles whose size is way bigger than that of any molecule. For example, the radius of a mesoscopic particle has the dimension of a fraction of a millimetre, while the average radius of a molecule has the dimension of a few angstroms. In this sense, mesoscopic particles can be considered as clusters of liquid molecules.

It is worth noting that, when building a simulation of this model, particles size and interparticle distance must be chosen accurately. In fact, it is fundamental to work with an appropriate spatial resolution in order to correctly simulate a given phenomenon and to achieve good computation efficiency.

The forces introduced to describe the interaction between mesoscopic particles have the same form as the ones acting between molecules at the microscopic level. In this way a satisfying description of real physical systems can be obtained. Thus, this mesoscopic approach has the advantages of the microscopic one, and at the same time allows teachers/students to simulate large portions of liquids overcoming the issues concerning the computational complexity.

To implement our numerical simulations, we use a computational method called smoothed-particle hydrodynamics (SPH) (Monaghan, 1992; Lucy, 1977). This algorithm is used for simulating the mechanics of continuum media, such as solid mechanics and fluid flows and it was initially developed to address astrophysical problems. Thanks to its flexibility, SPH turned out to be useful in the study of a wide range of phenomena involving fluid dynamics (Battaglia and Fazio, 2018; Zhu and Fox, 2001, Zhu et al., 1999; Monaghan, 1994). More insights on this model and its implementation are presented in the following paragraph.

2.1 The model

Smoothed Particle Hydrodynamics (SPH) is a Lagrangian numerical method used to obtain approximated solutions of the equations governing fluid dynamics. This algorithm models the liquid with an ensemble of particles which have the same properties of a liquid element in classical fluid mechanics. However, differently from the classical approach, here the liquid is discretized. A simulation based on SPH methodology usually considers the particles much bigger than the molecules, to both obtain a high computational efficiency and preserve good resolution and numerical accuracy of the results. Moreover, the physical properties (mass, density, etc) of the liquid are associated to each liquid particle. Each physical quantity is then obtained by interpolation.

In the SPH model, a continuous quantity $Q(r)$ at position r can be expressed by the following convolution integral over the entire space of the field

$$Q(\boldsymbol{r}) = \int Q(\boldsymbol{r}')\delta(\boldsymbol{r} - \boldsymbol{r}', H)d\boldsymbol{r}' \tag{6}$$

By approximating the Dirac delta function with a weighting function W, the following smoothed field is obtained

$$Q_s(\boldsymbol{r}) = \int Q(\boldsymbol{r}')\, W(\boldsymbol{r} - \boldsymbol{r}', H)d\boldsymbol{r}'. \tag{7}$$

The weighting function W is defined in a range $2H$, where H is the so-called "smoothing length" (see Fig. 11).

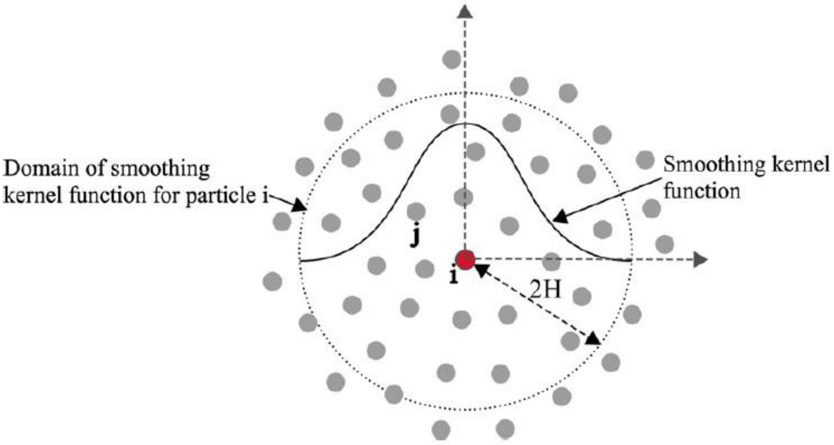


Fig. 11: Schematic representation of an SPH liquid. We show the smoothing Kernel function and its domain (2H), where the parameter H is the ‘smoothing length’.

To determine the properties associated with a particle i at position $\boldsymbol{r}_i$, the integral (7) can be approximated by the following sum:

$$Q_i = \sum_j \Delta V_j Q_j W\big(\boldsymbol{r}_i - \boldsymbol{r}_j, H\big) = \sum_j m_j \frac{Q_j}{\rho_{\ j}} W\big(\boldsymbol{r}_i - \boldsymbol{r}_j, H\big) \qquad (8)$$

where ΔV_j and ρ_j represent the volume and the density of the j_{th} particle and depend on its position $\boldsymbol{r}_j$. The gradients of these quantities can also be approximated by a sum. The dynamics and properties of each particle can be computed then by replacing the quantities (fluid properties and their gradients) appearing in the Navier-Stokes equations with their discretized versions, as explained above.

Several versions of SPH approximations to the Navier-Stokes equations have been reported in the literature (Monaghan, 1992). In our analysis we exploit the following momentum-conservation equation suggested by (Tartakovsky and Meakin, 2005)

$$\frac{d\boldsymbol{v}_i}{dt} = -\sum\nolimits_j m_j \left(\frac{P_j}{{\rho^2}_j} + \frac{P_i}{{\rho^2}_i}\right) \boldsymbol{\nabla}_i\, W\big(\boldsymbol{r}_i - \boldsymbol{r}_j, H\big) +$$

$$+2\eta \sum_j m_j \frac{(v_i - v_j)}{\rho_i \rho_j \big(\boldsymbol{r}_i - \boldsymbol{r}_j\big)^2} \big(\boldsymbol{r}_i - \boldsymbol{r}_j\big) \cdot \boldsymbol{\nabla}_i\, W\big(\boldsymbol{r}_i - \boldsymbol{r}_j, H\big) + \boldsymbol{g} \qquad (9)$$

where $\boldsymbol{v}_i$ represents the velocity of the i_{th} particle. The first term on the right-hand side, which is the SPH formulation for the pressure gradient, was derived by (Lucy, 1977). The second term on the right-hand side indicates the SPH representation of the viscous force and was obtained by (Morris et al., 1997). In this study, we consider the liquid as slightly compressible, because this makes the SPH numerical method more stable as suggested by Monaghan (2005). The pressures in eq. (9) can be determined directly by the equation of state. In our analysis we model the liquid pressure by using the Tait equation [18]

$$P = \frac{\rho {c^2}_0}{7}\left[\left(\frac{\rho}{\rho_0}\right)^7 - 1\right], \qquad (10)$$

where ρ the density of the liquid and ρ_0 is a reference density (in our analysis we use $\rho_0 = 1000$). We set up the sound speed 50 times greater than the maximum speed available for an SPH fluid particle. In this way, sound speed is large enough for the density fluctuations to be negligible (Monaghan, 2005). The kinematic viscosity of the liquid is simulated by considering the "artificial viscosity" (Monaghan, 2005), widely used in basic SPH algorithms to minimize instabilities in the simulation.

To reproduce physical situations involving surface phenomena and, in particular, to simulate the effect of surface tension and fluid-solid interactions, an additive term was included in the equation (9) accounting for particle-particle interactions (Battaglia, Agliolo Gallitto et al., 2019; Tartakovsky and Meakin, 2005). Thus, the equation (9) becomes:

$$
\begin{aligned}
\frac{d\boldsymbol{v}_i}{dt} = -\sum\nolimits_j m_j \left(\frac{P_j}{\rho^2{}_j} + \frac{P_i}{\rho^2{}_i}\right) \boldsymbol{\nabla}_i\, W\left(\boldsymbol{r}_i - \boldsymbol{r}_j, H\right) + \\
+2\eta \sum\nolimits_j m_j \frac{\left(\boldsymbol{v}_i - \boldsymbol{v}_j\right)}{\rho_i \rho_j \left(\boldsymbol{r}_i - \boldsymbol{r}_j\right)^2} \left(\boldsymbol{r}_i - \boldsymbol{r}_j\right) \cdot \boldsymbol{\nabla}_i\, W\left(\boldsymbol{r}_i - \boldsymbol{r}_j, H\right) + \\
+\boldsymbol{g} + \frac{1}{m_i} \boldsymbol{F}_i \qquad (11)
\end{aligned}
$$

where $\boldsymbol{F}_i$ is the force acting on particle *i*, exerted by all the other liquid particles. The interaction force introduced in our analysis is given by

$$
\boldsymbol{F}_{ij} = \begin{cases} s_{ij} cos\left(\frac{3\pi}{4H} \left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|\right) & \left|\boldsymbol{r}_j - \boldsymbol{r}_i\right| \leq 2H \\ 0 & \left|\boldsymbol{r}_j - \boldsymbol{r}_i\right| > 2H \end{cases} \qquad (12)
$$

where s_{ij} represents the magnitude of the force acting between particles *i* and *j* and $\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|$ is the distance between them. System dynamics is strictly related to the parameter *H*.

The inter-particle force $\boldsymbol{F}_{ij}$ is antisymmetric (i.e., $\boldsymbol{F}_{ij} = -\boldsymbol{F}_{ji}$) and this ensures momentum conservation. Particle-particle interaction should be repulsive at short distances and attractive at large distances. Therefore, the magnitude of this force depends only on the distance between particles, and it is not related to the physical properties of the liquid.

To achieve good computational efficiency, it is necessary to reduce the number of inter-particle interactions. This can be done by setting a long-distance cut-off. In our study, we set the cut-off at a distance $2H$.

Since the origin of surface tension is strictly connected to intermolecular interactions, it is reasonable to introduce in the mesoscopic model a force which accounts for both short-range repulsive and long-range attractive interactions. The implementation of this force into the SPH model allows us to simulate both surface tension and fluid-solid interactions when the liquid is in contact with solid boundaries. The interaction force introduced in our analysis is repulsive for inter-particle distances lower than $2/3H$, attractive for inter-particle distances between $2/3H$ and $2H$ and tends to zero for inter-particle distances larger than $2H$.

The repulsive force contribution is crucial for reproducing the behaviour of a liquid surface consistent with experimental observations, as reported in the literature (Tartakovsky and Panchenko, 2016; Akinci at al., 2013; Tartakovsky and Meakin, 2006). In our analysis, we use the Wendland smoothing kernel function (Monaghan, 2005), since this polynomial function exhibits very good stability against the tensile instability (Gonzalez et al., 2011). Time evolution is obtained by a second-order accurate method (Monaghan, 2005) which is a variant of the leapfrog scheme.

Boundary conditions represent a crucial issue when liquid dynamics is simulated by using the SPH method. In the simulations described in Section 2.1.1 the component of the inter-particle forces together with a set of fixed particles at the boundary, reproduces liquid-solid interaction quite accurately.

2.1.1 Simulative experiments

To implement the mesoscopic model of liquid through the SPH algorithm we used a custom-built Fortran code. All the simulation results reported in this section were obtained by running this code on common computers available in our didactic laboratory. We used MATLAB to produce graphs and movies. It is worth noting that the intensity used for the forces varies according to the model used to build the molecular-like force. In particular, in the qualitative simulations (see *Formation of a liquid drop in absence of gravity, Formation of liquid menisci*, and *Liquid sessile drop on a solid surface*) the expression of the force depends on the kernel (Battaglia, Agliolo Gallitto et al., 2019), while in the semi-quantitative simulation (see *The Young-Laplace law in a SPH liquid droplet*) a cosine-like force (Tartakovsky and Meakin, 2005) is introduced.

Formation of a liquid drop in absence of gravity

At the beginning of the simulation, SPH particles were homogeneously arranged into a rectangular configuration characterized by interparticle distance d_s in absence of gravity and they are not in mechanical equilibrium.

We performed many simulations by varying the dimensions of the initial rectangle in order to reproduce droplets of a given liquid for different radii. For each simulation, after many time steps, we computed the radius of the droplet at the equilibrium. Fig. 12 shows an example of droplet at the mechanical equilibrium and the molecular-like and pressure forces acting on it. Simulation results shown in Fig. 12 were obtained by setting the liquid-liquid interaction force $S_{ij} = -10^{-5}$ a.u. and the interparticle distance $d_s = 0.16$ mm.

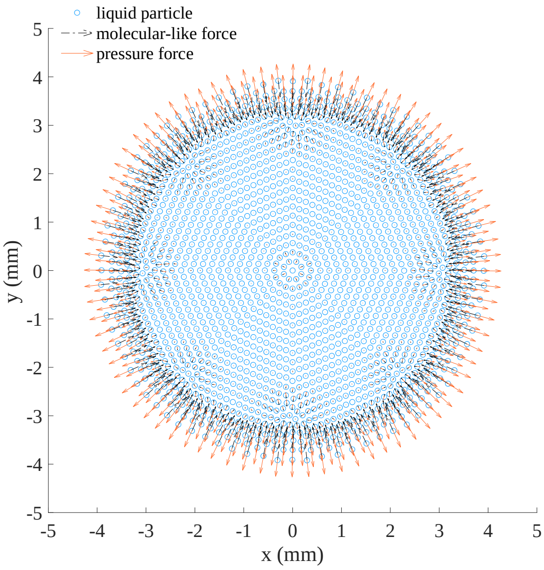


Fig. 12: Liquid droplet at the equilibrium obtained after several simulation steps by setting the liquid-liquid interaction force $S_{ij} = -10^{-5}$ a.u. and the interparticle distance $d_s = 0.16$ mm. Black dashed arrows represent the molecular-like force, the solid orange ones the pressure force.

Formation of liquid menisci

We designed a simulation to analyse the behaviour of two different liquids inside a tank. At the beginning of the simulation, SPH particles, with gravity, were homogeneously arranged into a rectangular configuration characterized by interparticle distance d_s. and they are not in mechanical equilibrium. The walls of the tank are made up of fixed particles. This simulation allows us to reproduce and study the formation of menisci in a water-like and mercury-like liquid, respectively, by varying the values of molecular like forces S_{ij} (Battaglia, Agliolo Gallitto et al., 2019). By setting the intensity of the interaction between two liquid particles close to the intensity of the interaction between a liquid particle and a solid one (we refer to SPH particles), we can simulate the behaviour of a water-like liquid. At the equilibrium, as can be seen in Fig. 13, the simulated SPH liquid forms a concave meniscus comparable to that experimentally observed for water contained in a glass tank.

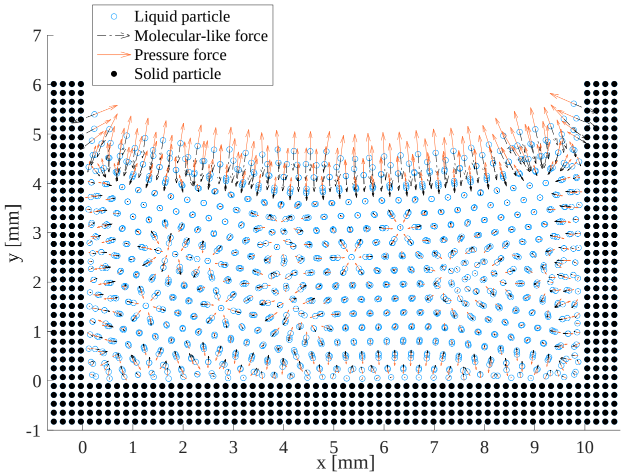


Fig. 13: Water-like liquid in a tank at the equilibrium, obtained after several simulation steps, by setting liquid-liquid and solid-liquid interaction force equal to 3.1 and 2.6 a.u., respectively, and the initial interparticle distance $d_s = 0.2$ mm. The black dots are the (fixed) SPH particles composing the solid walls. Black dashed arrows represent the molecular-like force, the solid orange ones the pressure force.

By setting the intensity of the interaction between two liquid particles remarkably greater than the intensity of the interaction between a liquid particle and a solid one we can simulate the behaviour of a mercury-like liquid. At the equilibrium, as can be seen in Fig. 14, the simulated SPH liquid forms a convex meniscus comparable to that experimentally observed for mercury contained in a glass tank.

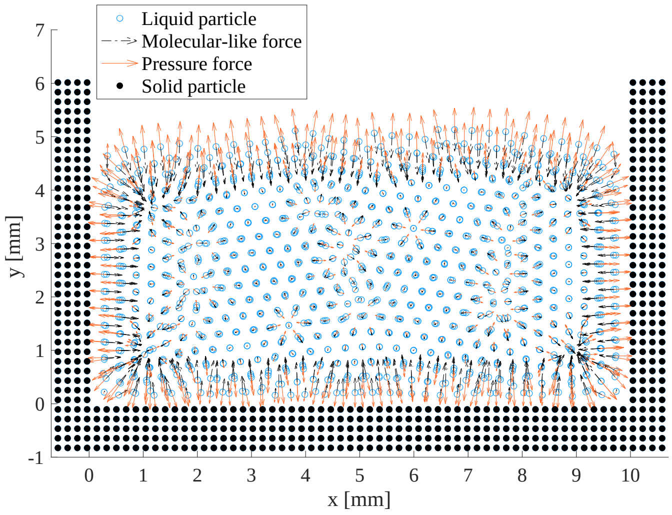


Fig. 14: Mecury-like liquid in a tank at the equilibrium, obtained after several simulation steps by setting liquid-liquid and solid-liquid interaction force equal to 3.1 and 1.85 a.u., respectively, and the initial interparticle distance d_s = 0.2 mm. The black dots are the (fixed) SPH particles composing the solid walls. Black dashed arrows represent the molecular-like force, the solid orange ones the pressure force.

Liquid sessile drop on a solid surface

This simulation was designed to reproduce a sessile drop, that is, a liquid drop lying on a solid surface. Also in this case, the solid is simulated by introducing SPH fixed particles. We reproduce the behaviour of a small bidimensional drop lying on a perfectly rigid solid surface in presence of gravity, for two different values of the intensity of the solid-liquid interaction. By setting the intensity of the solid-liquid interaction to 1.85, a liquid drop which does not wet the solid surface is obtained. In this case the angle α between the liquid and the solid is lower than $\pi/2$. On the other hand, by setting the intensity the solid-liquid interaction to 2.70, a liquid drop wetting the solid surface is obtained. In this case the angle between the liquid and the solid α is higher than $\pi/2$.

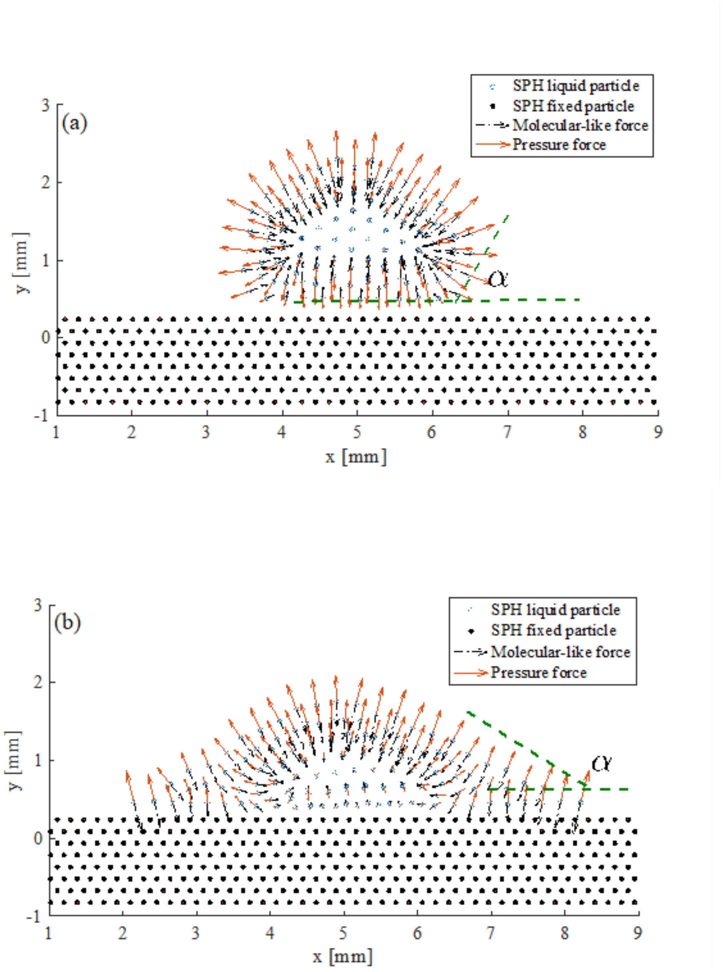


Fig. 15: Liquid drop lying on a solid surface for (a) non-wetting α angle (liquid-solid interaction set to 1.85 a.u.) and (b) wetting α angle (liquid-solid interaction set to 2.6 a.u.). The liquid-liquid interaction is set to 3.0 a.u. in both cases. The black dots are the (fixed) SPH particles composing the solid surface. Orange solid arrows represent the resultant of the molecular-like forces, black dashed ones the pressure force.

The Young-Laplace law in a SPH liquid droplet

At the mechanical equilibrium, the pressure inside the liquid droplet described above is related to the surface tension and the droplet radius through the Young-Laplace law

$$P_T = \frac{\gamma}{R} \tag{13}$$

where γ is the surface tension, R and P_T the radius and the pressure inside the droplet, respectively. Thus, the surface tension can be determined once the pressure inside the droplet is known.

Since SPH representation of a liquid is isomorphic to molecular dynamics with many-body particle-particle interactions (Hoover, 1998), the SPH equations and the particle-particle interactions can be treated in a consistent manner.

The pressure P_T can be computed through the virial theorem (Lion and Allen, 2012) as follows

$$P_T = P_k + \frac{1}{4\pi r^2}\sum_i \sum_j \boldsymbol{r}_{ij} \cdot \boldsymbol{R}_{ij}, \qquad i \neq j \tag{14}$$

where P_k is the ideal gas (kinetic) contribution to the pressure, r is a radius of a circumference inscribed in the drop and $\boldsymbol{R}_{ij}$ is the particle-particle interaction force. The summation in Equation (14) is performed over the i particles that lie inside the radius r and the j particles in the drop[1]. In this calculation self-interactions are not considered. When the system achieves the mechanical equilibrium, the viscous forces are zero, so the interaction force is given by

$$\mathbf{R}_{ij} = \boldsymbol{T}_{ij} + \mathbf{F}_{ij.} \tag{15}$$

where $\boldsymbol{T}_{ij}$ is the "pressure" force. By replacing $\mathbf{R}_{ij}$ found in the equation (14) into (15), and considering that at the equilibrium $P_k = 0$, the pressure inside the droplet P_T can be obtained as output of the simulation. Fig. 2 shows the pressure P_T of the simulated liquid, computed by using equation (14) as a function of the inverse of the radius R. The linear fitting obtained by using the equation (13) is also reported.

As can be seen Fig. 16, the linear regression curve shows a good agreement between the simulations results and Young-Laplace law.

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[1] In a computer simulation, the pressure is usually calculated via the Virial Theorem of Clausius. It is worth noting that our simulation works in a bidimensional space and for this reason we calculated the pressure as the ratio between the "virial" and the area $4\pi r^2$ of a circle of radius r inside the droplet (see Eq. (14)).

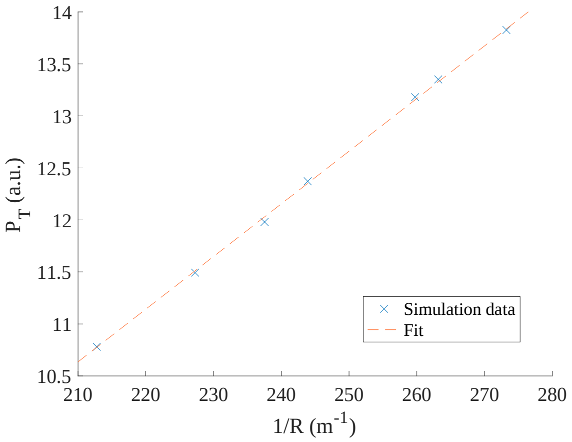


Fig. 16: Droplet pressure as a function of the inverse of the droplet radius for the simulated liquid. The blue symbols represent the simulation data, while the dotted line is the linear regression curve. The determination coefficient is about 0.99.

CHAPTER 3

PEDAGOGICAL APPROACHES

This section describes the general idea of Teaching/Learning Sequence (TLS), and the theoretical and pedagogical frameworks and methodologies on which a TLS can be based.

3.1 Introduction

Several research-inspired pedagogic activities and approaches for improving students' understanding of scientific knowledge have been developed as a result of '70s and early '80s research studies eliciting students' conceptions regarding natural phenomena and concepts and to theoretical developments on teaching and learning as a constructive activity (e.g., Lijnse, 1995; 1994; Artigue, 1988, Kattman et al., 1995 and following papers).

A notable line of inquiry involves the design and implementation of topic-oriented sequences for teaching physics (and more generally science), set in a more general context regarding a specific content to be developed.

This line can be traced back to a science education research tradition which investigates teaching and learning at a micro level (e.g., specific session) or medium level (e.g, single topic sequence) rather than at the macro level of a full year or multi-year curriculum (Kariotoglou and Tselfes 2000).

These pedagogic activities and products involve both research and development aiming at creating a close linking of the teaching and learning of a given topic.

Actually, teaching sequences of this kind are based on the tradition of action research, being both research tools and innovations aiming at the handling of specific topic-related learning problems. Lijnse (1995, 1994) brought to the attention of the European research community questions and issues regarding the character of research into teaching sequences. It is argued that this sort of activity is a kind of "developmental research" involving the linking of design, development, and application of a teaching sequence on a specific topic, usually lasting a few weeks, in a cycling evolutionary process enlightened by rich research data. In the context of mathematics education, Artigue (1988) suggested a fruitful theoretical framework for developing teaching sequences drawing the attention to a priori epistemological analysis of the topic to be taught, an approach which has also proved effective for science education.

Starting from 1995, Kattman et al. have developed a framework for elaborating and improving the design of teaching learning sequences in terms of “Educational Reconstruction” (Kattman et al., 1995). This framework has gained a significant popularity among the science education researchers, and we will describe it in some detail in Section 2.4, as we will adopt it in our study.

Although various terms have been proposed in the past, the term ‘Teaching-Learning Sequence’ (TLS) is today commonly used to indicate the relation between proposed teaching and expected student learning as a distinguishing feature of a research-inspired topic-oriented sequence (Psillos and Méheut, 2001). A TLS is both an interventional research activity and a product, like a traditional curriculum unit package, which embeds well-researched teaching-learning activities empirically adapted to student reasoning. Sometimes teaching guidelines covering expected student reactions are also included.

A TLS is involved in a gradual research-based evolutionary process aiming at linking the scientific and student perspective and trying to fill the gap between scientific models and pupil’s alternative representations of natural phenomena. In this sense, in the designing of a TLS it is crucial to consider different aspects such as content analysis, epistemology, student’s conceptions and motivations, learning and pedagogical theories (e.g., constructivism), didactic methodologies and learning environments (e.g., active learning (Meyers and Jones, 1993; Bonwell and Eison, 1991), Inquiry/Investigation-based learning environments (Etkina et al., 2019), and other educational constraints.

3.2 Student’s conceptions

There are several reasons why students find learning difficult in science and in planning a TLS the teacher should know at least about the fundamental difficulty types. For some science topics, learning is difficult because the concepts are very abstract and lack any connection to students’ common experiences. Other topics are difficult because instruction centres on problem-solving and planning strategies to find solutions. A third, important type of difficulty students face when learning sciences involves topic areas in which their prior knowledge is contrary to the targeted scientific concepts. Knowledge of this type is commonly referred as misconceptions or spontaneous models and it is a common feature of science learning problems.

In fact, scientific models are often different from the common man personal views of the world, deeply rooted in mind because developed in years of real-life experience, the so-called spontaneous models (Gentner and Stevens, 1983). When dealing about interpretation of natural phenomena, pupils are other than “tabula rasa”, bringing, instead, a complex set of representative and interpretative schemes of phenomena and trying to adapt new information gained at school to them, perceived as more familiar and adherent to real life evidence. In contrast, the targeted scientific concepts may seem incoherent and useless to the learner. For this reasons, pupil’s knowledge very often diverts from the scientific canons and became a personal interpretation based on alternative representations, i.e. spontaneous ideas about reality, often responsible of mechanisms of resistance or conflict against scientific concepts learned, dealing with same real-life situations.

Decades of research studies about the psychology of learning processes made evident that learning is a process in which the learner increases his competence not only by simply accumulating new facts and skills directly communicated by a teacher, but by reconfiguring his knowledge structures, adapting novelties to his pre-existent mental models, automating procedures and chunking information to reduce memory loads, and by developing strategies and models that tell him when and how facts and skills are relevant (Mislevy, 1993).

For these reasons an approach to physics teaching not taking into account the conflicts between scientific and spontaneous models may often result in pupils (Gilbert et al., 1982):

- not changing at all their personal interpretation of natural phenomena;
- mis-interpreting learned concepts, using them to substantially confirm their spontaneous models;
- developing ideas resulting from the mixing of scientific ideas and spontaneous models, with not resolved internal contradictions;
- accepting the taught contents just in scholastic situations and only to gain good marks in assessment activities.

3.3 Constructivism

Teaching of physics is often textbook-based. Science results are presented to the students, leaving no doubt about their validity. This traditional method gives the teacher a role of dogmatic transmission of information and notions, and students have only to memorize facts and concepts more or less mechanically. However, according to many research results, the teaching of physics, and more generally of science, should be thought of as a continuous research work that proceeds by trial and error, to face new problems or to critically review problems already addressed.

Traditional teacher-centred visions were questioned during the nineteenth and twentieth centuries. Several psychological and pedagogical theories about learning, contributed to the definition of new teaching methodologies and to a student-centred vision, placing the students and no longer the teachers at the centre of teaching.

In particular, constructivism, which was developed starting from the 1950s with the work of the American psychologist George Kelly, questions the possibility of an "objective" knowledge that represents external reality authentically. Knowledge does not exist independently of the subject who knows, it cannot be received or acquired passively but results from the relationship between an active subject and reality.

According to the constructivist theory, each subject builds itself by simultaneously integrating cultural products and mental processes (Chiosso, 2018). Knowledge is a subjective construction of meaning starting from a complex internal reworking of sensations, knowledge, beliefs, emotions.

For constructivism, learning is an active process leading to the construction of knowledge. In this view, traditional lesson loses its centrality, while direct experience, understood as the manipulation and construction of objects, as well as the fruition and deconstruction of different materials and texts, plays a key role.

Based on constructivism and Vygotskian ideas (Pass, 2004), social constructivists begin to underline that knowledge always takes place within a context that influences and enriches it. Each subject, acting on the surrounding environment, develops systems of organization of reality and cognitive enrichment (Chiosso, 2018).

Research frameworks for the teaching of scientific disciplines are dominated by the constructivist model of learning. The observation of facts and the spirit of research should characterize effective science teaching. In this context, it is important to implement activities that involve students directly, that encourage them, without a rigid temporal order and without forcing any phase, to ask questions about phenomena and things, to design experiments/explorations following working hypotheses and building their interpretative models (Italian National Curriculum Guidelines, 2012).

Physics is an experimental science. Thus, educating in physics means not only developing knowledge and understanding of the physical laws and phenomena but also observational and operational skills and, more generally, scientific behaviour and attitudes (Allasia et al., 2003). For this reason, it is necessary to promote education in experimental sciences from an early age, thus promoting the development of behaviours, attitudes, observational and operational skills.

3.4 The model of Educational Reconstruction of the content to be taught

The model of “educational reconstruction”, developed by Kattmann et al. (1995), provides a possible framework for designing and validating teaching-learning sequences (TLSs). This model is based on planning instruction models that were developed in the German pedagogical tradition. In particular, it combines the German hermeneutic tradition on scientific content with constructivist approaches to teaching and learning. One of the key points of this model is the idea that to improve the quality of teaching and learning science subject matter issues and student learning needs and capabilities must be approached with the same attention.

Clarification of science subject matter is fundamental to develop and improve the instruction of a given science content. Clarification of science subject matter occurs through the process of “elementarisation” which contributes to build the core ideas (i.e., elementary ideas) of the content to be taught.

Frequently, the clarification process is mostly or uniquely informed by issues coming from the structure of the science content considered. Educational issues are addressed only after the science subject matter educational issues are addressed. This can happen only after the scientific content has undergone the process of elementarisation.

In the educational reconstruction-based approaches, the analysis of science content considers not only epistemic dimensions (genesis, function and meaning of the concepts), but also context, applications, and ethical and social implications. In this model, the reflections on the science concept structure are closely related to the analysis of the educational significance of the content and to the empirical studies on students' interests and learning processes.

Students' conceptions are considered in a constructivist perspective aiming at reconstructing science content structure by answering to questions as "Which are the most relevant elements of the students' conceptual framework to be respected? Which opportunities are opened by certain elements of students' conceptions or perspectives? Which conceptions of students correspond with scientific concepts in such a way that they can be used for a more adequate and fruitful learning?" (Kattmann et al., 1995).

The model is based on an integrated constructivist view in which the processes leading to the acquisition of knowledge are considered *active* individual construction processes within a given social and material environment, while science knowledge is considered a tentative human construction.

Results obtained by analysing the content structure (linking clarification of the core concepts and the analysis of the educational significance) and preliminary ideas about the construction of instruction must be taken into consideration when planning empirical studies on teaching and learning. In fact, the results of empirical studies affect the processes of educational analysis, elementarisation, and even the setting of detailed goals and objectives.

Although this procedure it is not very common in educational research, it turns out to be suitable when a particular content structure for instruction has to be developed according to students' point of view, especially according to their pre-instructional conceptions and their learning paths.

In the process of educational reconstruction, science content structure and students' conceptions and frames of interpretation are recognized as parameters of equal importance**,** equally required to reach science teaching goals.

An interesting feature of this model is that knowledge achieved in one of the components affects activities and interpretation of the results of the other components in a dynamic process. A way to apply a didactic reconstruction of the contents to be taught consists in designing teaching/learning sequences based on active learning methodologies.

3.5 Active Learning

In the last decades there has been a shift from teacher-centred instruction to student-centred one, involving students in actively participate in the construction of knowledge. Conventional teacher-centred education usually consists in imparting knowledge and providing information. In this context, contents to be taught are often syllabi-directed (Degago and Kaino, 2015), and teachers are rarely engaged in building meaningful and constructive interactions with students. Students are considered as passive recipients of information, who must constantly be told what they need to know and perform (Thang et al., 2023). Teachers own the knowledge, students' participation in the acquisition of knowledge is minimal. This kind of approach hampers students' ability to direct their own learning experience (Lojdová, 2019). To engage and empower students in their learning experience, student-centred approaches have to be introduced. A student-centred approach is strongly based on the constructivist idea that learners confer meanings to what they learn by relating new information to what they have already known (Emaliana, 2017). Student-centred approaches recognize that students have responsibility of acquiring information and making sense of it, with teachers acting as facilitators (Kang, 2018).

In its most ideal sense, students take charge of their own learning, design their content of learning, and define their learning paths in a student-centred approach (Murphy at al., 2021).

However, we must consider that teacher-centred and student-centred approaches are not mutually exclusive. Before student-centred learning can be fully realized, teachers must make an effort to promote a change of students' conceptions of learning (Chen and Tsai, 2021). In a teaching experience based on active learning, students are actively engaged in their learning by discovering, processing, and applying information. They are involved in higher order thinking tasks such as analysis, synthesis, and evaluation (Bloom, 1956). Active learning is based on the assumptions that learning needs an active effort and that individuals learn in many different ways. At the same time, it is worth noting that active learning alone cannot increase student learning, in the absence of content, reflection, or objectives. The definition of active learning is broad, and many authors, such as Bonwell and Eison (1991) explicitly recognize a given range of practices that can be traced back to it. They suggest a spectrum of practices to foster active learning. These practices range from pausing lecture to allow students to clarify and organize their ideas by discussing with neighbours, to introduce students to case studies as a focal point for decision-making. The National Survey of Student Engagement (NSSE) and the Australasian Survey of Student Engagement (AUSSE) provides a very simple definition: active learning involves "students' efforts to actively construct their knowledge." This definition is based on the items that the AUSSE uses to evaluate active learning: working with other students on a project, making a presentation, asking questions or contributing to discussions, participating in a community-based project as part of a course, working with other students outside of class on assignments, discussing ideas from a course with others outside of class, tutoring peers (Carr et al., 2015).

Meyers and Jones (1993) identify three fundamental factors, strictly related to each other, on which active learning is based: basic elements, learning strategies, and teaching resources. The basic elements of active learning are speaking, listening, reading, writing, and reflecting. These five elements involve cognitive activities that allow students to clarify the question, consolidate and appropriate the new knowledge. The second factor is represented by the learning strategies that embed the five elements introduced above. Learning strategies include small work-groups, cooperative work, case studies, simulation, discussion, problem solving and journal writing. The third factor is given by the teaching resources that teachers use to encourage students to interact and participate actively in the activities.

It is clear from the research that more discovery-oriented and student-active teaching methods ensure higher student motivation, more learning at higher cognitive levels, and longer retention of knowledge (e.g., Nilson, 1998).

Feldman (1989) identified two tasks relevant in fostering students' achievements: to help students to understand the relevance and importance of the information, and to make it understandable. The dimensions of teaching that seem to be most strongly related to students' achievements are: (1) preparation and organization, (2) clarity of communication, (3) perceived outcome of the instruction, and (4) stimulating student interest in the course content (Feldman, 1989). The first two concern the organization of information and its effective presentation and have traditionally been part of a teacher's preparation. The second ones deal with motivation and engaging students in their learning.

In the context of active learning, learning must be seen a "meaning making" process. Learners can create new learning by finding connections among existing concepts, knowledge, and experience.

One of the challenges faced by teachers is to help students to build knowledge. Teachers must consider that lots of students did not establish an elaborate network of structures to build upon and create memory hints that should improve their knowledge of the material. Moreover, it is important to reflect on the fact that not all activities are suitable for producing new knowledge. For example, activities in which students are asked to create constructs of important concepts and links among these constructs are not sufficient to produce new knowledge. To produce new knowledge students must also think and reflect about their experiences. They need to explain the concepts to themselves, to their peers, and to teachers. This reflection makes it possible the active meaning-making process. It allows students to form concepts and schemes, improve them, use them repeatedly, and create those long-term links that make the subject “make sense”. When students deeply understand why information is important and useful, when their curiosity is encouraged, when they are properly challenged, and when they perceive relevance of the content, they will put more effort and will achieve better results.

Another aspect to reflect on concerns factors that might hinder active learning. According to Michael (2007) they can be traced back to three categories: (a) student characteristics or attributes (e.g., students do not know how to do active learning, they are unprepared or unwilling to engage in active learning), (b) issues directly impacting faculty (e.g., it takes too much preparation, faculty have less control over the class, poorer evaluations, there is no reward structure, or faculty do not know how to do it), and (c) pedagogical issues (e.g., classroom set-up does not lend itself to active learning, it takes too much class time, student assessment is difficult, class size, hard to predict learning outcomes or quality control). Anyway, in the light of what was discussed above, all these barriers can be broken down through creativity, flexibility, institutional resources, and support from teachers.

3.6 Learning in the Inquiry perspective

The definition of inquiry-based teaching/learning approach covers a variety of ideas in education (Dobber et al., 2017; Pedaste et al., 2015). We can distinguish three main kinds of inquiry approaches, which overlap many others by meaning and using:

1. Problem-based learning;
2. Project-based learning;
3. Inquiry-based Science learning.

After a brief introduction on Problem-based learning and Project-based learning, we will discuss in detail the Inquiry-based Science learning, that we consider particularly suitable for our research aims.

3.6.1 Problem-based learning

Problem-based learning is a specific approach to inquiry-based learning developed in higher education contexts. Based on the ideas of Dewey at the beginning of the last century (Sorzio, 2009; Dewey, 1922), problem-based learning started to spread in many disciplines, not necessarily scientific (Yew and Goh, 2016; Barrows, 1996). This approach turns to be particularly effective when long-term knowledge retention and applications are considered (Yew and Goh, 2016).

Although in the literature it is possible to find numerous definitions for this approach (Yew and Goh, 2016), it is possible to identify some main features (Barrows, 1996) that can be summarized as follow:

- learning is student-centred;
- learning is based on teamwork;
- each group has a facilitator, that is a person who acts as a guide;
- authentic problems are presented as starting point of a teaching-learning sequence before students have researched or studied the topic;
- issues faced during a teaching-learning sequence are exploited as tools to achieve the required knowledge and the problem-solving skills necessary to solve more general problems;
- self-directed learning allows students to acquire new information and competencies.

3.6.2 Project-based learning

According to Project-based learning, learning has to be structured on the basis of projects, that consist of complex tasks containing challenging questions and problems.

Students are involved in design, problem-solving, decision-making, and investigative activities that allow them to work relatively autonomously over extended periods, and culminate in realistic products or presentations (Thomas, 2000).

As in other inquiry-based learning approaches, in Project-based learning approach students actively learn through recurrent cycles of analysis and synthesis, action and reflection. Unlike problem-based learning, this approach focuses on projects, which may consist of single or multiple activities, lasting from several weeks to an entire year. Projects are bridges between phenomena in the classroom and real-life experiences; the questions and answers that arise in their daily enterprise are given value and are shown to be open to systematic inquiry (Blumenfeld et al., 1991).

3.6.3 Inquiry-based Science learning

According to one of the recognized definitions, scientific inquiry learning is a tool for developing scientific thinking strategies and deep understanding of science content (Ben-David and Zohar, 2009). Thus, the term “Inquiry” refers to scientists’ work that may be understood as the study of the natural world, aiming at finding explanations for natural phenomena, on the basis of evidence coming from the world itself. “Inquiry” also concerns the activities of students such as posing questions, planning investigations, and reviewing what is already known in light of experimental evidence-that mirror what scientists do (Martin-Hansen, 2002).

In general, in inquiry-based classroom, students are engaged in the ’inquiry cycle’ based on thinking strategies for developing thoughtful inquiry processes. An inquiry-based learning approach is effective when students explicitly understand how and why scientists think in that specific way, not only what scientists investigate (Dobber et al., 2017).

The inquiry cycle can be articulated in different phases, depending on the considered model. Tab. 2, shows the the five-phase cycle as formulated by Byebee (Bybee et al., 2006).

Tab. 2: The inquiry cycle based on 5E model by Bybee (Byebee et al. 2006)

5E Instructional Model (Bybee et al., 2006)	
Phases	**Description**
Engagement	Teachers assesses learners' prior knowledge and engage them in new contexts and situations by introducing activities that promote curiosity and elicit prior knowledge.
Exploration	Learners carry out exploration activities through which their current concepts, processes, and skills are identified, and conceptual change is facilitated. Learners may be involved in hands-on activities that help them to use prior knowledge to generate new ideas, and design and conduct a preliminary investigation.
Explanation	The process of explanation provides learners and teachers with a common use of terms relative to the learning tasks.
Elaboration	Once learners have an explanation and terms for their learning tasks, they are involved in further experiences that allow them to extend and elaborate concepts, processes, and skills acquired. This phase can facilitate the transfer of concepts to new contexts and situations.
Evaluation	This is an important opportunity for learners to use the skills they have acquired and evaluate their understanding and abilities. Teachers have the opportunity to evaluate learners' progresses toward achieving the educational objectives.

The inquiry methodology aims at promoting the development of the ability and disposition to investigate, at building knowledge and understanding through active learning, to achieve specific science process skills, and communicating scientific explanations (Martin-Hansen, 2002). It is also credited to act on conceptual change on cognitive competencies and science process skill (Sahhyar and Nst, 2017).

It is possible to distinguish different levels of performing inquiry depending on factors such as the degree of teacher-centred or student-centred learning that takes place in the classroom. Different types of inquiry are used for specific needs in the science classroom (Martin-Hansen, 2002). In Tab. 3 the main characteristics of inquiry phases and levels are reported.

Tab. 3: Levels of inquiry (Martin-Hansen, 2002; National Research Council, 2000).

Inquiry Phase	**Level of Inquiry**			
	Confirmation/ Demonstrative Inquiry	**Structured Inquiry**	**Guided Inquiry**	**Open Inquiry**
Engage	Learner is involved in questions posed by the teachers, and use materials, or other	Learner sharpens or clarifies questions posed by the teachers, and materials, or	Learner examines the asked questions and poses new questions	Learner poses questions

	sources provided by them	other sources provided by them		
Explore	Learner is provided with data. Teachers explain how to analyse data them	Learner is provided with data. They are asked to analyse data	Learner is directed in the data collection process	Learner determines what constitutes evidence and collects it
Explain	Learner is provided with evidence	Learner is provided with possible ways to use evidence to formulate explanation	Learner is guided in the process leading to the formulation of explanations starting from evidence	Learner formulates explanation after summarising evidence
Elaborate		Learner is provided with possible connections	Learner is guided toward scientific knowledge	Learner independently explores resources and forms the links to explanations
Evaluate	Learner is provided with steps and procedures for communication	Learner is provided with broad guidelines to use sharpened communication	Learner is coached in development of communication	Learner forms reasonable and logical argument to communicate explanations

In the scientific inquiry learning paradigm, teachers assist students in comprehending physics and integrating themselves into the culture of science. In addition, the scientific inquiry learning model helps students develop critical thinking skills and enables them to construct knowledge like a scientist (Bao et al., 2013; Ali and Spencer, 2012). Thus, it is believed that understandings of Scientific Inquiry are crucial and necessary components of the modern battle cry of "scientific literacy" (Lederman et al., 2013). Then, scientific investigation has a significant impact on a student's ability to apply physics concepts in real-world situations (Dumbrajs et al., 2011; Hussain et al., 2011). In addition, Inquiry-based Science Teaching improves students' process skills and attitudes towards science (Ergül et al., 2011; Turpin, 2004).

3.7 The ISLE Approach

The acronym ISLE stands for Investigative Science Learning Environment. It is an intentional-holistic learning environment (Etkina, Brookes, et al., 2019). It is Intentional to curriculum design, which means how and what students learn has the same importance (Brookes et al., 2020), while holistic concerns learning Physics as a whole, coherent frame (Etkina, 2015a).

The ISLE approach can be considered as an extension of the inquiry approach: ISLE goes beyond the plan inquiry one by also paying particular attention to the emotional-psychological sphere in the context of learning.

The ISLE approach aims at:

- ”engaging students in the process of doing physics with a simplified model of the actual logical progression of the activities of physicists” (Brookes et al., 2020);
- fostering and improving students’ well-being in the process of learning Physics, engaging them in the process of doing Physics (Brookes et al., 2020).

These goals correspond to the two intentionalities of the approach itself (Etkina, Brookes, et al., 2021):

1. how students learn Physics;
2. how they feel while learning it.

Tab. 4: Main features of ISLE approach (Etkina, Brookes, et al., 2019; Etkina, Heuvelen, et al., 2006).

Learning process and learning tools	Developing Physics concepts as their idea through a series of ”knowledge-generating activities”, which mirror scientific practice.
	Representing physical processes using Multiple Representations as tools for conceptual building, reasoning, and evaluation.
Assessment and community of learners	Assessing student’s ability to reason like a physicist and simultaneously help them develop these abilities.
	Making social interactions and sharing ideas as a natural part of student progress.
Need to know and time for telling	Proving intrinsic motivation through jump-start of extrinsic one.
	Generating in-classroom moments where the students can share, reflect on, and compare ideas to what physicists think.

These intentionalities are the core of the ISLE approach, even determining the choices for its underpinned theoretical perspectives (Brookes et al., 2020). Tab. 4 reports some of the aspects of the ISLE approach that are crucial in promoting students' engagement in doing Physics. It is worth noting that ISLE practices are student-centred: students are actively engaged and learn content knowledge through constructing knowledge (Etkina, Brookes, et al., 2019). In this sense, the ISLE approach is an example of authentic inquiry (Brookes et al., 2020; Chinn and Malhotra, 2002). In the ISLE approach each activity is carried out on the basis of a well-defined process diagram (see Fig. 17). The process illustrated in the diagram is not intended as a linear progression (Etkina, 2015a; Etkina, Brookes, et al., 2019) but repetitive (Brookes et al., 2020), supporting students in their reasoning.

Through activities involving observational, testing and application experiments students can go back and revisit their assumptions and eventually change their explanations (Etkina, Brookes, et al., 2019). The experimental activities based on the ISLE approach differ from those performed in the classroom, in which the performance is for demonstrative or ”cookbook” experiments, such as ”demo”, ”labs”, or ”hands-on” experiments (Brookes et al., 2020). The ISLE approach involves students in experiments highlighting the interplay between experimentation and theory development (Brookes et al., 2020). Students are not passive viewers, but they are actively engaged in the process of doing Physics (Etkina, Brookes, et al., 2019). Students are encouraged to:

- develop new ideas about Physics starting from the need to explain something unexplained in an observational experiment;
- generate multiple explanations for a given physical situation and use them to predict possible outcomes of a testing experiment;
- apply the hypotheses tested to a new real physical situation to investigate using an application experiment.

In the Tab. 5 some details about these experiments are reported. The observational and testing experiments lead students to model and explain (using models in instructions, Hestenes et al., 1995; Treagust et al., 2003). It is possible to identify four types of simplification in modelling physical situations (Etkina, Warren, et al., 2006): model of objects, model of interactions between multiple objects, model of systems, qualitative and quantitative models of processes.

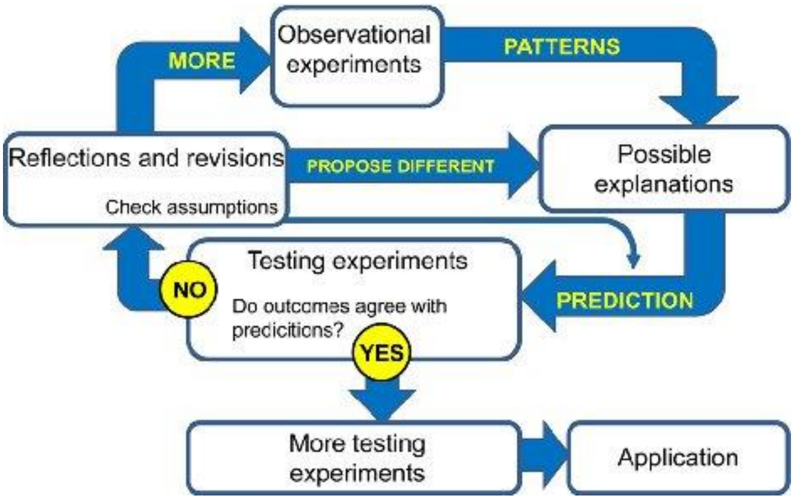


Fig. 17: Process for doing Physics according to the Investigative Science Learning Environment (ISLE) cycle (Etkina, et al. 2013).

ISLE activities, engage students in the process of using models to describe and explain phenomena and to predict new ones (Etkina, Warren, et al., 2006). In this context, students are also guided to think about the limitations of the models, change their assumptions, and revise the model adopted (Brookes et al., 2020). These practices help students do Physics as scientists do (Etkina, Warren, et al., 2006). The ISLE process in Fig. 17 shows as, every new concept starts with a simple observational experiment. Then, students investigate the phenomenon of interest and the data collected trying to identify and define a pattern (Etkina, Brookes, et al., 2019). Students by using different representations, create patterns helping them to connect the quantities they are observing. In this way, representations are used for sense-making and not only as answer-making, as they are commonly adopted in traditional use (Etkina, 2015a). In Tab. 6 main instances of representations used to create patterns are reported.

Tab. 5: Description of the three experiment categories involved in the ISLE approach (Etkina, Brookes, et al., 2019).

Type of experiment	Description	Students’ tasks
Observational experiments	Experiments designed to investigate a phenomenon by collecting qualitative or quantitative data without specific expectations of the outcome. They are properly designed hypothesis-generating and explanation-	Analysing a new phenomenon
		Identifying a pattern
		Developing an explanation or multiple explanations

	generating experiments, enacting the search for a recurring pattern/model that describes the observed phenomenology.	
Testing experiments	Experiments designed to predict the outcomes based on the hypothesis/explanation under testing.	Having multiple hypotheses to test
		Arguing which hypothesis applies to the situation
Application experiments	Experiments designed for problem-solving in a real context, for determining the value of some physical quantities using relations/models that have not been refuted by multiple testing experiments.	Applying existing knowledge to solve practical, real-world problems

Students use representations to reason, building a bridge between phenomena and algebra (Etkina, 2015a; Van Heuvelen, 1991; Van Heuvelen and Zou, 2001), helping them in the process of conceptualisation. The first step in building a concept is deeply connected to observational experiments and concerns the sphere of inductive reasoning (Etkina, 2015a). Consequently, students make up explanations, and exploit analogical reasoning because explanations are mainly based on p-prior knowledge (diSessa, 1993). Students test their reasonings through experiments proposals, comparing the observed measurements with their expected outcomes such that they can verify their hypothesis and possibly reject the wrong ones (Etkina and Planinšič, 2015). During this procedure, they activate hypothetic/deductive reasoning (Etkina, 2015a). And this happens in testing experiments. Eventually, in the application experiments, students apply reasoning in an authentic context, both exploring and extending the use of Multiple Representations in solving paper-and-pencil and experimental problems (Brookes et al., 2020). In this step instructional laboratories, where they project experiments, are also fundamental (Etkina, Brookes, et al., 2019).

In this context students gain skills (model building, use of multiple representations, experiment design, etc…) similar to the ones scientist exploit in their research (Etkina, Brookes, et al., 2019).

Therefore, the assessment needs to be implemented in the ISLE-based classroom to address those scientific reasoning abilities. The matching of learning goals with formative assessment is a detailed feature of the ISLE approach (Brookes et al., 2020). Scientific abilities are purposefully defined instead of the most common terms used in educational practices,”science-process skills” with a precise aim: ”to underscore that these are not automatic skills, but are instead processes that students need to use reflectively and critically” (Etkina, Heuvelen, et al., 2006, p.1).

Tab. 6: Representations involved in ISLE observational experiments (Etkina, 2015a).

Type of representations	**Examples**
Traditional Representations	Sketches, Graphs, Ray diagrams, Tables, Circuit Diagrams, Ray Diagrams
Modified Traditional Representations	Motion diagrams, Force diagrams
Novel Representations	Energy Bar Charts, Momentum Bar Charts (conserved quantity bar charts)

It is possible to identify seven scientific abilities (Etkina, Heuvelen, et al., 2006) that refer to habits like processes, procedures, and methods, which are typical physicists’ habits. They are:

1. representing information in multiple ways;

2. designing and conducting an experiment to investigate a phenomenon;

3. designing and conducting a testing experiment (testing an idea/hypothesis/explanation or mathematical relation);

4. designing and conducting an application experiment;

5. communicating scientific ideas;

6. collecting and analysing experimental data;

7. evaluating models, equations, solutions, and claims.

Scientific abilities promoted through the ISLE approach are assessed by rubrics. The ISLE rubrics (Etkina, Heuvelen, et al., 2006) guide instructors in implementing formative assessment for grading and promote students’ self-assessment skill (Buggé and Etkina, 2020). To foster students’ well-being in doing Physics in the ISLE framework, teachers encourage and allow students to revise and improve their work by adopting a re-submission policy (Etkina, Brookes, et al., 2019) for all kinds of learning products (homework assignments, lab reports and so on). Among the other ISLE resources used for the assessment there are the textbooks, *College Physics: Explore and Apply* (Etkina, Planinsic, et al., 2019), the Instructor Guide, *Active Learning Guide* (Etkina, Brookes, Planinsic, and Van Heuleven, 2019), the website of the ISLE approach (Etkina, Brookes, and Planinsic, 2021) with all info and online resources freely available. ISLE develops and constructs the process of learning Physics based on cognitive, epistemological, socio-cultural and human theoretical perspectives (Brookes et al., 2020). These underpinnings proceed from the two ISLE intentionalities (Bugg´e and Etkina, 2020). Teachers who want to adopt this learning system must revise their role in the classroom, enhancing these perspectives in their teaching framework.

All the aspects of the ISLE approach discussed above can be considered relevant for the research we develop in this thesis. The use of different kinds of experiments, interactive experiments, ways to represent, describe, and explain data, attention to psyco-cognitive aspects of learning and ISLE-inspired pedagogical tools (open questions, interrogative approaches, self-evaluation, …) will be used in the research as we will specify in the following chapters.

CHAPTER 4

THE RESEARCH

4.1 Research hypothesis, research question

As we already discussed in Chapter 1, from the teaching/learning perspective, it can be relevant to think about the explanatory power of the different scales that can be used to model surface tension (Marchand et al., 2011) and plan Teaching Learning Sequences recognizing the relevance of the modelling scales in fostering student understanding of the physical contents.

Starting from these considerations, we asked ourselves how we could contribute to improve the teaching and learning of this topic. We hypothesised that choosing an appropriate modelling scale to introduce this topic would appreciably enhance the teaching/learning processes at both school and university levels.

On the basis of this research hypothesis, we decided to study how and to what extent different didactical approaches based on the macroscopic and mesoscopic description, respectively, can foster the teaching and learning of surface phenomena, starting from the secondary school level. We designed two teaching-learning sequences (TLSs), one based on macroscopic modelling and the other on mesoscopic modelling, which were trialled each with a group of upper secondary school students.

The planning and implementation of the two TLSs on surface phenomena based on macroscopic and mesoscopic approaches, respectively, were guided by the general research question, “Which aspects of each approach can be considered relevant in promoting students’ scientific learning?”.

In trying to answer this question, we came across another question: “what does ‘promoting learning’ actually mean?”. To address this issue, we conducted preliminary literature research on all the features of learning the researchers and the teachers focus on when they investigate issues related to the concept of learning, finding that the “promotion of student learning” is quite a complex concept to study. Thus, the reflection on this general idea, and a subsequent extensive literature review on the topic, led us to build a conceptual map highlighting three main aspects of learning that can be considered relevant in the light of the research literature.

According to the literature, among the learning dimensions (Houseal, 2015; Marzano, 1992) useful to characterize the promotion of learning, with specific reference to the scientific one, there are:

1. Acquisition of conceptual knowledge,
2. Intellectual growth,
3. Development of a mindset suited to learning Science.

Each of these dimensions can be described at a finer grain level, also on the basis of the research literature on aspects of learning and of student learning difficulties (see section 4.2 for details). On the basis of the literature, we identified for our research 13 sub-dimensions of learning, henceforth named ‘study variables’ (or, simply, ‘variables’). We will study these variables to inspect the various aspects of our TLSs with respect to the general aim of promoting learning. We are aware that the choice of these 13 sub-dimensions may not be exhaustive as more or different sub-dimensions could be included. Our choice was guided by the abovementioned research literature and by our interest and experience in conducting pedagogical trials related to the promotion of learning in science. The 13 sub-dimensions we want to discuss in our study are depicted in Fig. 18.

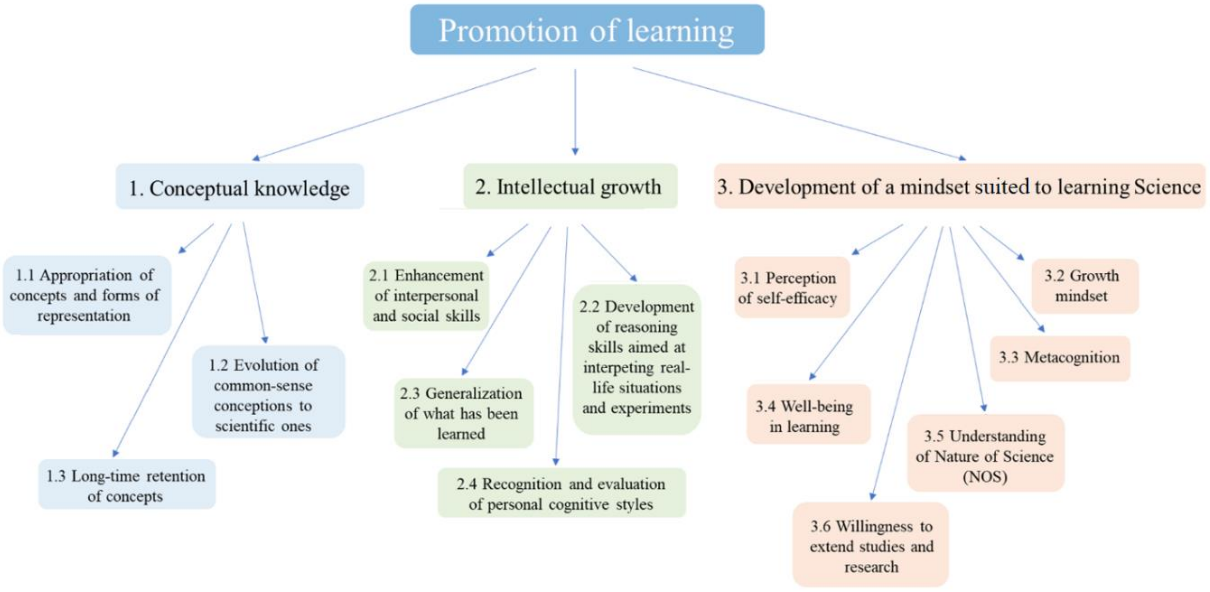


Fig. 18: Diagram showing the research-informed main dimensions of ‘promotion of learning’ in a teaching/learning sequence, with specific reference to scientific learning, and the related sub-dimensions/variables, of our study.

The dimensions of learning and, more specifically, the related variables depicted in Fig. 18 are obviously interrelated. Just to give an example, one can argue that variables 3.3: Metacognition and 3.5: Understanding of Nature of Science are also related to the 2. Intellectual growth dimension, and variables 2.1: Enhancement of interpersonal and social skills and 1.2: Evolution of common-sense conceptions to scientific ones could give a finer grain detail also of dimension 3. Development of a mindset suited to learning science". However, in this research, we will study, for the sake of simplicity, the variables as they are represented in Fig. 18.

4.2 The map: an overview

In the following sections, the variables analysed in our work will be described in relation to the literature. Even if these variables should deserve more extensive treatment, here we report the aspects that we believe are most relevant for a proper understanding of our research.

4.2.1 Appropriation of concepts and forms of representation

One of the main goals for teachers, at both school and university level, is to promote a deep and meaningful understanding of concepts and ways to represent them and the related data collected from the world. To achieve this goal, students must "own the content" and be able to represent it in different ways, modifying and transforming the reasoning patterns of their knowledge related to it. This means that students have to learn to shape content understanding and representation according to personal approaches.

Appropriation of contents implies deep conceptual understanding, but it also involves a reflexive process of transforming scientific discourse in a way that is authentic and personal (O. Levrini et al., 2015). On the other hand, appropriation of forms of representation of concepts is basically related to the ability to use different representation and communication channels. Verbal, iconic, tabular, graphic, and analytical representations are some of the most used in science.

As we already pointed out, in educational contexts, it is fundamental that teachers actively involve students in the study of all disciplines, including scientific ones. In fact, only through active involvement in their learning process students can interpret the contents studied, develop their personal thinking about what they study and consequently build their identity.

Creativity, interpretation, and experimentation are fundamental elements to promote deep comprehension. However, in science classes, students are usually not encouraged to pursue or become aware of their personal ways of building the content they learn and how that relates to who they are as people (Sjøberg, 2002). For these reasons students can move away from scientific fields of study.

Learning scientific disciplines, including physics, can support students in constructing and developing their personal narrative of themself.

Although for long-time teachers believed that their main role was to transmit content to students, there is today an increasing consensus among educators and researchers on the need to focus on broader and deeper aspects of learning, such as appropriation and deep understanding of the contents and enhancement of students' identity.

The term *appropriation* was introduced by Bakhtin in linguistics to describe the process operated by the subject to adapt a word living in a world of others to his or her personal world by populating the word with idiosyncratic intentions, accents, and purposes (O. Levrini et al., 2015). This definition was not born in the educative field, but it highlights the dialogic and social nature of learning. The social dimension is well explained by Rogoff (1995), that stated that appropriation occurs in the process of participation, as the individual changes through involvement in the situation at hand. This participation contributes both to the direction of the evolving event and to the individual's preparation for involvement in other similar events. (Rogoff, 1995, p. 153).

The term appropriation stresses very strongly that the agent of the process is the student itself. Appropriation is a reflective process in which "*I* make something *mine"*. Word's etymology clarifies the meaning well: *autos* in ancient Greek and *proper* in Latin have indeed the same meaning: "of one's own." Such etymological closeness to *authenticity* enlarges the semantic meaning of *appropriation* and makes it particularly evocative for capturing the connection between learning and identity as a reflexive process of creating and recreating a narrative of oneself (Levrini et al., 2015). Therefore, appropriation of contents means "make your own", "epitomize", or "assimilate". The focus of this process cannot be outside of students but inside. Each student has to question his/her own prior knowledge and find a way to nurture his/her personal and creative thinking through the learning of science. Studies show that each student focuses his or her attention on different pieces of knowledge (diSessa, 1993) whose coordination (diSessa and Sherin, 1998) constitutes what is usually called a "concept" and reassembles them according to an idiosyncratic idea.

When students are involved in metacognitive reflections and they explain their thinking about physics contents, they use words or expressions that can be very different from those used by other students, which reveal the authenticity of their discourse. The repetition of words and expressions can be recognized as a personal way of expressing or developing an idiosyncratic idea.

In the discussion about physics contents, teachers can observe appropriation when first personal signature ideas grounded in the discipline emerge in students, and they are able to describe and discuss the contents using not-incidental expressions, i.e., expressions that are consistently used during classroom activities and are characterized by a social value since highlight student position within the classroom community. These descriptions and discussions can be more or less scientifically correct but nevertheless give evidence of the involvement of students in scientific practice, i.e., in debating on a concept and its understanding/appropriation.

A second, deeper appropriation occurs when students can apply the contents to solve problems and face situations. Thus, appropriation is a complex, reflexive process of transforming scientific discourse so as to embody it in one’s own personal story, discuss and debate it, and use it appropriately to solve problems. This process results in a discourse populated with one’s own intentions, idiosyncratic tastes, and purposes, respects the rules and constraints of science as a discipline and is intrinsically social in nature (Levrini et al., 2015).

4.2.2 Evolutions of common-sense conceptions to scientific ones

The process of knowledge construction in human beings begins at birth, if not before, and is a spontaneous process by which each individual gathers experiences from the natural world and information from the social community in which they live and organises them into patterns and models of reality (Ogborn, 2011; Vicentini and Mayer, 1996).

Over the years, therefore, each person acquires different levels of shared (or common) knowledge that are endowed with stability until new experiences or new information undermine the existing patterns. The latter is not all-encompassing, but each has a delimited field of application and a specific functionality determined by the relationship between the organism and its environment.

Common knowledge is therefore the body of knowledge, not explicitly transmitted, on which everyday life is based (Vicentini and Mayer, 1996). It has an ontogenetic development rooted in the individual and the culture to which he or she belongs. The language of common knowledge generally presents a redundancy of meanings in which the most appropriate one for the specific context must be sought. The introduction of new elements of knowledge into the common knowledge schema may occur naturally and without problems, or it may require a change in the network. However, there are certainly moments of partial adaptation of the knowledge itself.

Often, in contrast to common knowledge, we find scientific knowledge: in it, we no longer find the individual, but the protagonist is the individual scientist (or the scientific community), who collects information, experimental data from the natural world, from the artefacts of the laboratory and from the social community, in which the sub-community of scientists working in the same field is distinguished. The relationship between the scientist and the natural world/scientific community is no longer unidirectional but bidirectional, receiving information but also producing artefacts that extend the world of the laboratory. Scientific or formal knowledge is a planned intervention imposed by the school.

The language of scientific knowledge is precise and unambiguous; there is often a continuous osmosis between the two types of language, since the popular language appropriates scientific words, attributing to them a multiplicity of possible meanings, and the scientific language uses popular words, attributing to them a single meaning. In addition to language, other characteristics can be identified that distinguish the two types of knowledge: in popular knowledge, the validity of the schemes of knowledge of reality is mostly implicit, whereas in the scientific community, the validity of the schemes must be proven through critique and cross-checking. In general, there is almost a conflict between the two types of knowledge; the interpretative schemes of naive physics are constantly confirmed by the experiences of everyday life, and this makes them stronger and more credible in the eyes of the subject. What is important is to learn how to use the right knowledge in the right context. It is the context that allows us to determine whether patterns of knowledge are appropriate and legitimate.

In learning physics, however, there is the problem of the similarity/difference between the strategies for building common knowledge and the strategies for building scientific knowledge.

Students therefore come to school with already constructed mental representations of physical reality; these are conceptual schemes that are rarely made explicit, but which nevertheless guide the very perception of reality. Such 'naive theories' of reality are used as a framework for interpretation until they are disproved.

It is precisely the experiences of everyday life that form the experiential basis on which scientific theories are based, but sometimes students' spontaneous patterns of knowledge, although based on the same experiential basis, differ from each other, and can lead to misunderstandings.

From the point of view of meaningful learning, the two different types of knowledge must complement each other, but this does not always happen; in fact, sometimes there can be a total rejection. In general, people tend to hold on to their beliefs as long as possible, as long as they are compatible.

We are talking about a real conceptual change, which inevitably implies a change of attitude towards others, towards oneself, and towards the facts of life. Watzlawick analysed the problem of change in a psychological context and identified two levels of change (e.g., Magnusson, and Templin, 1997.). The first is essentially cognitive, as it occurs when new elements of knowledge are added, but no change in the internal rules of the system takes place. The second level of change, on the other hand, involves changing the rules of the system and requires moving to a higher level, to a meta-level. In this case, a complete change of perspective is required. However, it is possible to identify a third type of change in which a substantial modification of the belief system takes place. Here the affective components of the subject become central, and this is the most difficult and rare change. Learning must lead to different types of change: from the simple enrichment of a schema to the construction of new ones suitable for new contexts.

The conceptual change must therefore take on a new and important meaning: by these words we mean the construction of a scheme of knowledge capable of encompassing both spontaneous and scientific schemes of knowledge, and the definition of the respective rules of use in relation to the contexts of action (Vicentini and Mayer, 1996). The new knowledge must have certain specific characteristics for the subject: he must be able to recognise its explanatory or predictive validity, it must allow him to solve previously unsolvable problems and it must be comprehensible.

4.2.3 Long time retention of concepts

Cornoldi (1995) defines memory as one of the basic psychophysical functions, a prerequisite for cognitive functioning. In general, memory is the capacity to retain traces of external stimuli, more or less complete, over time. Thus, the memory becomes the psychic structure that organises the temporal aspect of behaviour, which determines the links whereby one current event depends on another that occurred previously (Comer, 2013).

It is important to highlight that memory is not static and unchangeable but is an active, dynamic, continuously evolving process. The ability to store new information in one's long-term memory implies, in fact, the ability to effectively integrate and modify the network of one's previous knowledge.

Educational activities should be based on the assumption that the teaching process results in lasting learning. Teachers often believe that after acquiring new knowledge, students will always possess that information. It is recognized that education’s value strongly depends on the long-time retention of what has been learned (Bahrick, 2000). For this reason, the preservation of knowledge learned in designated school courses has been a long-standing interest of educators and teachers.

Both teachers and students find it difficult to maintain long-term memory. Popular beliefs about 'remembering almost nothing' may exert a negative influence on the learning process: if students and teachers enter the classroom well indoctrinated with the philosophy that the factual material students acquire will soon be lost, then why bother to learn it if not to pass exams (Kastrinos, 1965)?

Knowledge decay always implies a period of non-use -the retention interval- and is obviously most problematic in situations where individuals learn something they may not be expected to retrieve or use for a long time (Arthur et al., 1998).

There is evidence that for very long retention intervals (e.g., a decade or more), a dissociation between actual memory performance and individuals' confidence ratings of their own knowledge occurs, suggesting that people are to some extent unaware that they are still in possession of knowledge they acquired long ago (e.g., Conway et al., 1991).

There is no single agreed measure to verify knowledge retention, but several different means, which may not always produce equivalent results. In educational contexts, the two most commonly used measures are recall (i.e., open-ended questions) and recognition (true-false questions). Multiple-choice questions (MCQs) are often based on a mixture of recall and recognition (Arzi et al., 1986).

Most studies report relatively large losses for short retention intervals (months), which accumulate, but they level off, for longer retention intervals (years). According to Bahrick (1984, 1979) and Conway et al. (1991), knowledge should be acquired over a long period in a cycle of repeated re-learning or practice. In this sense, the number of courses an individual has taken in a particular subject influences knowledge retention much more than a high grade received in a single course (Bahrick and Hall, 1991; Bahrick, 1984).

In the context of science education, the long-term retention of learning plays a key role. Students should develop skills and knowledge that foster the reasoning abilities needed to solve problems in everyday life.

Science education should be considered effective when it produces lifelong learning (Streveler at al., 2008; Redish and Smit, 2008). In this view, science education is carried out by fostering the development of the process of inquiry -learning through questioning- and the practice of scientific reasoning is nowadays considered the most effective framework for teaching or learning science, in terms of active construction of long-term meaningful knowledge, supporting the overcoming of both conceptual and epistemological difficulties in problem solving (Kuo at al., 2013; Hammer and Helby, 2003).

The stability of the learning outcomes can be seen in line with the Threshold Concept Theory (TCT) (Meyer and Land, 2005), where it is proposed that once a student has passed certain disciplinary "conceptual gateways" or "portals of understanding" there is no "way back", i.e., the learning that has taken place is transformative and irreversible (hard to forget) and integrative (Adorno et al., 2018). The study conducted by Adorno et al. (2018) showed that master's graduates who continue to practice scientific reasoning through specialised studies showed further improvement in problem-solving. On the contrary, the results obtained suggest that a lack of research-like experiences could be a cause of regression towards a more descriptive epistemological profile in those students who have not completely crossed the conceptual gateways mentioned by the TCT (Meyer and Land, 2005).

4.2.4 Enhancement of interpersonal and social skills

Through the learning process, which occurs through an exchange of direct and indirect messages, individuals learn to play a specific role in the society they live in. The socialisation process consists in the knowledge and assimilation of the value system of the social context in which one lives. Thus, it is a form of interaction with the socio-cultural environment that leads individuals to assume models and possibly adapt to them. However, this process does not imply the loss of personality and individuality. Individuals, from the very beginning of their existence, are social persons with their own personal characteristics.

Social competence is important because it has become clear that the development of oppositional, antisocial behaviour problems begins early in life and these problems are stable over time (Kazdin, 1987; Oleweus, 1979).

Several approaches to defining and measuring social competence have been proposed and analysed in the literature. On a general level, social skills might be defined as socially acceptable behaviours that enable a person to interact effectively with others and to avoid socially unacceptable or aversive responses from others. Social competence can be conceptualized as a multidimensional construct including adaptive behaviour, social skills, and peer relationship variables (Gresham, 1983). In McFall's view (1982), social skills are the specific behaviours that a person exhibits to perform competently on a social task. Social competence, on the other hand, is an evaluative term based on judgments that a person has performed a social task adequately (Gresham, 1983).

Socialisation must be understood as a process of constant mediation between the impulses and feelings of the inner world (subjective point of view) and the external context (objective point of view), through which the personality is formed and matures.

A fundamental and primary role in the socialisation process is played by the educational contexts experimented at schools, universities etc. Instructors guiding students through these educational contexts should value the peculiarities of each individual and guide them towards respect for differences. Learning is thus strongly linked to socialisation, since in the educational perspective “learning to reason” and “learning to live in a social context” are necessary to each other.

The French sociologist Emile Durkheim defined a learning environment as a social microcosm since he identified it as a so-called agency of socialisation. For students, the classroom is the place they meet going out from the family environment. The classroom is the place where different forms of socialisation take place, from the more traditional to the progressive ones, which foster autonomy, collaboration and sharing. School is the place where students can and must overcome the emotional identification with the family, where the transition from natural childish egocentrism to altruism takes place, and where they learn to compare with others about values and norms of society. In this sense, peers group play a priority function, fostering the sense of belonging necessary for the development of self-esteem and the construction of personality and identity.

Important social outcomes include but are not limited to peer acceptance, significant others' judgments of social competence (teachers, peers, and parents), academic achievement, adequate self-concept, and absence of maladaptive problem behaviours. From the educational point of view, the quality of social interaction tends to progress more and more as relationships with peers become more varied and complex, evolving in the direction of the development of social competence, i.e., the ability to interact with others to communicate and to resolve conflicts. This progression makes it possible to overcome the emotional dependence on parents and develop personal autonomy and interaction. Since the development of these social skills is not automatic, explicit and intentional teaching is required. The development of students’ social and interpersonal skills must be one of the main educational objectives. Transversal skills such as knowing how to work in a team, cooperating, the ability to help and support those who are in difficulty, and recognising and accepting differences represent the base on which all the other competencies can be built.

The Italian National indications for the 2018 Curriculum (MIUR) emphasise that social and civic competences can be built by providing a balanced and cooperative school climate, through the critical reading of social phenomena characterizing several environments (not just the lived one), through direct actions to educate to solidarity, empathy, responsibility and by proposing meaningful experiences that enable students to work by exercising cooperation, autonomy, and personal responsibility.

In this context, the teaching of science is not exempt from this task. Scientific disciplines tend to be perceived as a world apart in the didactic curricula, as they only foster the learning of notional contents given by formulas to be learnt mnemonically, while the development of transversal competences is entrusted to the humanities.

Actually, this is just a preconception. In fact, through active learning and teaching methods, which use laboratory and cooperative approaches, it is possible to enhance both scientific rigour and the creativity and curiosity of students.

All the disciplines must contribute to the development of social skills: through the scientific disciplines it is possible to set up learning environments centred on discussion, communication, cooperative work, and the contextualisation of knowledge in reality, in order to improve it (Italian National Indications for the Curriculum, 2012).

4.2.5 Development of reasoning skills aimed at interpreting real-life situations and experiments

There are many cognitive theories explaining student reasoning in terms of structured cognitive concepts or mental models that are of special interest for physics education. For this reason, a lot of research has been dedicated to the analysis of the mental models of students at different school and university levels (https://archiv.ipn.uni-kiel.de/stcse/).

Often teachers ask their students to create explanations for an everyday-life phenomenon and to do this, students can use different models.

Sometimes, physics systems' properties are not directly observable, for this reason the model construction and validation processes require the building of several hypothesis typologies: empirical law hypothesis, synthesis of regularities (arising from phenomenological observations and condensed into rules), and hypothesis for the construction of explicative models introducing theoretical representations and often containing non-observable entities. In building explicative models, inductive reasoning is involved, but an important role is also played by analogical reasoning (Duit and Glynnn, 1996), i.e., the ability to see similarities and differences between a "source" (something perceived as similar to what we are going to analyse) and the "target" (the real phenomena we are studying).

Research in science education has shown the strong presence of causal explanations in common reasoning (Besson, 2010; Silva, 2007). For this reason, the teaching of formal laws and functional relationships alone seems insufficient to promote students' learning and understanding. Students need a causal explanation that supplies a mechanism which can account for the dynamics of facts and effects that have led to a given situation (Fazio et al., 2013).

Cognitive theories explain learning in terms of changes in mental processes and knowledge structures resulting from the learner's efforts to make sense of the physical world (Silva, 2007). Cognitive scientists have described people's personal conceptions of the world by introducing the term ''mental model'' and defining its main features (Johnson-Laird, 1983; Norman, 1983). Greca and Moreira's (2002) define a mental model as ''an internal representation, which acts out as a structural analogue of situations or processes. Its role consists into account for the individuals' reasoning both when they try to understand discourse and when they try to explain and predict the physical world behaviour.'' This representation contains structural information about the properties of the system and functional knowledge about its behaviour.

Gilbert and Boulter (1998) highlight the private nature of mental models and suggest that the researchers must rely on some expressed form of the mental model to infer what it can be. This is mainly done by means of external representations of individual's reasoning, like speech, writing, or other actions (Fazio et al., 2013).

Students' reasoning can be referred to mental models describing their personal views of the world (the spontaneous models (Gentner and Stevens, 1983)), or scientifically accepted models. However, students' reasoning can also be related to a different kind of mental model, defined in literature as ‘‘hybrid models’’ (Greca and Moreira, 2002) or ‘‘synthetic models’’ (Vosniadou, 1994), which represent a composite mental model that unifies different features of initial spontaneous models and scientifically accepted models. Such models are inconsistent (in one or more features) with both models from which they are derived. Research reveals (Bao and Redish, 2006; Maloney and Siegler, 1993) that a student can use different mental models in response to a set of situations or problems considered equivalent by an expert. In particular, Bao and Redish developed a way to deal with these composite mental models ‘‘by considering the student as being able to simultaneously possess multiple models with a distribution of probabilities for the activation of the different models.’’ They define students' model states and analyse changes of such states with specific contextual features in different equivalent questions. Moreover, they point out that probing the context dependence of students' mental models, and the consistency in their deployment, is relevant for teaching, as well as for the construction of assessment tools.

Research conducted by Fazio et al. (2013), deepened the quality of mental models of university engineering students when asked to create explanations for phenomena or processes and/or use a certain model in the same context. Students were asked to answer a questionnaire about the evapouration of a water puddle at different temperatures and to discuss their related explicative model(s) and propose other experimental situations. A careful reading of the students' answers within a framework provided by domain-specific expertise and previous research in the field of the description of student modelling competencies (Sperandeo-Mineo, 2006) allowed to classify students' responses into three phenomenographic categories of mental models: practical or everyday, descriptive, and explicative.

The three categories represent ‘‘idealized sets’’ containing the answering strategies that can be considered typical of each mental model category. These categories highlight the reasoning procedures’’ran’’ by students when searching for explanations about phenomena and/or proposed situations.

The category "practical or everyday" is linked to common knowledge and reflects the creation of situational meanings derived from practical, everyday contexts. Students use other situations to try to explain the proposed ones (Fazio et al., 2013). Students refer to their previous knowledge acquired through direct experiences and to what is observable in everyday life.

Students using the "descriptive" category describe and characterize the analysed process by finding or remembering the relevant variables and/or recalling from memory their relations, expressing them by means of different language (verbal, iconic, mathematical). Students oriented to the description do not explain the causal relations of the physics parameters involved on the basis of a functioning model (microscopic or macroscopic) (Fazio et al., 2013). Therefore, in this context, students have a scientific knowledge of the phenomenon, know the formulas, and try to remember the information studied, expressing them by means of different language (verbal, iconic, mathematical).

Students using the "explicative" category propose a model (qualitative and/or quantitative) based on a cause or effect relation or provide an explanatory hypothesis by introducing models which can be seen at a theoretical level. These students do not have a superficial knowledge of physical laws, but they achieved a deep and aware understanding of the phenomenon.

Many students do not have a single reasoning line, and they use several reasoning approaches. These "mixed-type" students clearly show to have more than one view about nature and the use of explications in science. They also often implement strategies which are inefficient at correctly connecting mathematical modelling to real situations in order to build explanations. Very often, reference to a well-known mathematical model seems to stimulate a recalling procedure, i.e., a search in memory for examples that fit in with the formula, without a clear understanding of its physical meaning (Fazio et al., 2013).

Based on these considerations, it is clear that the analysis of students' reasoning lines is crucial for teachers to design learning environments that can enhance students' ability to use explanatory models.

4.2.6 Generalization of what has been learned

When a person practices under untrained circumstances contents and techniques learned in a given situation, generalization is seen. This usually happens if the conditions in the circumstances are regarded as similar to the situation where learning happened (Gluck et al.,

2008). To more effectively navigate the world, the learner draws on generalized patterns, principles, and other commonalities between familiar experiences and unexpected ones (Banich et al., 2010). Generalization of knowledge: Multidisciplinary perspectives. Psychology Press).
Generalization is regarded to be closely related to the transfer and application of knowledge in many contexts (Shea and Bauer, 2007). Because the learner abstracts a rule or pattern of features from prior encounters with similar stimuli, the knowledge that needs to be communicated is frequently referred to as abstractions (Banich et al., 2010). Through the use of generalization, people may notice the parallels in knowledge gained in one scenario and apply that knowledge to new ones.

It would probably be exceedingly challenging to get about the world in a productive way without the ability to generalize. (Banich et al., 2010) Because every occurrence of a situation would be wholly distinct from earlier instances that were similar, a person who was unable to generalize from one experience to the next would not be able to use prior experience to help them understand how to respond to this stimulus that appeared to be novel. In fact, even if the person encountered the identical circumstance repeatedly, he or she would have no means of knowing what to anticipate in each occasion and it would be as if the circumstance were being encountered for the first time. Therefore, generalization is a useful and essential component of education and daily life.

A generalization gradient is frequently employed in scientific research that examines generalization and its level. Depending on whether the stimuli are judged to be similar or distinct from one another, this technique is used to gauge how frequently and strongly people react to various stimuli and the quality of generalization enacted.

4.2.7 Recognition and evolution of personal cognitive styles

Meaningful didactics aiming at promoting personalised learning should be guided by the analysis of cognitive styles.
Cognitive style indicates “the mode of processing that the subject predominantly adopts [...]. We can define cognitive style as a constant tendency to use a certain class of strategies, for example verbal strategies or imaginative strategies” (De Beni et al., 2003, p. 165). Cognitive style is a mode to process information that can be manifested in different tasks and areas of behaviour (Boscolo, 1986). It is important to highlight the difference between style and

skill. Style can be interpreted as a mode or tendency of the subject to use a skill in a certain way (for example, more frequently than others). It concerns the totality of the individual. In this sense, it is related not only to the individual's approach to cognition, but also to his attitudes and the way he relates to others or reacts to unusual situations.

Everyone has a personal way of perceiving, remembering, thinking, learning, storing, transforming, and using information acquired from the surrounding environment. In other words, style is the personal way of perceiving and processing environmental stimuli into coherent and meaningful structures on the basis of which each individual interacts with the environment. Cognitive styles are of particular importance in school learning.

Learning style can be defined as the way in which individuals habitually learn, the use they make of their skills, their attitude towards school subjects in the classroom and during individual study (Pedone, 2012). It refers to a person's preferred way of learning to study; it consists in the use of preferred channels and strategies. Knowledge of students' cognitive styles can help the teacher to understand how they perceive and interact with the learning environment.

Cognitive styles and learning styles have long been investigated in the literature, resulting in various interpretative models.

According to Barbe, sensory preferences activate three different learning modes: visualisation (shapes, pictures, paintings, sculptures), listening (singing, music, rhythm, sound), kinaesthesia (gestures, body movements, manipulation, positioning). (Barbe et al., 1979).

In the early 1990s, Neil Fleming introduced the visual/auditory/reading-writing/kinesthetic (VARK) model, which gained relevance within the scientific community. Fleming described the four main learning styles that would be useful to understand the VARK framework and designed a questionnaire suitable to recognise and classify students' learning styles. In one of his papers (Fleming, 1995), Fleming outlined the basic principles behind the VARK approach, arguing that some students were "advantaged or disadvantaged" by certain didactic materials selected by the instructors. Fleming (1995) defined learning styles as: "An individual's preferred characteristics and ways of gathering, organising and thinking about information. VARK is part of the category of learning preferences because it concerns perceptual modes".

According to Fleming, visual learners learn best through maps, tables, graphs, diagrams, pictures, markers and different colours. Auditory learners prefer to learn by discussing topics with their teachers and other students, explaining new ideas to others, and using a recorder. Reading/writing students prefer to learn through essays, textbooks, definitions, reading and taking notes. Kinaesthetic learners prefer learning through field trips, by using pragmatics for understanding, by taking part in workshops, by using hands-on approaches.

The individual's multimodal preference also has to be considered as a learning style preference. Everyone has his/her own preferred learning style and learns best when this style is activated. For this reason, it is important that the instructors know and use the different styles to alternate stimuli and approaches so that all learners can experience their preferred learning style.

Promoting students' awareness of their own styles fosters the development of self-regulation, which guides them to control their own mental processes in order to use them pertinently in different situations.

It is important that instructors help students to achieve awareness of their own style and at the same time it is also useful making them to reflect on limits and strengths of each style. Different styles, in fact, have a functional value that varies according to contexts and objectives. It is not straightforward to affirm that one style is preferable to the others, since the advantages offered by one learning mode may become limitations depending on the context (Smorti et al., 2016). Learning styles, on the other hand, are fluid, they are also socially, institutionally, and culturally connoted, taking shape as dynamic approaches capable of adapting to different contexts and the multiple tasks they propose.

One of the most well-established instruments to study cognitive and learning styles is the Index of Learning Style (ILS), developed by Felder and Silvermann (Felder and Silverman, 1988). ILS describes the learner's cognitive style according to four strands: informational provenance (perceptual-intuitive), informational code (visual-verbal), information processing (applicative-reflective), informational synthesis (sequential-global). For each characteristic, the theory describes typical learner behaviour. For example, the perceptual learner prefers to acquire knowledge from the outside, he/she is practical, tolerant of detail, good at memorising, oriented to observable facts and phenomena. It is therefore appropriate to introduce him/her specific examples of concepts and procedures applicable in practice. The ILS provides both the tool to identify cognitive style and the guidelines to match each student with the best teaching resources.

4.2.8 Perception of self-efficacy

“The ultimate goal of the educational system is to shift to the individual the burden of pursuing his [sic] own education.” (Gardner, 1963), former U.S. secretary of Health, Education, and Welfare)

The development of academic competencies represents a demanding cognitive and motivational challenge that young students begin to face even before they enter school and that occupies most of their time until adulthood. It is through their educational paths that young students acquire their sense of academic agency.

The sense of self-efficacy strongly influences students’ ultimate level of accomplishment. To enable young people to achieve John Gardner’s (1963) goal of self-education, schools need to go beyond the teaching of intellectual skills and promote the personal development of students’ self-beliefs and self-regulatory capacities for long-lasting self-education.

Although the role of self-conceptions in academic achievement has long been recognised (McCombs, 1989), their measurement and scientific study has been hindered by a multiplicity of conceptual and psychometric problems (Zimmerman, 1989b; Wylie, 1968). This impasse was broken in 1977 when Bandura proposed a theory of the origins, mediating mechanisms, and multiple effects of beliefs in personal efficacy. It also provided guidelines for measuring self-efficacy beliefs across different domains of functioning. Particular attention has been paid to the acquisition of self-regulatory skills to manage one’s learning activities (Zimmerman, 1990; 1989a).

The validity of self-efficacy beliefs in predicting student motivation is an important empirical issue. Bandura (1977) suggested that efficacy beliefs influence the level of effort, persistence, and choice of activities. Students showing a high sense of efficacy in completing educational tasks will participate more willingly, work harder, and persevere longer when they encounter difficulties than those who doubt their abilities.

According to Bandura (1993), perceived self-efficacy involves more than the belief that effort determines performance. Judgments of one’s own knowledge, skills, strategies, and stress management also contribute to the development of efficacy beliefs. Berry (1987) also focused on the role of efficacy beliefs in supporting persistence in facing failures and in transferring this motivation to new tasks. According to Bandura (1986), “self-regulatory skills require tools of personal agency and the confidence to use them effectively” (p. 435).

In socio-cognitive theories, self-regulation operates through a series of psychological sub-functions (Bandura, 1991b; 1986) as the self-monitoring of one’s activities, applying personal standards for judging and directing one's performances, enlisting self-reactive influences to guide and motivate one's efforts, and employing appropriate strategies to achieve success (Zimmerman and Martinez-Pons, 1990; 1988; 1986).

Sometimes, to possess self-regulatory skills does not imply to be able to apply them persistently when facing difficulties and stress factors necessarily.

Students report a high sense of efficacy in managing the content aspects of instruction but a low sense of efficacy in managing themselves when they must complete academic activities (Zimmerman et al., 1992). Beliefs about personal abilities influence the goals people choose and the effort they put into achieving them. More capable people believe themselves to be more challenging goals they set for themselves (Bandura, 1986).

Self-efficacy for self-regulated learning measured students' perceived capability to use a variety of self-regulated learning strategies. Previous research on students' use of these learning strategies revealed a common self-regulation factor (Zimmerman and Martinez-Pons, 1988). Self-involving motivation and continued personal improvement are ensured by the careful structuring of activities, incentives, and personal challenges. Self-directed mastery experiences are provided to reinforce and generalise students' sense of self-efficacy. These sources of influence are organised to promote students' beliefs that they have what is necessary to control their educational development. Research that establishes the role of efficacy beliefs in key self-regulatory processes acquires an important role in educational development.

Efforts to promote self-directed learning must focus on self-referential processes, mainly students' evaluation of their efficacy. Enhancing sources of personal agency and meta-cognitive skills prepares students not only to gain new knowledge and cultivate new abilities but to accept responsibility for their own education which is John Gardner's (1963) ultimate educational goal.

4.2.9 Growth mindset

Research results in cognitive psychology show that learning often depends on the learner's mindset (Dweck, 2006). Particularly, it may depend on the fact that the learner believes that their abilities are fixed or they can evolve and the efforts they put in learning can affect that evolution.

Through her research, Carol Dweck has identified two mindsets that people can adopt about their talents and skills.

Students with a growth mindset see intelligence and skills as something that can be developed over time. They see talents and skills as things that can be developed, as potentials that can be realised through effort, practice, and instruction. In a growth mindset, talent is something you build and develop, not something you simply show the world and try to coast to success. Conversely, students who hold a fixed mindset tend to see them as inherent and unchangeable traits (Dweck, 2006). They have a certain amount of them and that’s it.

Although skills are always a product of both nature and nurture, the importance of the growth mindset is becoming more and more clear. Research in psychology and neuroscience demonstrates the enormous plasticity of the brain, that is its ability to change and even reorganise itself when people put serious effort into developing a set of skills.

People’s mindset, that is the way people think, has nothing to do with their level of ability in a particular area, at least not in the beginning. People, independently from the level of their skills, can have both kinds of mindsets, but over time those with the growth mindset seem to gain an advantage on their fixed mindset peers beginning to outperform them. Mindsets can be fairly stable, but they are beliefs and beliefs can change. For this reason, it is crucial to design didactic activities that can help people in changing mindsets and have a significant impact on their motivation and performance.

Research on mindset allows teachers to understand how mindset fosters goals, attributions, and reactions to setbacks (Yeager and Dweck, 2012) in learning. Students who hold a growth mindset set self-improvement as achievement goals, optimize the use of their resources, and look for feedback from teachers and peers. Most important, they attribute failure to something that is under their control and work harder when faced with setbacks. Students with a growth mindset accept and look for possible new learning strategies and exploit all available resources.

Conversely, students with a fixed mindset aim for performance-oriented goals, see failures as something that is beyond their control, and easily give up when they experience setbacks (Yeager and Dweck, 2012).

The main goal of a student with a fixed mindset is to look talented at all costs, whereas the goal of a student with a growth mindset is simply to learn and explore new possibilities.

Carol Dweck notes that when researchers give students with a fixed mindset a choice between a challenging task that they can learn from and a task that makes them look smart, most students choose the second option. Since they believe that their intelligence is fixed and that they cannot improve it, they need to look good all the time.

On the other hand, students with a growth mindset, even if they care about grades, they show to be more interested in learning. These students achieve higher grades, even though they may not have had a higher ability to begin with. For example, they study harder, manage their time better and stay motivated. If they do badly at first, they find out why and fix it.
Students with a fixed mindset preferred to hide their deficiencies rather than take advantage of an opportunity to correct them even if the deficiency put their future success at risk. Fixed mindset students don't work too hard or practise too much, whereas growth mindset students are passionate and committed and believe that effort is the key. People with a fixed mindset also believe that if they are naturally gifted in a particular discipline, they shouldn't have to work very hard at it. Having to work hard should lead them to doubt their innate abilities.
Students with a fixed mindset never learn to work productively. When they reach their limits, they cannot overcome them. Conversely, students with a growth mindset know they have to work hard, and they enjoy it. They recognise effort and practice as fundamental tools to enhance their abilities over time.
Research has shown that students who hold growth mindsets are better equipped to pursue valuable learning achievements (Zhang et al., 2017). Fostering growth mindsets can improve students' performance, increase students' motivation, and reduce social class gaps.

Students with a growth mindset are self-encouraged to put deliberate (Ericsson, 2007) and contextualized (Scherr, 2007) effort and practice at increasing levels of complexity. In this way, they can succeed in leaving the "zone of cognitive comfort" related to things that they know they can do well, that may be unproductive from a learning point of view (Pelley, 2014). When students think they can improve, they put effort into things to do, like learning activities. So, efforts, time, and support in doing things at increasing complexity levels allow students to obtain skills comparable to those of an expert, help to foster conscious and persistent learning and develop self-confidence and metacognition. An important feature of deliberate practice is the exercise and active development of skills at ever higher levels, which allows students to acquire these skills in the best way (Mayer, 2008). Through deliberate practice processes, students can develop a personal awareness of their knowledge and skills, which allows them to better identify their strengths and weaknesses and to reflect on their learning and how to optimize it.

Carol Dweck underlines how mindsets are strongly affected by the way teachers evaluate and "praise" students. Many studies have shown that praising children's or young people's intelligence or talent should lead them to develop a fixed mindset, with all its vulnerability.

Rather than instilling confidence, it tells them that teachers evaluate their intelligence or talent directly from their performance. Conversely, praising students' efforts or strategies, that is, the process they are engaged in and the way they face difficulties and challenges, fosters the development of a growth mindset, thanks to which students seek and enjoy challenges and remain highly motivated even after prolonged difficulty.

4.2.10 Metacognition

Metacognition literally means 'beyond cognition' and refers to the ability to reflect on one's cognitive abilities. The first author to introduce this term into the literature was Flavell in 1976, who described this ability as "one's knowledge concerning one's own cognitive processes or anything related to them, e.g., the learning-relevant properties of information or data. For example, I am engaging in metacognition if I notice that I am having more trouble learning A than B; if it strikes me that I should double-check C before accepting it as fact" (Flavell, 1976).

Metacognition is generally defined as a person's knowledge of their own cognitive processes (Baker, 2002; Flavell, 1976).

Today, when we talk about metacognition, we can say that it is an ability that is extended/superordinated to different intelligences and different styles. It promotes the awareness and strengthening of cognitive and emotional functions and activates reflection on one's own mental processes. Developing a metacognitive attitude, therefore, means reflecting on one's own processes and being aware of how best to use them to address the problems of the context. Metacognition refers to those activities of the mind that have the mind itself as its object, both in the moment of reflection and in the moment of control. This skill acts as a "cognitive accelerator", i.e., it improves the effectiveness of cognitive processes by monitoring the progress of thought.

The metacognitive approach aims at building an open mind; it does not favour what is learned but how a subject learns and activates the tendency to make people reflect on aspects of their own personal ability to learn, to pay attention, to concentrate, and to remember.

Most definitions of metacognition have focused on these distinct but related aspects: the knowledge/awareness of cognitive processes and the regulation and control of cognitive activities (McCormick, 2003; Flavell, 1979).

The first aspect includes both knowledges of how thinking works in general and awareness of how one's own thinking works, which is a necessary condition for understanding and controlling cognition itself. (Pedone, 2012).

The second aspect, related to the regulation and control of cognitive activities, refers to the actual strategies used to control cognitive processes, such as planning how to approach a task, monitoring comprehension, and evaluating progress and presentations (ibidem).

Three different types of metacognitive knowledge have been identified: declarative knowledge, procedural knowledge, and conditional knowledge (Harris et al., 2009; McCormick, 2003).

Declarative knowledge includes knowledge about the self, the task, and the strategies applicable to a task. Procedural knowledge is the knowledge required to carry out procedures, including strategies, to apply declarative knowledge and achieve goals. Conditional knowledge is fundamental to the effective use of strategies and refers to knowing when, where, and why to use declarative knowledge and procedural knowledge, i.e., the procedures or strategies. (Pedone, 2012).

The use of metacognitive strategies promotes the development of critical thinking, motivation to learn and the construction of a positive self-concept. Ultimately, metacognitive teaching does not refer to individual disciplines but oversees them by guiding the effective strategic use of basic skills. The positive outcome of metacognitive teaching is represented by the presence of a good ability to self-regulate one's own learning.

The difference with traditional teaching is the insistence on student autonomy. A standard approach that does not consider the metacognitive processes that take place in learning will make the student "dependent" on the figure of the teacher as a dispenser of knowledge and understanding. The metacognitive approach, on the other hand, allows each student to gradually develop his or her own very personal learning method, which allows him or her to find appropriate strategies to overcome his or her shortcomings and to develop his or her inclinations and aptitudes.

4.2.11 Well-being in learning

Nowadays, the question of well-being is debated in many fields of research. To understand what this construct means today, it is necessary to analyse how the meaning of health and well-being concepts has evolved in the last decades.

The concept of 'health' was first defined in 1948 by the World Health Organisation (WHO) as a state of complete physical, mental and social well-being. To achieve it, the individual or group must be able to identify and realise their aspirations, satisfy their needs, modify their environment, or adapt to it. In 1986, the WHO presented the Ottawa Charter (WHO 1986), based on the socio-ecological theory of health, emphasising the strict link between individuals and the subsystems that make up the ecosystem in which they live (family, community, physical and socio-cultural environment). On this basis, the Charter defines the concept of 'health promotion' as the process that enables people to exercise greater control over their health and improve it. Health is therefore considered as a daily life resource, not as a life goal, a positive concept that emphasises social and personal resources as well as physical capabilities. Consequently, health promotion is not the responsibility of the health sector only and requires synergetic and cross-sectoral actions with other areas of society. In the last years, global awareness of the interdependent relationship between individuals and the environment has contributed to increase the interest toward health promotion issues. The World Health Organisation (WHO) has defined the concept of health as "a condition of complete physical, mental and social well-being and not exclusively the absence of disease or infirmity". Thus, the 'static' conception of health, as the absence of disease, has evolved into a 'dynamic' one that recognises the state of health as adaptability. The concept of adaptability is crucial: individuals survive because they adapt to different environmental situations, i.e., they can keep in harmony various aspects of their life (biological, psychological, and social) by rebalancing them depending on the situations. According to this dynamic conception of health, the individual is responsible for himself and for maintaining his own quality of life. As pointed out by Sarason (1997), 'well-being is an individual phenomenon, but it is always embedded in an interpersonal, socio-familial or institutional context'. Indeed, school is the main place for promoting health and well-being among children and adolescents (Konu and Rimpela, 2002). For children and adolescents, schools represent an important growth environment in which they spend a great deal of time. Students' experiences at school, in many cases, may have important implications on their subjective well-being throughout their lives (Park 2004).

Well-being in learning has long been kept separate from other aspects of learning. The introduction of well-being within educational contexts dates to 1950 when the WHO established a Committee of Experts on School Health Services (St Leger, 1999). Year after year, more and more complex school health programmes have been developed. Among them, there is the WHO's program based on the idea of a 'health-promoting school' (Turunen et al., 1999; Parsons et al., 1996) and the 'Coordinated School Health Programme' in the USA (Marx and Wooley, 1998; Allensworth and Kolbe, 1987). Over time, school health programmes have moved towards an increasingly broad interpretation of the concept of health but drawing their conceptual basis from the theory of health and health promotion and not from the concept of well-being. Health remains the key concept of these programmes, and the practice of health promotion in schools is often reduced to rather traditional health interventions.

Only since the beginning of the 2000s global school health programmes (ENHPS and CSHP) started to apply the WHO definition of health (McKenzie and Richmond, 1998; Parsons et al., 1996) and strongly refer to social and mental aspects of health. However, well-being at school has not yet acquired a central role in development programmes, and it is mainly seen as a separate subject from the overall goal of schooling. School well-being model considers health education and health promotion as important parts of schooling but do not consider them as priority issues.

Soon it will be understood that students' well-being at school and, more generally, in educational contexts, is a much broader issue: it is necessary to integrate the perspective of results and processes with students' well-being (Konu and Rimpela, 2002).

Educational institutions must consider students' well-being as a priority. In this sense, they must work to promote positive lifestyles, fight the most common pathologies, prevent addictions and related behavioural pathologies etc. Several studies have revealed significant relationships between the frequency of students' positive emotions at school and academic achievement, such as school engagement and academic performance (Patrick et al. 2007; Sellström and Bremberg 2006). From this point of view, it is crucial for instructors to understand the close link between the development of academic well-being and content learning since both factors support each other in a directly proportional relationship.

Students' well-being is determined by several variables affecting the quality of life: adequate preparation, ongoing training and support of teachers, valid aids to enhance the individual's ability to adapt to their environment, opportunities to acquire skills and activate cognitive and learning processes, identification and experimentation of specific techniques for both normally gifted and differently-abled, creation of a fun environment in which divergent and creative thinking can be developed through all possible forms of play.

In addition to physical conditions and social relationships, educational contexts should promote opportunities for growth and self-fulfilment for students. Each student should be regarded as an equally important member of the community and should be able to participate in the decision-making process concerning his or her schooling and other aspects of school life that affect him or her.

Many different competences and interdisciplinarity are needed for schools and universities to become environments where it is pleasant to live, teach and learn. Often instructors mainly pay attention to students' academic performance, much less to students' subjective evaluations of schooling and their emotional experiences at school (Dello-Iacovo, 2009). In contrast, some educational researchers recognize as crucial the role of well-being in education. Only through the achievement of well-being (understood in all its complexity), it is possible to build effective and lasting learning. Noddings (2003) have argued that "Happiness and education are, properly, intimately connected. Happiness should be a goal of education, and good education should contribute significantly to personal and collective happiness".

4.2.12 Understanding of Nature of Science (NOS)

When teaching scientific disciplines, in addition to transmitting contents through the explanation of different topics, teachers must reflect and make students reflect on the nature of science (NOS).

Students develop personal ideas about what "nature of science" (NOS) is through experience, observation, and study. Science is seen as Nature itself, but it is actually the study of Nature carried out by humans, understood as sentient minds. Particularly, Science does not provide us with absolute certainty, as is often believed.

The nature of science (NOS) refers to values and assumptions about scientific knowledge and its development (Schwartz et al., 2004). It plays a crucial role in enhancing students' literacy in science so they can understand functionally scientific facts (Abd-El-Khalick, 2012).

To help students to understand the nature of science, good science teachers have to introduce students to NOS throughout their instruction (Wenning, 2006).

It is not hard to find students and teachers with a good level of knowledge about scientific contents. However, even the most prepared students and teachers in scientific disciplines can find it difficult to understand what science is and how it proceeds.

Traditional frontal lessons are not suitable for developing the concept of the nature of science adequately. Traditional approaches lead students to think that science consists in the study of laws and theories obtained by the scientists after trials and attempts.

It is impossible for students to develop ideas about NOS without ever having carried out lab activities, and experiments and without ever having adopted a scientific approach. To make students familiar with the concept of nature of science, it is necessary to focus on some fundamental aspects during school activities: students must familiarize themselves with experimental observations and data collection, with the identification and control of the variables of interest. They must be involved in the prediction and explanation of phenomena, in the construction of graphs and diagrams and in the use of technology.

Understanding the nature of scientific processes is important since it helps students to make informed decisions related to science-based issues, to achieve an authentic understanding of science topics, and help them to distinguish science from other ways of knowing (NSTA, 2003). NOS literacy helps students to defend themselves against unquestioning acceptance of pseudoscience and reported research (Park, 2000; Sagan, 1996).

The concept of the “nature of science” is complex and multifaceted and involves aspects of philosophy, sociology, and the history of science (McComas et al., 2002). Lederman et al. (2002) define NOS by referring in part to understandings about the nature of scientific knowledge. These understandings deal with science’s empirical nature, its creative and imaginative nature, its theory-laden nature, its social and cultural embeddedness, and its tentative nature. They also focus on the implications derived from “the myth of the scientific method.” According to Project 2061 (American Association for the Advancement of Science (AAAS), 1993), a scientific world view consists of beliefs that the world is understandable, that scientific ideas are subject to change, that scientific ideas are durable, and that science cannot provide complete answers to all questions (Wenning, 2006). Inquiry science is much more complex than “make a lot of experiments” and it is not limited in the labs. Inquiry science is much more flexible than the rigid sequence of steps commonly described in textbooks as "the scientific method." Scientific inquiry involves more imagination and inventiveness than one can imagine. Many students develop misconceptions about science. For example, they think that exists a scientific method that is general and universal or that high objectivity is the hallmark of science or that the scientific method leads to absolute truth.

The nature of science can be best taught and understood when considered in the appropriate context. Students can develop a functional understanding of the nature of science only when they are taught in the context of scientific inquiry. NOS should not be treated as a subject matter apart from the content of science, be it physics, chemistry, biology, earth and space science, or environmental science. The nature of science is best taught experientially and systematically (Wenning, 2006).

In the inquiry labs, students can learn the nature of scientific inquiry by asking questions, discovering new concepts, principles, or laws through the creation and control of their own experiments, carrying out practical procedures and observing cause-and-effect relationships. Often, however, teachers themselves transfer their misconceptions about science to students. For example, they think that the scientific method leads to absolute truth or that science is less creative than it is procedural. Teachers can transfer to their students only what they themselves possess. For this reason, teachers must therefore possess an understanding of the nature of science if they want to transfer that understanding to their students. In addition, to achieve an authentic understanding of the nature of science, teachers need to have appropriate models and activities to help their students acquire an adequate understanding of NOS (Bell et al., 2000, Abd-El-Khalick et al., 1998).

4.2.13 Willingness to extend studies and research

When researchers ask themself what it means to promote deep learning, they know there are several aspects to be analyzed. A teacher that promotes deep learning helps their students to set goals, make links with previous knowledge, to value their work and reflect on it, collaborate with their classmates to achieve a common goal, and transfer their knowledge to other contexts. This all leads to carry out one of learning’s main goals: to make the student independent in developing abilities and competences that allow him/her to develop critical thinking to meet the challenges of the modern world. Autonomy must be viewed as an end-goal and not an approach (McDevitt, 1997).

Therefore, teaching does not mean only transmitting information, but promoting attitudes, infusing values and encouraging the students’ personality.

In this prospective, the teacher is seen as a guide that accompanies, supports, and directs but never replaces the learners. This means that the focus of learning-teaching’s processes must be moved from teacher to student. Ultimately, educators help the learner to become aware of himself.

Future-ready students need to exercise agency in their own education and throughout life. Agency implies a sense of responsibility to participate in the world and, in so doing, to influence people, events and circumstances for the better. Agency requires the ability to frame a guiding purpose and identify actions to achieve a goal (OECD, 2018).

Today traditional teaching is giving way to activities methodologies that place at the centre of learning's process the student, who owns an active role and not passive.

Students should be offered a diverse range of topic and project options and the opportunity to suggest their own topics and projects, with the support to make well-informed choices (OECD, 2018).

However, the current educational system often focuses on surface-level learning, where students are taught to memorize and regurgitate information without fully understanding the underlying concepts. This approach can hinder their ability to think critically and creatively and limit their potential for further academic growth.

To combat this issue, educators must broaden and extend the study of topics beyond the surface level. This approach involves delving deeper into the subject matter and exploring it from various perspectives. It allows students to develop a deeper understanding of the topic and its relevance to their lives, enabling them to apply their knowledge in real-world scenarios.

Students must be encouraged to ask questions to go beyond definitions; it must be their curiosity to move their attention and pushes them to deepen. If they are appropriately involved in the lessons and understand that their study has concrete implications in their everyday life, learners will have more motivation to learn autonomously and not only for final evaluation. Students should not stop in the mnemonic study, but they should always look for the cause and the connections and investigate the reasons that are hidden behind the theories. To do this, they must be motivated to extend their studies in the classroom with personal research to appeal to their curiosity and natural desire for knowledge that is inherent in the human being.

Studies have shown that broadening and extending the study of a topic at school can have significant benefits for students. One study conducted by the University of California found that deep learning approaches, such as exploring topics in-depth and connecting them to real-world situations, led to higher levels of academic achievement (Freeman et al., 2014).

To achieve this level of learning, educators must use a range of teaching methods, such as inquiry-based learning, problem-based learning, and project-based learning. These methods allow students to explore the topic in-depth and develop critical thinking and problem-solving skills. They also provide opportunities for collaboration and communication, which can enhance students' social and emotional development.

Teachers have to leave the freedom to learners to explore new aspects independently that go beyond the topics that are normally studied at school. In this way, students can deepen and go beyond books by following an individual study that stars with their experience. This means they became responsible for constructing their own knowledge.

In conclusion, broadening and extending the study of a topic at school is critical to developing students' critical thinking and problem-solving skills. Educators must move beyond surface-level learning and use a range of teaching methods to explore topics in-depth and connect them to real-world scenarios. This approach can have significant benefits for students' academic, social, and emotional development.

CHAPTER 5

RESEARCH DESIGN

Based on what has been discussed in the previous chapters, we have designed a research path based on the implementation of two Teaching-Learning Sequences (TLSs) on surface phenomena. The TLSs, designed to confirm the research hypothesis and to answer the research question (see Chapter 4), are both based on an ISLE-type approach and differ in the scale of modelling of surface phenomena (macroscopic and mesoscopic, respectively).
The TLSs were targeted at upper secondary school students. We do not refer to a specific school grade since the topic on which we focus in our research path can be addressed at different years, according to the school curriculum.

Each TLSs have specific features suitable to pursue specific aims, as will be explained later. Many data were collected by means of a wide range of experiences and activities.

The activities proposed represent an example of extracurricular activities. Students were selected voluntarily, i.e., they chose to attend the activities attracted by physics, or in general by scientific disciplines, since they wanted to learn more about them. The activities were carried out in the afternoon, and their whole duration was 24 hours divided into 6 days (not consecutive).

The sample on which the TLSs were trialled is made up of about 40 students attending the fourth year of "Liceo Scientifico", which is the Italian science-oriented upper secondary school (age range 16-17, 20 females and 18 males). All the students have been studying physics since the first year of Liceo Scientifico. The research sample is composed of students coming from four different classrooms in the same school in Palermo, Italy. Both the physics teachers of these students hold master's degrees in physics. Moreover, they have a similar approach to teaching since they were all trained in professional development activities at the Università degli Studi di Palermo, which prepared them for the use of inquiry methodologies. Therefore, the sample of students was selected to be as homogeneous as possible in terms of preparation, method of study, and motivation.

Before the start of the activities, the entire sample of students was randomly split into two sub-samples of about 20 students each. The first sub-sample, namely "Group A", experimented with a traditional macroscopic approach to the study of surface phenomena.

The second sub-sample, namely “Group B”, analysed the same topic as “Group A”, following a mesoscopic approach.

Since the student sample is not very large, when we formed groups A and B, we selected students randomly within different classes in order to make the sample more uniform as possible. In particular, students attending different classrooms met up with each other for the first time during the experimentation activities. Since teamwork activities are an important part of our TLSs, creating working groups composed of students who do not know each other ensured that all the students could find their place in the group and express themselves freely away from the dynamics of the class they came from.

In carrying out the experimental activities, our research group, composed of three researchers, was supported by the two aforementioned schools. Their role during the experimentation was different from the role they assumed during traditional school lessons. During the trialling, they did not have to lecture, define terms, or provide explanations to students. They were only asked to promote student interest in the analysed topic and activate their curiosity. Similarly, the researchers supported the students and were at their disposal if they asked for help, but left students free to explore and experiment even beyond the addressed topic.

5.1 The main features of the TLSs

The main goal of this research is not to identify which group highlights the best learning depending on the different approaches but to verify the aspects of each approach that can be considered truly relevant in fostering meaningful learning. In fact, we aim to formulate, at the end of the trialling, a teaching/learning sequence that combines all the aspects that have proved to be significant in fostering learning during the trialling of the two approaches.

Each teaching/learning sequence is characterized by the same basic structure. First, students answer a pre-instruction questionnaire on general topics related to surface phenomena and not specifically related to the topics discussed and analysed during the course. A second questionnaire, on topics that will be specific to the teaching/learning sequence, is administered to students after the first one.

Then, qualitative and quantitative experiments, modelling activities, and discussions are performed in the classroom. The observation of phenomena by means of audio/video material and gathering of further information by means of different media (books, journals, YouTube videos, websites, etc.) are performed in the classroom at increasing levels of complexity and involvement of students.

Experiments and modelling activities are also performed with progressively increasing levels of complexity, and information is shared by using several communication styles. First, students are asked to make previsions and compare them with the experimental results, then they are invited to discuss and express their agreement with the group conclusion, using different forms of representation (verbal, iconic, tabular, graphical, analytic). Finally, students are invited to reflect on their perceptions of self-efficacy in understanding.

At the end of the trialling, students answer two post-instruction questionnaires identical to the previous ones. A satisfaction questionnaire on the TLSs activities and methodologies is also administered to the students after instruction. A couple of months after the end of the activities, students answer a questionnaire identical to the post-instruction one that deals with topics specific to the teaching/learning sequences.

As anticipated, both TLSs include qualitative and quantitative laboratory activities. Qualitative activities are carried out according to a guided inquiry approach (Martin-Hansen, 2002; National Research Council, 2000) in which students are free to choose which tools to use and which path to follow to answer the questions asked by the teachers. Quantitative activities are carried out according to a structured inquiry approach (Martin-Hansen, 2002; National Research Council, 2000), in which students are guided during the activities that lead them to answer the questions asked by the teachers.

Both groups reflect on the same topics, being involved in active learning activities based on the same observations, experiments, modelling activities, small and great group discussions, etc.

A common aspect of both TLSs is the use of a "Predict-Observe-Compare-Explain" strategy in every phase of the activities to facilitate the active and conscious participation of the students in building their own knowledge. On the other hand, the substantial difference between the two groups concerns the method of analysis of the physical quantities involved in the situations of interest and the building of the explanatory model.

One TLS leads students toward the construction of an explanatory model based on a purely macroscopic approach, focused on the description of the experimental results on the basis of forces acting at interfaces between media and energy. This approach, which can be defined as traditional, coincides with the one reported in most textbooks at the school level.

The second TLS leads students toward the construction of an explanatory model based on a mesoscopic approach implemented through computer-based simulations.

5.2 The activities

In this section, a brief description of the activities carried out during each day of the trialling is reported. The worksheets for each of the proposed activities are reported in Appendixes D-H.

It is worth specifying that the qualitative and quantitative experiments proposed to the students of Group A and Group B are the same. The questions proposed to students during the phase of conceptual pit stop after qualitative activities are the same for both groups too.

On the other hand, the two groups were involved in modelling activities based on different liquid models. In particular, as previously mentioned, Group A carried out modelling activities based on a macroscopic description of liquid, and Group B based on a mesoscopic description.

The qualitative activities carried out during the trialling are not described in detail since they are well known, and it is easy to find material about them online. On the other hand, quantitative and simulative experiments proposed during the trialling are described in more detail in the next sections. Tab. 7 resumes the activities carried out by the two groups.

Tab. 7: Table summarizing the activities carried out by each group of students during each activity day.

	Group A	**Group B**
Day 1	**Qualitative activities (see Appendix D):** ▪ Observation: gerridae on the water surface ▪ Qualitative experiment: Objects on the water surface ▪ Qualitative experiment: soap water films in metal frames	**Qualitative activities (see Appendix D):** ▪ Observation: gerridae on the water surface ▪ Qualitative experiment: Objects on the water surface ▪ Qualitative experiment: soap water films in metal frames

Day 2	**Qualitative activities and conceptual pit stop (see Appendix E):** ▪ Qualitative experiment: liquids in capillary tubes ▪ Qualitative experiment: sessile drops and contact angles ▪ Qualitative experiment: objects on the water surface when soap is added ▪ Conceptual pit stop	**Qualitative activities and conceptual pit stop (see Appendix E):** ▪ Qualitative experiment: liquids in capillary tubes ▪ Qualitative experiment: sessile drops and contact angles ▪ Qualitative experiment: objects on the water surface when soap is added ▪ Conceptual pit stop
Day 3	**Macroscopic modelling (see Appendix G):** The researchers provide students with an explanation of surface phenomena based on the macroscopic model, as found in most textbooks. To support a description of surface phenomena based on this approach, researchers use videos, images and diagrams strongly based on a macroscopic view of surface phenomena (see Fig. 19).	**Mesoscopic modelling (see Appendix F):** ▪ formation of a liquid drop in absence of gravity; ▪ formation of liquid menisci; ▪ formation of a liquid sessile drop on a solid surface.
Day 4	**Quantitative experiments (see Appendix H):** ▪ measurement of the surface tension of water by the ring method; ▪ measurement of the surface tension of water by the water drop method; ▪ measurement of the water-glass contact angle by the variable section capillary method.	**Quantitative experiments (see Appendix H):** ▪ measurement of the surface tension of water by the ring method; ▪ measurement of the surface tension of water by the water drop method; ▪ measurement of the water-glass contact angle by the variable section capillary method.

5.2.1 Day 1 – Qualitative activities

Observation: gerridae on the water surface

Description

In this activity, students are asked to watch a video and make some reflections and considerations on what they have observed. The YouTube video proposed shows a gerridae moving on the water surface.

Activity Purposes

The main purposes of this activity are:

- to introduce surface phenomena;
- to understand students' level of knowledge of this topic at the beginning of the trialling.
-

Qualitative experiment: Objects on the water surface

Description

In this activity, students are asked to analyse the behaviour of generic objects (paperclips, pins etc.) on the water surface. Even if materials for this experiment have been provided ready to use, students have full freedom to choose to use also other materials present in the didactic laboratory to carry out the experiment.

Activity Purposes

The main purposes of this activity are:

- to introduce surface phenomena;
- to understand students' level of knowledge of this topic at the beginning of the trialling;
- to monitor the impact of the proposed activities on student learning.

Qualitative experiment: soap water films in metal frames

Description

In this activity, students are required to analyse the behaviour of soap water films formed inside metal frames of different shapes. The physical system analysed in this experiment is slightly more complex than the previous one due to the introduction of soap. So, students have the opportunity to observe and analyse how surfactants affect water properties.

Activity Purposes

The main purposes of this activity are:

- to introduce surface phenomena;

- to understand students' level of knowledge of this topic at the beginning of the trialling;
- to monitor the impact of the proposed activities on student learning.
- to analyse the behaviour of water in the presence of soap.

5.2.2 Day 2 – Qualitative activities and conceptual pit stop

Qualitative experiment: liquids in capillary tubes

Description

The purpose of this activity is to analyse the behaviour of a liquid inside the capillary tubes. During this activity, students reflect on the liquid-solid interaction, in particular, on the water-glass one.

Activity Purposes

The main purposes of this activity are:

- to introduce surface phenomena;
- to understand students' level of knowledge of this topic at the beginning of the trialling;
- to monitor the impact of the proposed activities on student learning.
- to introduce capillary phenomena (liquid menisci, contact angles etc.).

Qualitative experiment: sessile drops and contact angles

Description

The purpose of this activity is to analyse the behaviour of sessile drops of different liquids in contact with the same material and the behaviour of sessile drops of the same liquid in contact with different materials.

Activity Purposes

The main purposes of this activity are:

- to introduce surface phenomena;
- to understand students' level of knowledge of this topic at the beginning of the trialling;

- to monitor the impact of the proposed activities on student learning.
- to introduce capillary phenomena (liquid menisci, contact angles etc.);
- to deepen the concept of contact angle introduced in the previous activity.

Qualitative experiment: objects on the water surface when soap is added

Description

This experiment is similar to the previous experiment ‘Objects on the water surface’, but involves a complication: the addition of soap. This activity requires students to analyse the behaviour of generic objects on the water surface when soap is introduced. Also, in this case, even if materials for this experiment have been provided ready to use, students can also use other materials present in the didactic laboratory.

Activity Purposes

The main purposes of this activity are:

- to introduce surface phenomena;
- to understand students' level of knowledge of this topic at the beginning of the trialling;
- to monitor the impact of the proposed activities on student learning.
- to analyse the behaviour of water in the presence of surfactants;
- to deepen surface tension concept.

Conceptual pit stop

Description

This activity requires students to answer some general questions on the topics previously discussed. For the first time, students are asked to provide a graphic representation of a liquid and to represent the forces acting on a liquid in contact with solid and or with gas interface.

Activity Purposes

The main purposes of this activity are:

- to understand if and how students' level of knowledge of this topic has evolved since the beginning of the trialling;
- to monitor the impact of the proposed activities on student learning.
- to investigate which liquid description is preferred by students (microscopic, macroscopic or mixed);
- to investigate students' ability to graphically represent the physical systems of interest.

5.2.3 Day 3 – Macroscopic modelling (Group A)

Description

This activity consists of two phases. In the first phase, the researchers provide students with an explanation of surface phenomena based on the macroscopic model, as found in most textbooks (e.g., Mazzoldi, Nigro et al., 2002 (Vol. I)). To support a description of surface phenomena based on this approach, researchers use videos, images and diagrams strongly based on a macroscopic view of surface phenomena (see Fig. 19).
In the second phase, students are asked to reflect on what they have observed and learned through the macroscopic approach and discuss the addressed topics first in a small group and then in a large group.

In this phase, students are asked to answer some specific questions which aim to bring out the knowledge acquired through the macroscopic treatment of surface phenomena.

Activity Purposes

- to understand if and how students' level of knowledge of this topic has evolved since the beginning of the trialling;
- to monitor the impact of the proposed activities on student learning.
- to introduce the surface phenomena through a traditional macroscopic approach
- begin to understand if the macroscopic approach has been effective in favouring a better understanding of surface phenomena.

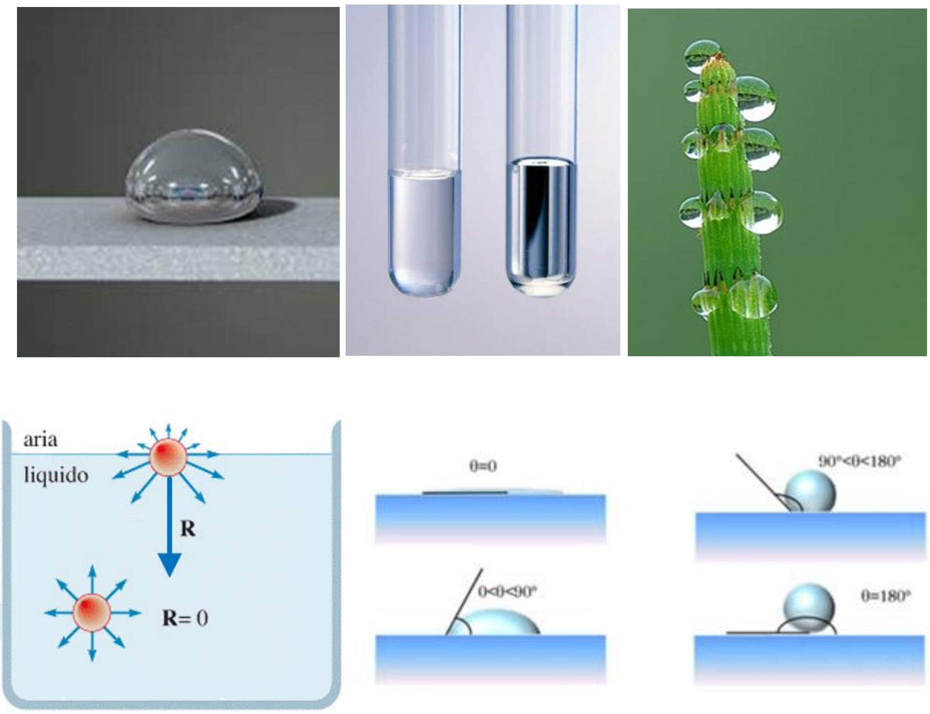


Fig. 19: Examples of images and diagrams commonly used in the textbooks to introduce surface phenomena.

5.2.4 Day 3 – Mesoscopic modelling (Group B)

Description

This activity consists of three phases. In the first phase, researchers provide students with an explanation of surface phenomena based on a mesoscopic model of liquid. Thus, they introduce students to the SPH algorithm, which was used to implement the mesoscopic model of liquid. In the second phase, the researchers introduce the main parameters of the system and explain to students how to manage the numerical code in order to vary them depending on the physical system to be simulated.
The computer simulations proposed to the students of Group B during the TLS allowed them to observe the physical systems at equilibrium and also its evolution over time.

In the third phase, students are asked to reflect on what they have observed and learned through the mesoscopic approach and discuss the addressed topics first in a small group and then in a large group.

In this phase, students are asked to answer some specific questions which aim to bring out the knowledge acquired through the mesoscopic treatment of surface phenomena.

Activity Purposes

- to understand if and how students' level of knowledge of this topic has evolved since the beginning of the trialling;
- to monitor the impact of the proposed activities on student learning.
- to introduce the surface phenomena through a mesoscopic approach;
- begin to understand if the mesoscopic approach has been effective in favouring a better understanding of surface phenomena.

The simulated experiments carried out in this phase reproduce the following physical phenomena:

- formation of a liquid drop in absence of gravity;
- formation of liquid menisci;
- formation of a liquid sessile drop on a solid surface.

These experiments are described in detail in Section 2.1.1.

5.2.5 Day 4 – Quantitative experiments

Description

This activity involves students in quantitative experiments that allow them to obtain an estimation for the surface tension of water and water-glass contact angle.

In addition, thanks to the quantitative experiments, students can focus on some aspects of surface phenomena analysed during the TLS. During this activity, students have to assemble the experimental set up independently, and in a first phase, they are encouraged to propose their personal way to conduct the experiment.

The experiments carried out in this phase are:

- measurement of the surface tension of water by the ring method;
- measurement of the surface tension of water by the water drop method;
- measurement of the water-glass contact angle by the variable section capillary method.

Activity Purposes

The main purposes of this activity are:

- to understand if and how students' level of knowledge of this topic has evolved since the beginning of the trialling;
- to monitor the impact of the proposed activities on student learning. In particular:
- to involve students in hands-on experiments, as well as in the design of the experimental setups;
- to introduce the surface phenomena through a quantitative approach;
- to encourage students to be more independent in their learning process.

Quantitative experiments for surface tension estimation

In this section, we introduce some quantitative experiments proposed during the trialling of our TLSs. Through these experiments, we support the development and testing of innovative and challenging strategies to improve the teaching-learning processes of surface phenomena at undergraduate level. Students’ involvement in hands-on and minds-on experiments in the context of interactive lessons aimed at supporting students’ active learning (Fazio, 2020; Bonwell and Eison, 1991) may foster students’ interest and authentic reasoning (Joyner et al., 2013) about physical phenomena.

All the experimental apparatus used to carry out the quantitative experiments were assembled by us using materials inexpensive and easily accessible in educational laboratories or at home.

Estimation of the surface tension through the Du Noüy ring method

A simplified custom-built version of the well-known Du Noüy ring (Du Noüy, 1925) was used for investigating and determining the surface tension γ of several common liquids.

Du Noüy method exploits the interaction of a metallic (usually gold or platinum) ring with the surface of the liquid. The ring is submerged below the interface by moving the adjustable table on which the liquid tank is placed. After the ring has been immersed, as the adjustable table is gradually lowered, the ring pulls up the meniscus of the liquid until this meniscus tears from the ring. Before this event, the force exerted of the meniscus achieves its maximum value and begins to drop before the actual tearing event.

The calculation of the surface tension by this method is based on the measurement of the aforementioned maximum force, which from now on we will denote by F. The depth of immersion of the ring and the level to which the ring is raised when it experiences the maximum pull are not relevant factors to this technique.

The ring used in this experiment was designed to have the profile immersed in the liquid very thin. This ensures that the liquid adheres to the ring forming a thin circular layer and determining a net break of this meniscus in correspondence with which it is possible to measure the force F required to detach the ring from the liquid surface. The force F can be related to the surface tension γ as follows:

$$F = F_{ring} + 2(2\pi R)\gamma \tag{16}$$

where F_{ring} is the weight of the ring and R its inner radius. Since the thickness of the ring is negligible with respect to its radius, it can be assumed that inner and outer radius are the same size. The multiplying factor 2 in the Eq. 16 is due to the internal and external forces applied on the circular profile of the ring.

Thus, Eq. 16 allows us to estimate γ once F, F_{ring} and R have been experimentally determined.

Experimental apparatus and results

The experimental apparatus that we designed to reproduce the Du Noüy experiment is shown in Fig. 20. Forces F and F_{ring} used to determine the surface tension γ of the liquids of interest were measured by using a digital scale with resolution of 0.01 g.

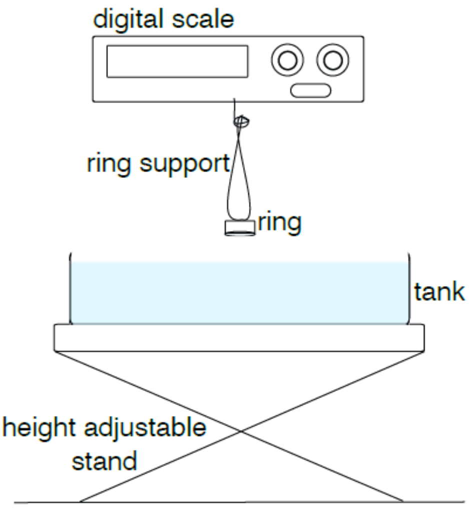


Fig.20: Sketch of the experimental set-up designed to carry out surface tension measurements through the Du Noüy ring method. The main elements of the experimental apparatus are indicated with their own labels.

Since to make it easier for the ring to get in and out of the liquid we used a support (Fig. 20), in our case F_{ring} is equal to the weight of the ring with its support. In this experiment, the force F acting on the ring is measured in traction by hanging the ring and its support on the scale by means of a suspension hook.

The material chosen to shape the ring is the aluminium, both because it is cheap and easy to model with common lathe. The aluminium ring used in our experiment is characterized by a very thin profile on the side getting wet, as the professional Du Noüy's rings. The inner radius of the ring used in our experiment is $R = (1.410 \pm 0.005)\ cm$.

Fig. 21: A picture of the ring at the moment of its detachment from the water surface. The meniscus of the water, that is the deformation of the elastic film formed by the water at the liquid-air interface, it is clearly visible.

This low-cost apparatus allowed us to estimate the surface tension of many common liquids, such as commercial demineralised water, 99% ethyl alcohol, pure glycerol, common commercial peanut, sunflower, corn oil and 30 ml dishwashing soap with 100 ml demineralised water mixture. Surface tension values measured for this sample of liquids, their uncertainties and reference values (Matavž et al., 2017; Melo-Espinosa et al., 2014) are reported in Tab. 8. The uncertainties shown in the Tab. 8 were obtained as the sum of two contributions: a random uncertainty (for each liquid repeated measurements were made) and an instrumental uncertainty. We found that the random uncertainty is always greater than or equal to the instrumental one. For example, in the case of sunflower oil, the random and instrumental uncertainties are about 0.0027 Nm^{-1} and 0.0022 Nm^{-1}, respectively.

Tab. 8. Reference and measured values of surface tension γ, expressed in Nm^{-1} at $\sim 20\,^{\circ}C$.

Liquid	Measured Value	Reference value
Demineralised water	0.069±0.004	0.073
Glycerol	0.064±0.012	0.064
Peanut oil	0.036±0.003	0.035
Corn oil	0.033±0.003	0.034
Sunflower oil	0.034±0.003	0.033
Soap solution	0.026±0.003	0.025
Ethyl alcohol	0.025±0.003	0.022

Estimation of the surface tension through the drop’s method

This experiment allowed us to determine the value of the surface tension of water starting from the knowledge of the weight of a drop (Meneghini and Bruni, 2019).

In the process of drop formation from a capillary tube or dropper (Fig. 22), at a certain time, the drop has a roughly spherical shape at the bottom, while a bottleneck is formed at the top.

When the neck breaks, the drop detaches and its behaviour is very similar to that observed when a balloon is filled with water: when its weight exceeds a certain limit, the neck breaks and the balloon falls.

In the case of the drop, its surface behaves like an elastic membrane which holds water and does not let it fall. When the weight force of water is greater than the resistance of the surface (i.e., surface tension) the drop detaches. At the moment of detachment, the forces acting on the surface of the drop are the weight force due to the mass of water $F_p = Mg$ vertical directed downwards, and the reaction of the surface tension.

On the neck of the droplet the vertical force due to surface tension is:

$$F = L\gamma = 2\pi r\,\gamma \tag{17}$$

where $L = 2\pi r$ is the circumference of the neck, approximately equal to the external circumference of the capillary.

Material used to carry out this experiment involves a laboratory scale with a sensitivity of 0.01 g, pipettes or capillaries, demineralised water. In this case all the material used are also readily available and cheap.

Fig. 22: A picture showing some phases of the process leading to drop formation from a capillary tube or dropper. The drop breaks when its neck can no longer bear its weight.

To determine the surface tension of the water, we have to measure the diameter of the capillary and the weight of a single drop of water, m.

A certain number N of drops ($\sim 20 - 30$) is dropped onto the scale plate; M is the total mass of N drops. The weight indicated by the scale is not constant and the recorded M values will fluctuate, (typically on the last digit) due, for example, to air currents and bench vibrations. We can consider the extent of the variation as the experimental error on M, σ_M . The average mass of a drop is $m = M/N$ and the error associated to it is $\sigma_m = {}^{\sigma_M}/_{N}$.

From the equation describing the forces acting on the neck of the drop at equilibrium

$$2\pi r\,\gamma = mg$$

it is possible to determine the value of surface tension of the water γ.

Estimation of the water-glass contact angle through the variable diameter capillary method

This experiment allowed us to determine the water-glass contact angle by using a “particular” kind of capillary.

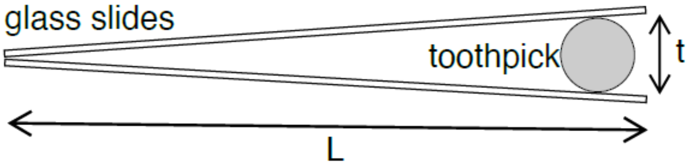


Fig. 23: A sketch showing a top view of the experimental apparatus.

Experimental apparatus and results

The apparatus used in this experiment is composed by two microscope glass slides facing each other. On one side, the slides are in contact, on the opposite side, they are separated by a toothpick which creates an inter-slide separation of about 2 mm as can be seen in Fig. 23. The glass slides are held tight by a set of tweezers, as shown in Fig. 24. In this way, we made a sort of continuously variable-size capillary.

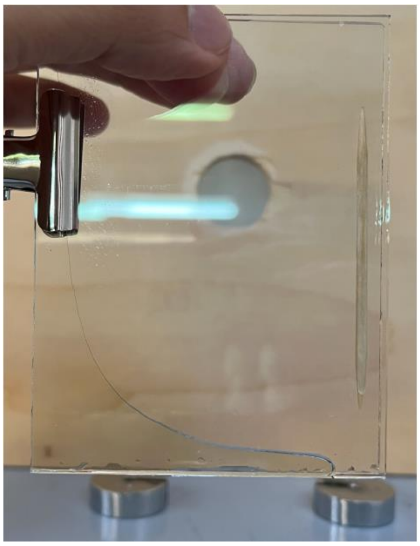


Fig. 24: A photo of the experimental apparatus used to determine water-glass contact angle. The meniscus formed by the water between the glass slide is well visible.

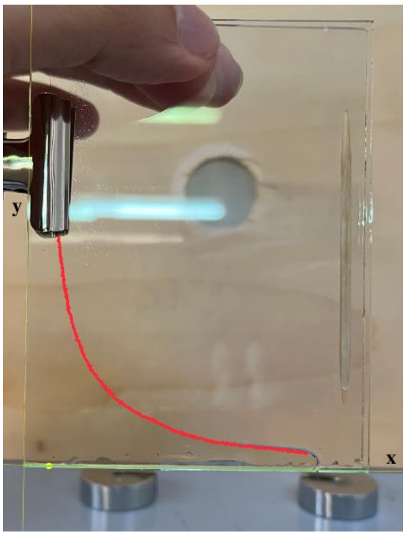


Fig. 25: A photo of the two glass slides in the graphical analysis phase. The yellow lines indicate the axes of the reference frame. Red dots along the liquid profile highlight the curve to be fit.

When we immerse the bottom base of the slides in a vessel filled with water, we observe that the liquid rises between the slides. In Fig. 24 it is evident that the rising of water between the two glass slides varies with the position along the horizontal direction. The height reached by the water increases as the distance between the slides decreases.

To determine the water-glass contact angle through this apparatus, we had to conduct a video analysis of some pictures taken in the laboratory. In particular, we used the tools of the commercial software LoggerPro (https://www.vernier.com/product/logger-pro-3/) to add red dots along the liquid profile (Fig. 25) before performing the fitting of these data.

We know that when we deal with a system given by a capillary tube, the water-glass contact angle can be determined through the Jurin's law. However, the system composed by the two glass slides is not a "simple" capillary but can be rather considered a set of capillaries with variable diameters.

We derived the relationship between the height reached by the liquid and the horizontal position x, by following a thermodynamics approach.

The distance between the two slides is a function of the coordinate x along the glass slide. The mass dm of water contained between the two slides in an infinitesimal interval dx in a generic position x, is $dm = \rho\, y(x)\, d(x)\, dx$ where $y(x)$ is the height reached by the liquid as a function of x, $dV = y(x)\, d(x)\, dx$ is the raised volume of water, ρ its density and $d(x)$ the distance between the two slides. For a rise y of the water, the change of surface free energy due to the replacement of a solid-gas interface by a solid-liquid interface is equal to $dE_S = 2\,(\gamma_{sl} - \gamma_{sg})\, y\, dx$, where γ_{sl} and γ_{sg} and are the solid-liquid and the solid-gas tension, respectively. The two quantities γ_{sl} and γ_{sg} refer to energy per unit area.

The change of gravitational energy is $dE_g = \rho\, g\, d(x)\, dx\, \frac{y^2}{2}$, where g is the gravitational acceleration. At equilibrium, the total free energy $dE_T = dE_s + dE_g$ must be at a minimum value.

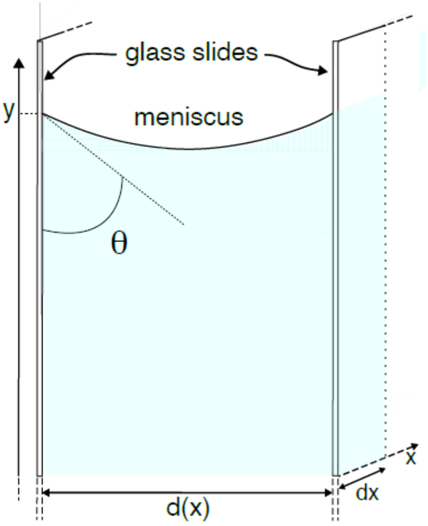


Fig. 26: Sectional view of the two glass slides. The water-glass-air contact angle θ is highlighted.

Thus, solving the previous equation by requiring that $\frac{dE_T}{dy} = 0$, we obtain that $y = \frac{-2\,(\gamma_{sl}-\gamma_{sg})}{\rho\, g\, d(x)}$. Our system can be seen as a series of capillaries whose size varies continuously. The distance separating the two slides can be written as a function of x (which varies between 0 and L) as $d(x) = \frac{x\, t}{L}$, where t is the maximum distance between the slides (i.e., the thickness of the toothpick), and L the horizontal size of the two slides, as shown in Fig. 23. Therefore, the height $y(x)$ reached by the liquid as a function of x is

$$y(x) = \frac{-2\, L(\gamma_{sl}-\gamma_{sg})}{\rho\, g\, t}\,\frac{1}{x} = \frac{a}{x} \tag{18}$$

where $a = \frac{-2\, L(\gamma_{sl}-\gamma_{sg})}{\rho\, g\, t}$. In our case, $L = 7.5\, cm$, $\rho = 1\, g/cm^3$, $t = 0.25\, cm$, $g = 980\, cm/s^2$. From the equation Eq. 18, we obtained that $\gamma_{sl} - \gamma_{sg} = (-0.048 \pm 0.004)\ \frac{N}{m}$.

By plotting the dots (red dots in Fig. 25) graphically obtained through the video analysis, we obtained a curve that can be fitted by the equation

$$y(x) = \frac{a}{x^b} \tag{19}$$

We chose to let free the exponent of the variable x in Eq. 19 to verify that the value obtained thorough the fitting, is compatible with 1.

By considering the Young-Dupré equation, $\gamma_{sl} - \gamma_{sg} = -\gamma_{lg} cos\, \theta$, the contact angle θ at the interface water-glass-air (see Fig. 27) ca be obtained as

$$\theta = acos\frac{\gamma_{sl}-\gamma_{sg}}{\gamma_{lg}} \tag{20}$$

At this point, by substituting the value of γ previously obtained through the Du Noüy ring method to γ_{lg} in Eq. 20, we get $\theta = 45° \pm 6°$. This value is correctly lower than 90° and is compatible with the values reported in the literature for water-glass interfaces (Jiang et al., 2020; Jewłoszewicz et al., 2020; Giang et al., 2019; Mitra et al., 2016). The uncertainties associated with the quantities of interest were obtained through the rules of propagation, known the error on the parameter a (from the fitting) and the instrumental uncertainties associated to L and t.

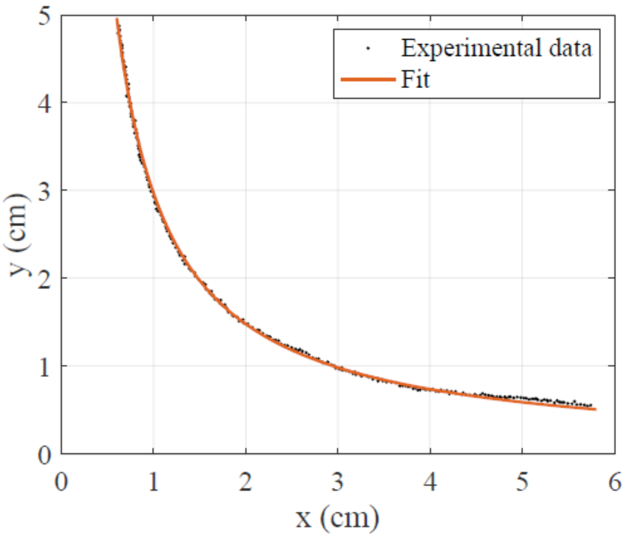


Fig. 27: Fitting by using the equation $y = \frac{a}{x^b}$, where $a = (2.968 \pm 0.009)\, cm^{b+1}$ and $b = 1.007 \pm 0.007$. The coefficient of determination is $R^2 = 0.9995$.

It is not easy to find in the literature a precise reference value for the contact angle since it depends on many factors such as the type of glass and its degree of smoothing and cleanness. In the case of well-polished glass with a high degree of cleanliness, contact angle values are around 30° (Jiang et al., 2020; Jewłoszewicz et al., 2020; Giang et al., 2019). However, contact angle values around 55° are also known (Mohsin et al., 2016). Even if the glass slides used in our measurements were carefully cleaned by using isopropanol, they certainly show some roughness that, as it is well known, determines an increase in the contact angle (Quetzeri-Santiago et al., 2019).

CHAPTER 6

DATA COLLECTION INSTRUMENTS AND METHODOLOGY OF ANALYSIS

During the teaching path, different kinds of data were collected. The choice of data collection instruments was strongly based on the type of analysis we intend to conduct on the data in order to address our research problem. We collected data trough:

- a questionnaire (Q1) on general topics related to surface phenomena but not specifically related to the topics discussed and analysed during the TLSs;
- a questionnaire (Q2) on topics specific to the TLSs;
- a questionnaire (Q3) to study students' opinions about the TLSs;
- students' worksheets;
- audio recordings of students group discussions at the end of each activity;
- students' feedback on the activities carried out during the TLSs;
- students' contributions during the final day brainstorming phase;
- Notes from researchers.

All these instruments allowed us to build different databases, which will be analyzed in Chapter 7, by means of different methodologies. In general, from each database collected with a specific methodology/tool, it is possible to extract information on some of the dimensions of learning that we have chosen to study. However, as we will see in the next chapter, some databases are more suitable than others for investigating a given dimension/variable related to learning. All the instruments used to collect the data are well-known in the literature and commonly used in research in education.

In the following sections, we give a brief description of each data collection instrument and of the variables it can help to study.

6.1 Data collection instruments

6.1.1 Questionnaires Q1 and Q2

The pre-instruction administration of both Q1 and Q2 questionnaires, being the first general tests on the analysed topics, helped us to, first of all, reflect on the structure of the TLSs and organize the activities.

Questionnaires Q1 and Q2 (see Appendixes A and B) were designed starting from other questionnaires used in previous trials carried out by our group. Some of the questions were built on the basis of the learning activities that had been included in the TLSs.

They were administered before and after instruction (pre-instruction administration of Q1 – post-instruction administration of Q1, and pre-instruction administration of Q2 – post-instruction administration of Q2) in order to get information on some of the study variables related to the first two dimensions of learning that we identified, “Acquisition of conceptual knowledge”, and “Intellectual growth”. Particularly, questions of questionnaire Q1 were mainly aimed at obtaining information on variables 1.2: Evolution of common-sense conceptions to scientific ones, and 2.2: Development of reasoning skills aimed at interpreting real-life situations and experiments.

Questions of questionnaire Q2 were aimed at obtaining information on variables 1.1: Appropriation of concepts and forms of representation, 2.2: Development of reasoning skills aimed at interpreting real-life situations and experiments, and 2.3: Generalization of what has been learned.

Questionnaire Q2 was also administered two months after the end of the pedagogical activities in order to obtain information also on the study variable 1.3: Long-time retention of concepts, studying the persistence over time of the knowledge acquired by the students as a result of the pedagogical intervention.

Since the choice to re-administer the questionnaire Q2 after a given time interval arises from the purpose of studying the persistence of concepts learnt by the students, we had to choose a time interval as long as possible compatibly with school constraints. In particular, since the trialling was carried out in the months of January-March 2022, we chose to re-administer the questionnaire Q2 at the end of May 2022 in order to still find the students in the same didactic setup, i.e., in their classrooms.

6.1.2 Questionnaire Q3

Questionnaire Q3 (see Appendix C) was built on the basis of satisfaction questionnaires found in the literature (e.g., https://www.stenio.edu.it/stenio/wp-content/uploads/2016/11/Questionario-progetti-alunni-1.pdf). It was aimed at studying variables related to the third dimension of learning, "Development of a mind-set suited to learning Science", and was administered only at the end of the pedagogical activities. It is a Likert scale questionnaire which also includes a final open-ended question in which students are asked for sincere feedback on their experience during the experimentation.

6.1.3 Students' worksheets

For each activity, we have designed worksheets containing several open-ended questions on the topic of interest.

The worksheets were submitted to the students during all the laboratory and modelling activities. They were aimed at actively involving the students in the TLSs' activities, allowing them to report results of personal, small and large group work, reflect on them and think about the knowledge they think they have built in the specific activity performed. The worksheets were also aimed at letting students express comments, "crazy ideas" (Etkina et al., 2019), agreement or disagreement with group conclusions, and more. For these reasons, we could use the answers to the worksheets to get information on almost all study variables, with the notable exception of variable 1.3: Long-time retention of concepts, which was studied only by means of the re-administration of questionnaire Q2, as discussed above.

6.1.4 Audio recordings of students group discussions at the end of each activity

Audio of students' discussions during large group discussions and the debates carried out during the final day of experimentation was recorded and transcribed. Again, we were able to use the related databases to get information on almost all study variables.

6.1.5 Students' feedback on the activities carried out during the TLSs

Students' feedback on the activities carried out during the TLSs has been collected through the final open-ended question in Q3 and an open discussion among the teachers and the students during the last day of activities. These databases gave us information on all dimensions of learning.

6.1.6 Students’ contributions during the final day brainstorming phase

The database given by students’ contributions during the final day brainstorming phase consists of a teacher-student question and answer. Therefore, it can be considered a multi-interlocutor interview conducted by the teacher. These databases gave us information on all dimensions of learning.

6.1.7 Notes from researchers

At the end of each day of experimentation, the researchers noted their considerations in a logbook. These notes allowed us to check the consistency of what was found in the other databases and sometimes to reconstruct the audio recordings when they were not clear.

6.2 Validation of questionnaires

Questionnaires Q1, Q2 and Q3 have been in part designed by the researchers and by using literature sources. They were all validated according to methods well-known in the literature (Jensen, 2003). We briefly describe the validation procedures we used as follows:

- Content/logical validation. It is a kind of validation procedure aimed at allowing researchers to understand how the test items are representative of the content they aim to investigate on. The reliability of this validation is influenced by content experts’ judgment since they are designated to indicate whether the test is suitable to measure what it aims to measure. All the researchers participated to content validation of the questionnaires, and teachers at the school from where the students’ sample came have been asked to review the questionnaires’ questions. They discussed with the researchers the usefulness of any specific questions in the view of the questionnaire learning outcomes.
- Face validation. It is a fundamental step to measuring the validity of a test, as it studies how the questionnaire questions are understood by the students and allows the researcher to modify “on the fly” a question that is not clear to students and verify the effect.

Questionnaires Q1, Q2 and Q3 were face-validated with a sample of 15 students attending the same school of the students of the research sample, at different classes of the same grade.

The face validation revealed that some students did not understand well some of the questions proposed. For example, the early version of question n. 11 in questionnaire Q1, was “Why does not the insect in the picture "sink"?”. The question posed in this way misled several students, who immediately assumed that the insect floated. Thus, we decided to modify the question as follows: “Why does the insect in the picture walk on water without "sinking"?” to lead students to reflect also on physical mechanisms other than floating. Furthermore, no images relating to questions 6-7-11 of the questionnaire Q1 were included in the initial version of the questionnaire. Noting that several students found out hard to imagine the physical situations proposed, we chose to include in the questionnaire images making them clearer.

6.3 Data analysis methodologies

Our research embraces different kinds of data collection methods and analysis techniques and can, therefore, be defined as research based on mixed-method approaches. Such approaches turn out to be particularly dynamic and suitable for expanding research aims and improving the analytic power of studies.

All the data we collected were coded and analysed by means of different methods, depending on their nature. In this way, we extrapolated detailed information and insights on the data that allowed us to achieve a meaningful and deepen interpretation of them in the light of our research aims.

Data coming from the questionnaires Q1 and Q2 were studied by means of phenomenographic methods (Marton, 1986) and refined by means of content analysis methods (Krippendorff, 2018). Data were coded in terms of the answers most frequently given by the students to the questions (Battaglia, Di Paola et al., 2019; Fazio et al., 2013) and quantitatively treated to give evidence of the recurrences of these answers.

Data coming from the other sources (students’ worksheets, audio recordings of students group discussions at the end of each activity, students’ contributions during the final day brainstorming phase, and students’ feedback on the activities carried out during the TLSs) were coded by means of another qualitative analysis inspired by thematic analysis methods (Braun and Clarke, 2006), so to synthesize their richness and complexity.

In the following sections, we will briefly describe the methods we used in our mixed-method analysis.

6.3.1 Qualitative and quantitative research

Behavioural sciences research can be divided into two categories, associated with two different paradigms in social research, that is, the positivistic (or neo-positivistic) and the interpretative one.

Quantitative research can be considered representative of the first category. Its main assumptions are that social facts have an objective reality, variables influencing them can be identified, and relationships can be measured. On the other hand, qualitative research is representative of the second category, and its assumptions are that reality is socially constructed and variables describing it are complex, interwoven, and difficult to measure.

Qualitative researchers are mainly focused on describing a process in a given context. They usually do not assign frequencies to features identified in the data and pay the same attention to the phenomena analysed regardless of the frequency with which they occur.

Since qualitative analysis does not require the data to be forced into a finite number of classifications, it allows to identify fine distinctions inside them. Ambiguities inherent in human language can be recognised in this kind of analysis. One of the main disadvantages of qualitative analysis approaches is related to the generalization of their findings. Since qualitative research results are not usually statistically tested, they cannot be extended to wider populations with the same degree of certainty as in quantitative analysis.

Quantitative researchers classify and count features identified inside the data and, in some cases, design more complex statistical models to explain the observed results. Quantitative research findings can be generalised to a larger population, and datasets can be compared when valid sampling and significance techniques have been used. Thus, quantitative analysis allows researchers to discover which phenomena genuinely reflect a variety of behaviours and which are casual occurrences. The more basic task of just looking at a variety allows one to get a precise picture of the frequency and rarity of a given phenomenon and, thus, their relative normality or abnormality.

Data picture emerging from the quantitative analysis is not characterized by the same complexity and richness as that which emerges from the qualitative analysis. For statistical purposes, classifications have to be of the hard-and-fast type (so-called "Aristotelian" type). An item either belongs to a specific class or it does not. Sometimes quantitative analysis leads to an idealisation of the data. Moreover, quantitative analysis tends to overlook less frequent occurrences. To ensure that statistical tests such as the chi-squared test provide reliable results, a minimum number of frequencies is required. This implies that categories may have to be collapsed into one another, causing a loss of data information.

Quantitative research is affected by further issues such as the validity of the method and reliability. The first one concerns the question of whether researchers are measuring what they say/want; the second one refers to the internal consistency of a measure and/or the repeatability of a measure or finding.

Some fundamental features of qualitative and quantitative research are summarized in Tab. 9.

Tab. 9: Main characteristics of qualitative and quantitative research.

Qualitative research	**Quantitative research**
"*All research ultimately has a qualitative grounding*". - Donald T. Campbell (*)	"*There's no such thing as qualitative data. Everything is either 1 or 0*". - Fred Kerlinger (*)
It aims at a complete and detailed description of the data.	In classifies features, count them, and designs statistical models to explain what is observed.
Recommended during earlier phases of research projects.	Recommended during latter phases of research projects.
Researcher does not have to know exactly in advance what he is looking for.	Researcher knows exactly in advance what he/she is looking for.
Data analysis design emerges as the study unfolds.	All aspects of the study are carefully designed before data is collected.
Researcher is the data gathering instrument.	Researcher uses tools, such as questionnaires or equipment to collect numerical data.
Data is in the form of words, pictures, or objects.	Data is in the form of numbers and statistics.
Qualitative data are complex, "richer", time consuming, and difficult to generalize.	Quantitative data are more efficient, suitable to test hypotheses, but may miss contextual detail.
Researcher tends to be subjectively immersed in the subject matter.	Researcher tends to remain objectively detached from the subject matter.

(*) Quotes are from Miles and Huberman (1994, p. 40). *Qualitative Data Analysis*

Sometimes researchers believe that quantitative research is better or more scientific than qualitative one since the first involves words and behaviours, while the second one involves numbers and counts. Miles and Huberman (1994) reflect on the debate among researchers on the alleged superiority of qualitative research methods over quantitative ones or vice versa. As many other researchers, they consider this debate unproductive since they believe the two research methods complement each other.

One of the major differences between the two research methods is that qualitative research is typically inductive, while quantitative research is deductive. In qualitative research, a hypothesis is not needed to begin research. However, all quantitative research requires a hypothesis for the research to begin.

Another significant difference between qualitative and quantitative research concerns the underlying assumptions about the role of the researcher. Ideally, a quantitative researcher is an objective observer. He/she does not influence the subject of study, being detached from it. On the other hand, in qualitative research, it happens that researchers achieve more insights about the subject of study by participating and/or being strictly involved in it. The choice of data collection instruments is guided by the basic assumptions of each methodology.

Some researchers believe that qualitative and quantitative methodologies cannot be combined since they originate from totally different assumptions. Other researchers believe that qualitative and quantitative research have their own specific filed of application. Each of them is suitable to answer specific kind of questions in specific conditions. In this sense, they can be combined but alternately. For other researchers, qualitative and quantitative methods can be combined simultaneously to address the same research problem.

Researchers who support one of the two approaches often tend to discard the other one because they focus only on its shortcomings. For example, qualitative research proponents consider absolutely negative that quantitative research often "constrains" responses and or the research subjects (people) into strict categories that may not always reflect them meaningfully. On the other hand, quantitative research proponents do not agree with qualitative researchers when they focus mainly on specific and narrow aspects of the research and misses to investigate connections among different research features and possible outcomes' origins.

6.3.2 Qualitative/semi-quantitative approaches

Phenomenographic analysis

Phenomenography is a semi-quantitative analysis methodology used in educational research, which investigates the way in which people experience something or think about something (Marton, 1986). Phenomenographic studies usually involve groups of people, and data collection consists of individual descriptions of understanding. It does not focus on the individual experiences. It aims to identify and investigate possible conceptions of experience related to the phenomenon of interest for the whole group. The object of phenomenographic study is not the phenomenon itself but the relationship between the actors and the phenomenon (Bowden, 2005). This kind of analysis consists in organizing qualitatively distinct perceptions which emerge from the data collected into specific "categories of description" (Uljens, 1996; Marton, 1986). These categories represent the phenomenographic essence of the phenomenon (Uljens, 1996).

Content analysis

Content analysis is a research tool used to detect the presence of certain words, themes, or concepts within some given qualitative data. Through content analysis, researchers can analyse the meanings of words, themes, or concepts and the relationships among them and quantify how many times they occur in the data. In this sense, content analysis can be defined as "a research technique for the objective, systematic and quantitative description of the manifest content of communication" (Berelson, 1952).

Practices of content analysis vary depending on the different disciplines. Anyway, they involve systematic reading or observation of texts or artefacts, which are labelled to indicate the presence of interesting, meaningful pieces of content (Tipaldo, 2014; Hodder, 1994). By systematically labelling the content of a set of texts, researchers can analyse patterns of content both quantitatively by using statistical methods or qualitatively by analysing meanings of content within texts.

In the context of the content analysis, it is possible to distinguish between dictionary-based quantitative approaches and qualitative approaches. Methods based on quantitative approaches convert the observations of the identified categories into quantitative statistical data, while methods based on qualitative approaches are more focused on the intentionality and its implications. There are strong parallels between qualitative content analysis and thematic analysis (Vaismoradi et al., 2013). In fact, content analysis has many aspects in common with thematic analysis (that will be described later) and in some ways, can be considered an earlier and less sophisticated version of it.

Other qualitative approaches

There are many other different types of qualitative data analysis (QDA), each characterized by different purposes and particular **s**trengths and weaknesses. Among the most popular QDA methods there is qualitative content analysis (Krippendorff, 2018; Neuendorf, 2017), narrative analysis (Oliver, 1998; Riessman, 1993), discourse analysis (Wooffitt, 2005; Brown et al., 1983), grounded theory (Strauss and Corbin, 1994; Martin, 1986), interpretive phenomenological analysis (Eatough and Smith, 2017; Smith, 2011) and thematic analysis (Terry et al., 2017; Braun and Clarke, 2012). Since the analysis of our qualitative databases is inspired by thematic analysis, this methodology will be described in more detail.

Thematic analysis

Thematic analysis is a very common form of analysis used in qualitative research (Guest et al., 2011; Braun and Clarke, 2006) which focuses on the identification, analysis, and interpretation of themes within qualitative data (Braun and Clarke, 2006). Themes have to be understood as patterns of meaning. It is possible to find several definitions of themes in the literature, the most common ones will be briefly discussed later.

Thematic analysis differs from most other qualitative analytic approaches as narrative analysis, discourse analysis or grounded theory, which can be considered as theoretically informed frameworks for research, specifying guiding theory, appropriate research questions, instruments to collect data and procedures for conducting analysis. Since thematic analysis encompasses a great variety of approaches based on different philosophical and conceptual assumptions, it cannot be considered as a singular method.

The psychologists Virginia Braun and Victoria Clarke (Braun and Clarke, 2019), leading thematic analysis proponents, identify three main types of thematic analysis: coding reliability approaches (Guest et al., 2011; Boyatzis,1998), code book approaches (King and Brooks, 2016; Groenland, 2014; Gale et al., 2013) and reflexive approaches (Langdridge, 2004; Hayes, 2000).

Thematic analysis goes beyond simply counting phrases or words in a text, as in content analysis, and investigates explicit and implicit meanings within the data (Guest et al., 2011). A fundamental process for developing themes is coding. Coding is about identifying items of analytic interest in the data and tagging them with a coding label (Boyatzis, 1998).
Coding is a process of labelling and organizing qualitative data to identify different themes and the relationships among them. The coding process consists in assigning labels to words or phrases which carry out significant information about the data.

These labels can be words, phrases, or numbers. The use of words or short phrases is recommended since they are easier to remember, skim, and organize. In our analysis, labels are words, and for each of them, we report a brief description of what it represents for us.

Methods of coding qualitative data can be automated or manual. Manual coding usually includes the following steps:

1. Choose whether to use deductive or inductive coding;
2. Read through the data to get a sense of what it looks like. Assign to them a first set of codes;
3. Go through the data line-by-line to code as much as possible. Codes should become more detailed at this step;
4. Categorize the codes and figure out how they fit into the coding frame;
5. Identify which themes come up the most and act on them.

In some thematic analysis approaches, as coding reliability and code book approaches, coding is carried out after theme development and is a deductive process of allocating data to pre-identified themes. In other approaches, as Braun and Clarke’s reflexive approach, coding is carried out before theme development and themes are built from codes (Braun and Clarke, 2019).
One of the most relevant features of thematic analysis is its flexibility relatively to framing theory, research questions and research design (Braun and Clarke, 2006). Researchers can use thematic analysis to explore questions about participants’ lived experiences, perspectives, behaviour and practices, the factors and social processes that influence and shape particular phenomena, the explicit and implicit norms and ‘rules’ governing particular practices, as well as the social construction of meaning and the representation of social objects in particular texts and contexts (Braun and Clarke, 2012). Thematic analysis can be

used to analyse a wide range of qualitative data as data collected from interviews, focus groups, surveys, solicited diaries, visual methods etc. Thematic analysis can be used to analyse both small and large datasets (Braun and Clarke, 2006). Datasets can range from short, perfunctory response to an open-ended survey question to hundreds of pages of interview transcripts (Saldana, 2009).

The process of thematic analysis of data can occur both inductively or deductively (Braun and Clarke, 2006). In an inductive approach, the themes identified are strongly linked to the data (Boyatzis, 1998). In this case, coding occurs without trying to fit the data into pre-existing theory or framework. However, in practice, it is not possible for the researchers to free themselves completely from ontological (theory of reality), epistemological (theory of knowledge) and paradigmatic (habitual) assumptions, and coding will reflect the researcher's philosophical standpoint, and individual/communal values with respect to knowledge and learning necessarily (Braun and Clarke, 2006).

Deductive approaches are more theory-driven (Crabtree, 1999) that is they tend to be more interpretative because the analysis is explicitly shaped and informed by pre-existing theory and concepts. Deductive approaches can use existing theory as a lens through which to organize, code and interpret the data or search for themes previously identified in other research in the dataset of interest. We can say we followed a deductive-like approach since the variables on which we chose to focus on in the analysis of our datasets come from the literature.

A thematic analysis can also combine inductive and deductive approaches, that is, it can account for a priori ideas from clinician-led qualitative data analysis teams and those emerging from study participants and the field observations (Huang et al., 2021).

Different approaches to thematic analysis

Coding reliability (Guest et al., 2011; Boyatzis, 1998) approaches are quite similar to qualitative content analysis. These approaches aim to obtain a measurement of coding reliability through the use of structured and fixed code books, the use of multiple coders who work independently to apply the code book to the data, the measurement of inter-coder agreement and the determination of final coding through consensus or agreement between coders. Coding reliability approaches represent a form of qualitative positivism or small q qualitative research (Kidder and Fine, 1987), which combine the use of qualitative data with data analysis processes and procedures based on the research values and assumptions of (quantitative) positivism. Researchers using this type of approach focus on the importance of establishing coding reliability. They consider researcher subjectivity and bias something that must be contained and controlled to prevent research results from being compromised.

Boyatzis (1998) presents his approach as one that can ‘bridge the divide’ between quantitative (positivist) and qualitative (interpretivist) paradigms. Some qualitative researchers criticize the use of structured code books, multiple independent coders, and inter-rater reliability measures. Janice Morse argues that such coding is necessarily coarse and superficial to facilitate coding agreement (Morse, 1997). Braun and Clarke (citing Yardley, 2007) argue that all coding agreement demonstrates is that coders have been trained to code in the same way, not that coding is ‘reliable’ or ‘accurate’ with respect to the underlying phenomena that is coded and described (Braun and Clarke, 2012).

Code book approaches such as framework analysis (Gale et al., 2013), template analysis (King and Brooks, 2016) and matrix analysis (Groenland, 2014) are based on the use of structured code books but, unlike coding reliability approaches, emphasise to a greater or lesser extent qualitative research values.

In both coding reliability and code book approaches, themes are developed at an early stage before coding, after a data familiarization phase consisting in reading and re-reading data to familiarize with them and their content. Once themes have been developed, the code book is created. Coding implies assigning data to the pre-determined themes following the code book as a guide. The code book can also be used to map and display the occurrence of codes and themes in each data item.

On the other hand, reflexive approaches are based on flexible coding processes. They do not indicate the use of a code book, coding can also be carried out by one researcher, and when multiple researchers are involved in the coding process, it is not configured as a process that should lead to consensus but as a collaborative process.

In reflexive approaches, codes are not fixed, and they evolve as the coding process goes on. Codes can be re-defined, can be split into two or more codes, collapsed with other codes, and sometimes they should be converted into themes (Braun and Clarke, 2012). Reflexive approaches typically involve later theme development, with themes created from clustering together similar codes. Themes should capture shared meaning organised around a central concept or idea (Braun et al., 2014).

In the context of thematic analysis, themes are not defined or conceptualized in a systematic way (DeSantis and Ugarriza, 2000). Some thematic analysis proponents, as well as Braun and Clarke, conceptualize themes as patterns of shared meaning across data items, which converge in a central concept. In this sense, themes should be relevant to the understanding of a given phenomenon and to the research question (Braun and Clarke, 2019).

On the other hand, most coding reliability, and code book proponents, look at themes as simply summaries of information related to a particular topic or data domain. Themes do not necessarily have to converge to a central concept (Braun and Clarke, 2019).

Although these two conceptualisations are associated with distinct approaches to thematic analysis, they are often mixed and confused. What Braun and Clarke call domain summary or topic summary themes often have one-word theme titles (e.g., Gender, Support) or titles like 'Benefits of...', 'Barriers to...' indicating the focus on summarising everything participants said, or the main points raised, in relation to a particular topic or data domain (Braun and Clarke, 2019). Topic summary themes are typically developed prior to data coding and often reflect data collection questions. Shared meaning themes that are underpinned by a central concept or idea (Braun et al., 2014) cannot be developed prior to coding since they are built from codes, so they are the output of a thorough and systematic coding process.

Braun and Clarke have been critical of the confusion of topic summary themes with their conceptualisation of themes as capturing shared meaning underpinned by a central concept (Clarke and Braun, 2018). Some qualitative researchers have argued that topic summaries represent an under-developed analysis or analytic foreclosure (Connelly and Peltzer, 2016; Sandelowski and Leeman, 2012).

The question of ‘themes emerge from data’ is debated. Braun and Clarke criticize this language because they think it gives a misleading idea of theme. In particular, saying that ‘themes emerge from data’ should lead to consider themes as entities pre-existing in the data while researchers passively watch them emerging from the data (Braun and Clarke, 2006). Braun and Clarke argue the researcher plays an active role in the creation of themes. Themes are built, created, and generated rather than simply emerging from data.

Others use the term to capture the inductive (emergent) creation of themes. However, it is almost never clear with which meaning the term is used.

Prevalence and recurrence are not necessarily good criteria that allow the researchers to establish what should be considered a theme. Themes can be considered relevant when they promote a better and deeper understanding of the phenomena of interest and allow to address the research question, so researchers’ judgement is the key tool in determining which themes are more crucial (Braun and Clarke, 2006).

Data can be coded, and themes can be identified at semantic and latent levels (Braun and Clarke, 2006; Boyatzis, 1998). Researchers who conduct thematic analysis on a semantic level do not look beyond what participant said or wrote, they stop at the explicit and surface meanings. Conversely, researchers who carry out thematic analysis on a latent level, through an interpretative and conceptual orientation to the data, can capture underlying ideas, patterns, and assumptions. Thematic analysis can focus on one of these levels or both.

For Braun and Clarke, there is a clear (but not absolute) distinction between a theme and a code. A code captures one (or more) insights about the data, and a theme encompasses numerous insights organised around a central concept or idea. They often use the analogy of a brick and tile house-the code is an individual brick or tile, and themes are the walls or roof panels, each made up of numerous codes.

Other approaches to thematic analysis don't make such a clear distinction between codes and themes - several texts recommend that researchers "code for themes" (Saldana, 2009). This can be confusing because, for Braun and Clarke, and others, the theme is considered the outcome or result of coding, not that which is coded. In approaches that make a clear distinction between codes and themes, the code is the label that is given to particular pieces of the data that contribute to a theme. For example, "SECURITY can be a code, but A FALSE SENSE OF SECURITY can be a theme (Saldana, 2009)".

Methodological issues affecting thematic analysis

Qualitative analysis is a form of interpretive research, for this reason, the positionings, values, and judgments of the researchers have to be explicitly expressed and acknowledged so they are taken into account in making sense of the final report and judging its quality (Creswell, 1994). Researchers model the analysis process. They can be considered the instrument for collecting and analysing data, so in order to acknowledge a researcher as the tool of analysis, it is useful to create a reflexivity journal (Creswell, 2007). In the reflexivity process, researchers reflect on and record their values, positionings, choices, research practices and how they affected the analysis of the data.

Throughout the coding process, researchers should have detailed records of the development of each code and potential themes. Variations made to themes and connections between them should be debated in the final report to make the reader understand the choices that have been made in the coding process (Guba and Lincoln, 1994). As the data analysis is performed, researchers should take notes on their considerations about the data. Recording ideas and reflections at each step of thematic analysis should help researchers to go on in the coding process in the next analysis phases (Saldana, 2009).

Researchers conducting qualitative analysis try to use the most suitable method for their research question (Braun and Clarke, 2012). However, there is rarely only one appropriate method of analysis. Among the criteria used for the selection of methods of analysis, there are, for example, researchers' theoretical commitments and their familiarity with particular methods. Thematic analysis is a flexible method of data analysis that allows researchers with various methodological backgrounds to engage in this type of analysis (Braun and Clarke, 2006). For positivists, 'reliability' is a crucial point. The numerous potential interpretations of data due to researchers' subjectivity should distort the analysis. For those committed to qualitative research values, researcher subjectivity represents a resource rather than a threat to credibility. There is no one correct or accurate interpretation of data, interpretations are inevitably subjective and reflect the positioning of the researcher. Quality is achieved through a systematic and rigorous approach and through the researcher continually reflecting on how they are shaping the developing analysis. Thematic analysis has several advantages and disadvantages (resumed in Tab. 10), and the researchers have to understand if this method of analysis is suitable for their research design and purposes.

Tab. 10: Overview of the main advantages and disadvantages thematic data analysis.

Advantages	**Disadvantages**
The theoretical and research design flexibility it allows researchers - multiple theories can be applied to this process across a variety of epistemologies (Braun and Clarke, 2006).	Thematic analysis may miss nuanced data if the researcher is not careful and uses thematic analysis in a theoretical vacuum (Guest et al., 2011; Braun and Clarke, 2006).
Well suited to large data sets (Guest et al., 2011; Braun and Clarke, 2006).	Flexibility can make it difficult for novice researchers to decide what aspects of the data to focus on (Braun and Clarke, 2006).
Code book and coding reliability approaches are designed for use with research teams.	Limited interpretive power of analysis is not grounded in a theoretical framework (Braun and Clarke, 2006).
Interpretation of themes supported by data (Guest et al., 2011).	Difficult to maintain sense of continuity of data in individual accounts because of the focus on identifying themes across data items (Braun and Clarke, 2006).
Applicable to research questions that go beyond an individual's experience (Guest et al., 2011).	Does not allow researchers to make technical claims about language usage (unlike discourse analysis and narrative analysis) (Braun and Clarke, 2006).
Allows for inductive development of codes and themes from data (Saldana, 2009).	

CHAPTER 7

ANALYSIS OF THE RESULTS

In this chapter, we will discuss in detail the analysis of the various databases and the related results. We start with the analysis of questionnaires 1 and 2.

7.1 Results of the analysis of questionnaires 1 and 2

As we said in Chapter 6, questionnaires 1 and 2 (Q1 and Q2, respectively) were designed mainly to get information on the study variables:

1.1: Appropriation of concepts and forms of representation (comparison between pre-, post- and post-post administration of Q2)

1.2: Evolution of common-sense conceptions to scientific ones (comparison between pre- and post-administration of Q1)

1.3: Long-time retention of concepts (analysis of post-post administration of Q2)

2.2: Development of reasoning skills aimed at interpreting real-life situations and experiments (comparison between pre- and post-administration of Q1, and between pre-, post- and post-post administration of Q2).

2.3: Generalization of what has been learned (comparison between pre-, post-, and post-post administration of Q2).

The questionnaires and the typical responses given by the students are reported in Appendixes A-C. The analysis of students' answers to the questionnaires with respect to variables 1.2 and 2.2 was performed by first using phenomenographic methods (Marton, 1986) and then refined by using a content analysis (Krippendorff, 2018) approach. As shown in Section 7.1.1, it allowed us to identify, based on previous research results (Battaglia, Di Paola et al., 2019; Fazio et al., 2013), three students' "epistemological profiles", related to three different ways of reasoning when dealing with problems and situations proposed in the questions (Fazio et al., 2013) (study variable 2.2), also related to the use of common-sense and scientific knowledge (study variable 1.2). All student answers were classified in one of these profiles, and numbers and percentages of occurrence were given, as we will see below.

We start below by discussing the results of the analysis of the students' responses to the pre/post-instruction administration of questionnaire Q1 with respect to the study variables 1.2: Evolution of common-sense conceptions to scientific ones and 2.2: Development of reasoning skills aimed at interpreting real-life situations and experiments.

We will continue with an analysis of answers to questionnaire Q2 with respect to the study variables 1.2 and 2.2. A further analysis of Q2 answers, discussed in sections 7.1.2 and 7.1.3, will give us insights into the development of conceptual knowledge and forms of representation (study variable 1.1), on long-time retention of concepts (study variable 1.3), and on generalization skills of what has been learned (study variable 2.3).

7.1.1 Variables 1.2 and 2.2

The phenomenographic/content analysis of the students' answers allowed us to study variables 1.2 and 2.2 with respect to the student answers to questionnaires Q1 and Q2. A further study of the variables was conducted on the other databases and will be discussed in section 7.2.2

We started by identifying, on the basis of previous research (Battaglia, Di Paola et al., 2019; Fazio et al., 2013), three students' "epistemological profiles" related to three different ways to reason and apply common-sense and scientific knowledge, when tackling the situations proposed in the questions. The profiles are resumed in Tab. 11, where a brief description of the reasoning procedures that the students use when tackling the questions is given for each profile. We note that the Practical/Everyday profile can be related to the use of common-sense knowledge. Both the Descriptive and Explicative profiles are related to the use of scientific knowledge, although at different levels of sophistication, as is evident from Tab. 11. For this reason, the analysis performed by means of the individuations of the three abovementioned profiles can give us insights on the evolution of both study variables 1.2 and 2.2.

Tab. 11: Description of students' "epistemological profiles" identified based on the ways to tackle problems and situations proposed in the questionnaires.

Practical/Everyday	**Descriptive**	**Explicative**
Reflects the creation of situational meanings derived from everyday contexts. The student uses other situations, perceived as analogous to the one proposed in the question, to try to describe/explain it.	The student describes and characterizes the proposed situation / analyzed process by searching in memory the variables perceived as relevant and/or recalling their relations. The variables and the relationships among them are expressed by means of different languages and communication channels (verbal, iconic, analytic). Causal relations among the variables on the basis of a functioning model (microscopic/macroscopic) are not given.	The student explains the proposed situation referring to a model (qualitative and/or quantitative) based on cause/effect relations. He may also provide explanatory hypotheses by introducing models which can be seen at a theoretical level.

Tab. 12 shows some examples of keywords and sentences identified on the basis of the content analysis of students' answers, which allowed us to trace back students' response strategies to a one of the three abovementioned profiles.

Tab. 12: Examples of terms and sentences in students' answers used to classify them in one of the three "epistemological profiles" described in Tab.10.

Practical/Everyday	**Descriptive**	**Explicative**
(according to my) experience ... *Like I see in real life ...* *Usually ...* *Real object ...* *Like an insect on water ...*	*I remember that ...* *I studied that ...* *I know that ...* *The formula says ...* *The graph shows ...* *There are adhesive and cohesive forces ...* *There is surface tension ...* *Chemistry/Physics say ...*	*Molecular Movement ....* *Is similar to ...* *Microscopic ...* *Inter-Molecular forces ...* *Interaction ...* *Equilibrium ...* *Molecules ...*

In the following sections, the results obtained by analysing questionnaires Q1 and Q2 to study variables 1.2 and 2.2 are reported and discussed.

Questionnaire Q1

Tab. 13 reports a contingency table with the classification of the answers given by the whole sample of students (Group A + Group B) before instruction (pre-instruction) and after instruction (post-instruction) in the three epistemological profiles discussed above. In this table, the number of answers classified in each profile is shown, and in Fig. 28, the percentage of answers is shown. In Table 12 (and in all the similar tables reported in the following), p-values obtained by running chi-squared tests are reported. These values are all less than 1%, showing that there are significant differences in the distributions of answers in the three epistemological categories used for the analysis among pre-, post-instruction testing and post-post instruction (only for Q2 analysis, see tables 15-26).

Tab. 13: $\chi^2 = 66{,}93$, $p < 1\%$.

All students - Q1	***Everyday***	***Descriptive***	***Explicative***	***No answer***
Pre-instruction	132	114	69	47
Post-instruction	61	136	135	14

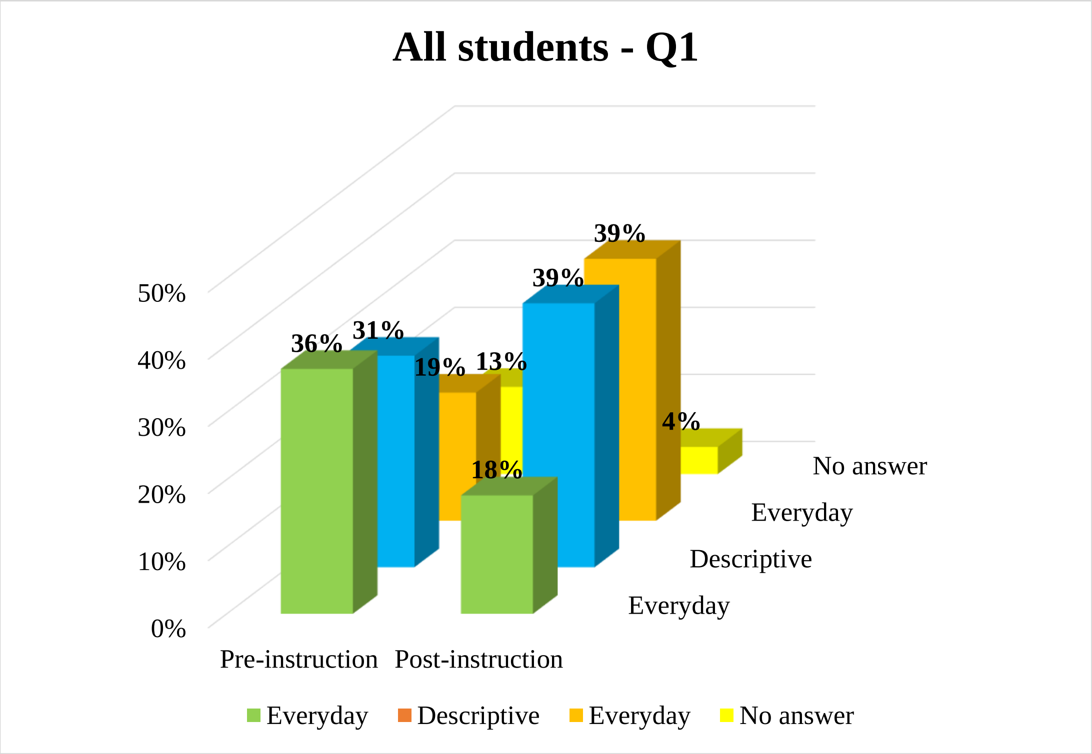


Fig. 28: Bar-diagrams showing the percentages of answers given by the entire sample of students (Group A + Group B) to the pre-and post-instruction questionnaire Q1. The answers are categorized according to the “epistemological profiles” identified in our analysis.

The bar-diagrams in Fig. 28 resume the results of the analysis of the answers given to questionnaire Q1 during pre-and post-instruction administration for the entire sample of students (Group A + Group B), respectively. As can be seen in Fig. 28, a general decrease in everyday-type answers from the pre-instruction questionnaire to the post-instruction is registered. After instruction, everyday-type answers are still present, but descriptive- and explicative-type answers are prevalent. Moreover, a decrease in the number of not-answered questions in the post-instruction questionnaire with respect to the pre-instruction one is highlighted.

It is worth noting that the most significant variations between the pre-instruction administration of the questionnaire and the post-instruction one regard the percentages of everyday- and explicative-type answers. Everyday-type answers decreased by 18% from the pre- to post-instruction questionnaire administration, while explicative-type answers increase by 20%.

Tab. 14 and Tab. 15 report the contingency tables for the answers given to Q1 by Group A and Group B students, respectively, before and after instruction. In these tables, the number of answers is reported, and in Fig. 29 the percentage of answers is reported.

Tab. 14: $\chi^2 = 24{,}69, p < 1\%$.

Group A - Q1	***Everyday***	***Descriptive***	***Explicative***	***No answer***
Pre-instruction	58	45	41	31
Post-instruction	35	72	55	10

Tab. 15: $\chi^2 = 55{,}07, p < 1\%$.

Group B - Q1	***Everyday***	***Descriptive***	***Explicative***	***No answer***
Pre-instruction	74	69	28	16
Post-instruction	26	64	80	4

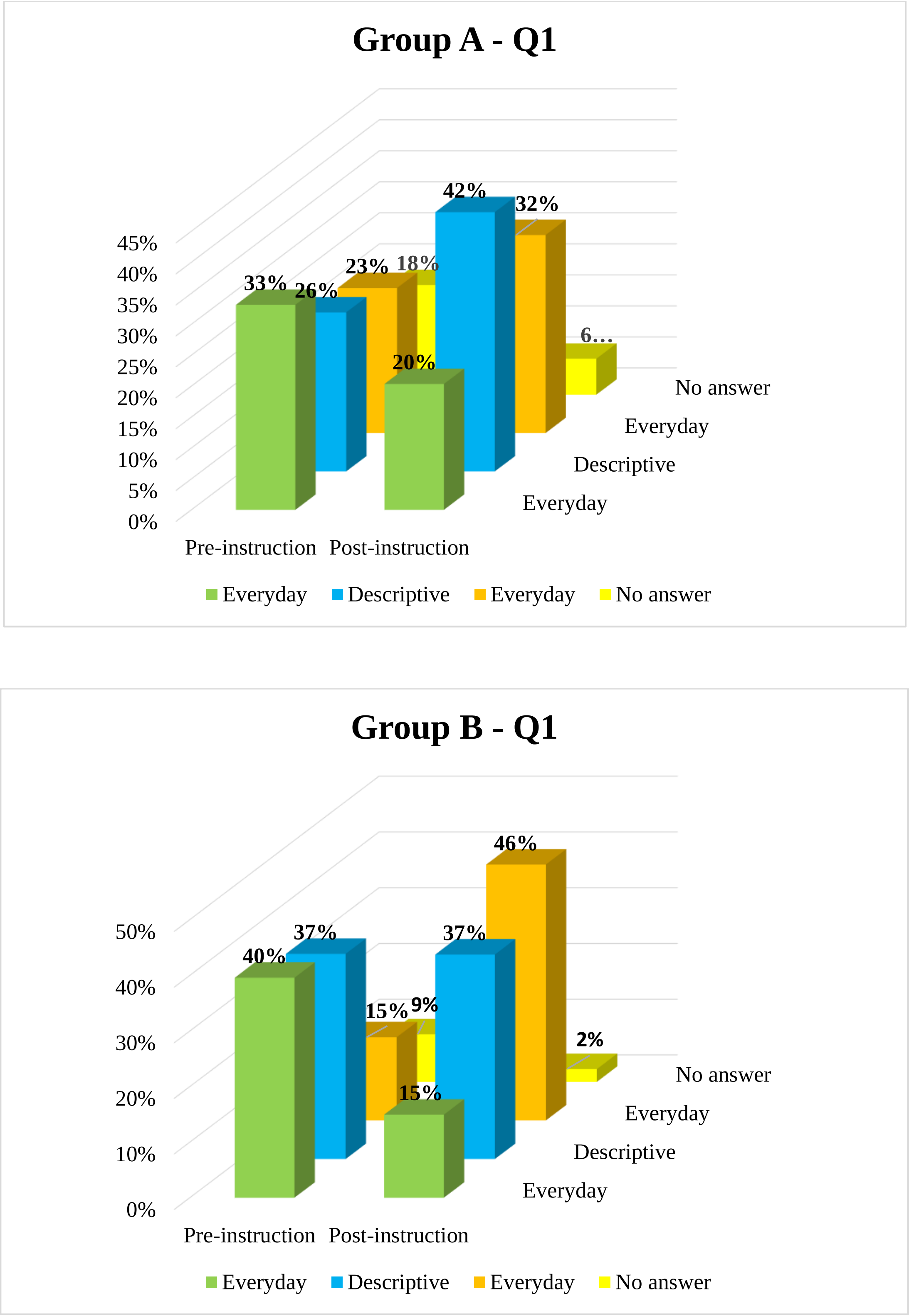


Fig. 29: Bar-diagrams showing the percentages of answers given by Group A and Group B students, respectively, to the pre-and post-instruction questionnaire Q1. The answers are categorized according to the “epistemological profiles” identified in our analysis and reported in Tab. 11.

Fig. 29 gives more detail about what happened in each group. It is again clear that in the post-instruction questionnaire, both groups still give everyday-type answers, but to a lesser extent than before. Both groups also show a decrease in the percentage of not answered questions from the pre- to post-instruction questionnaire administration.

In particular, Group A highlights an increase of 16% in descriptive-type answers. Moreover, a decrease of 12% in the number of not-answered questions from the pre- to post-instruction questionnaire is highlighted.

On the other hand, Group B maintains the percentage of descriptive-type answers and highlights a significant increase (31%) in explicative-type answers. Everyday-type answers show a clear decrease (25%) from the pre- to post-instruction questionnaire.

Questionnaire Q2

Questionnaire Q2 is based on content dealt with during the activities of the TLSs, which is usually not dealt with during traditional physics lessons in Italian high schools. We chose to administer it before instruction because students of the research sample had already heard about surface phenomena at school, in chemistry classes. However, in that context, several concepts typical of the topic, like surface tension, cohesion and adhesion forces, energy, etc., were introduced only superficially. Particularly, the interactions involved in surface phenomena had not been clarified and presented only in theoretical form. For that reason, we wanted to have information on content understanding and approaches followed by the students when trying to make sense of situations/questions related to surface phenomena.

Tab. 16 reports a contingency table for the answers given to Q2 by the whole sample of students (Group A + Group B), before instruction (pre-instruction), after instruction (post-instruction) and after a two-month pause (post-post-instruction). In this table, the number of answers classified in one of the three epistemological profiles is reported, and in Fig. 30, the percentage of answers is reported.

Tab. 16: $\chi^2 = 497{,}5$, $p < 1\%$.

All students - Q2	***Everyday***	***Descriptive***	***Explicative***	***No answer***
Pre-instruction	60	85	45	219
Post-instruction	1	156	187	11
Post-post instruction	5	175	150	30

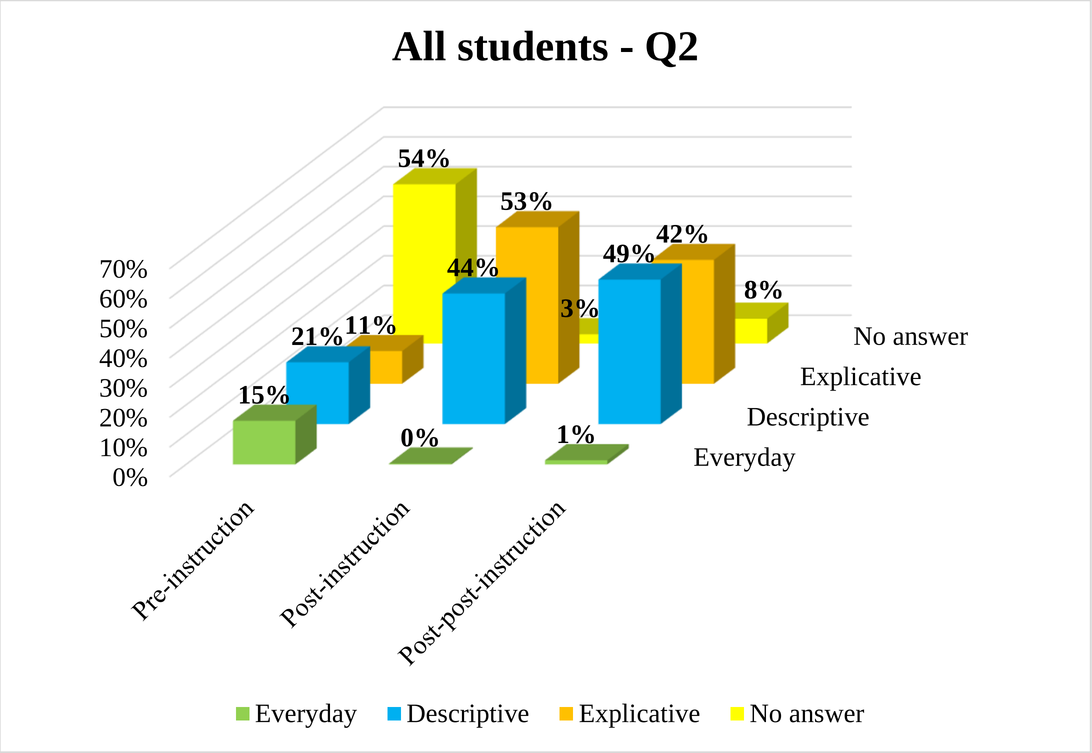


Fig. 30: Bar-diagrams showing the percentages of answers given by the entire sample of students (Group A + Group B) to questionnaire Q2 during the pre-, post-, and post-post-instruction administrations. The answers are categorized according to the “epistemological profiles” identified in our analysis.

We, first of all, compare the results of the analysis of students’ answers for the entire sample of students (Group A + Group B). As can be seen in Fig. 30, a general and sharp decrease in everyday-type answers from the pre-instruction questionnaire to the post-instruction (from 15% to 0%) is registered. The decrease is also confirmed after the two-months break. Furthermore, a huge decrease (from 54% to 3%) in not-answered questions between the pre- and post-instruction administrations is highlighted. It is worth noting that significant variations from the pre-instruction administration of the questionnaire to the post-instruction one also regard descriptive- and explicative-type answers. Descriptive answers increased by 23% from the pre- to post-instruction questionnaire, while explicative-type answers increased by 42%. The results obtained after the two-month pause show that the epistemological profiles highlighted by the students changed a bit, with a 5% increase in descriptive approaches and an 11% decrease in explicative ones.

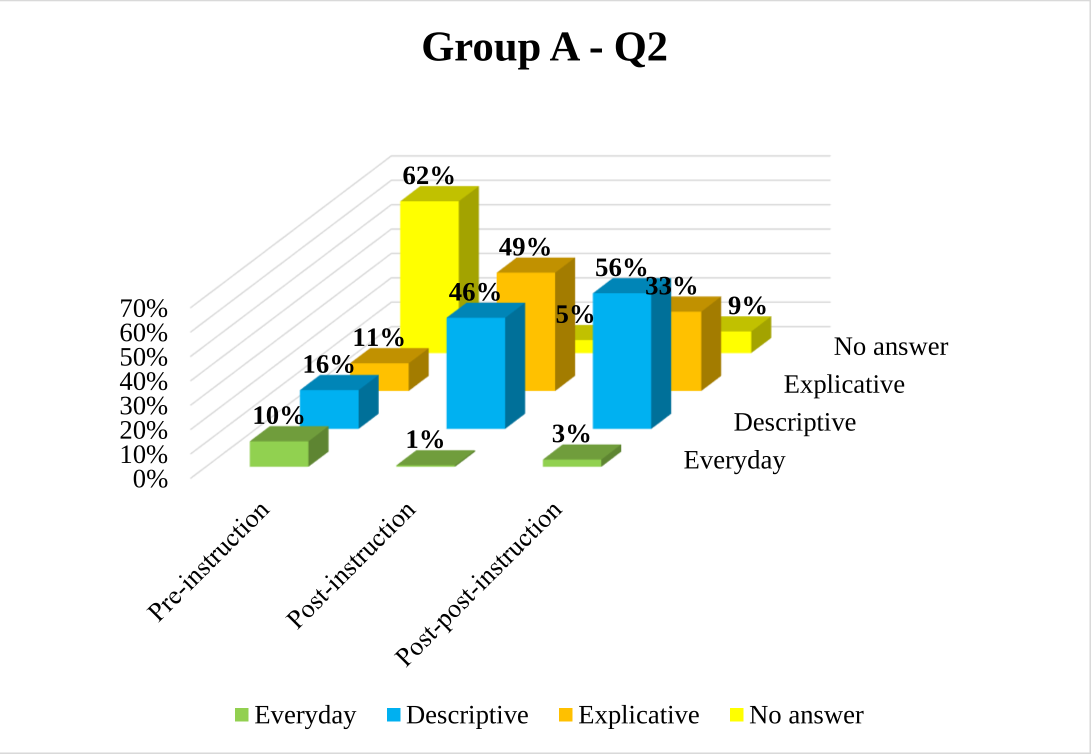
Tab. 17 and Tab. 18 report the contingency tables of the answers given to Q2 by Group A and Group B students, respectively, before, after instruction and after a two-months break.

Tab. 17: $\chi^2 = 253{,}4,\ p < 1\%$.

Group A - Q2	***Everyday***	***Descriptive***	***Explicative***	***No answer***
Pre-instruction	23	35	25	137
Post-instruction	1	77	82	9
Post-post-instruction	5	94	55	15

Tab. 18: $\chi^2 = 253{,}2,\ p < 1\%$.

Group B - Q2	***Everyday***	***Descriptive***	***Explicative***	***No answer***
Pre-instruction	37	50	20	82
Post-instruction	0	79	105	2
Post-post-instruction	0	81	95	15



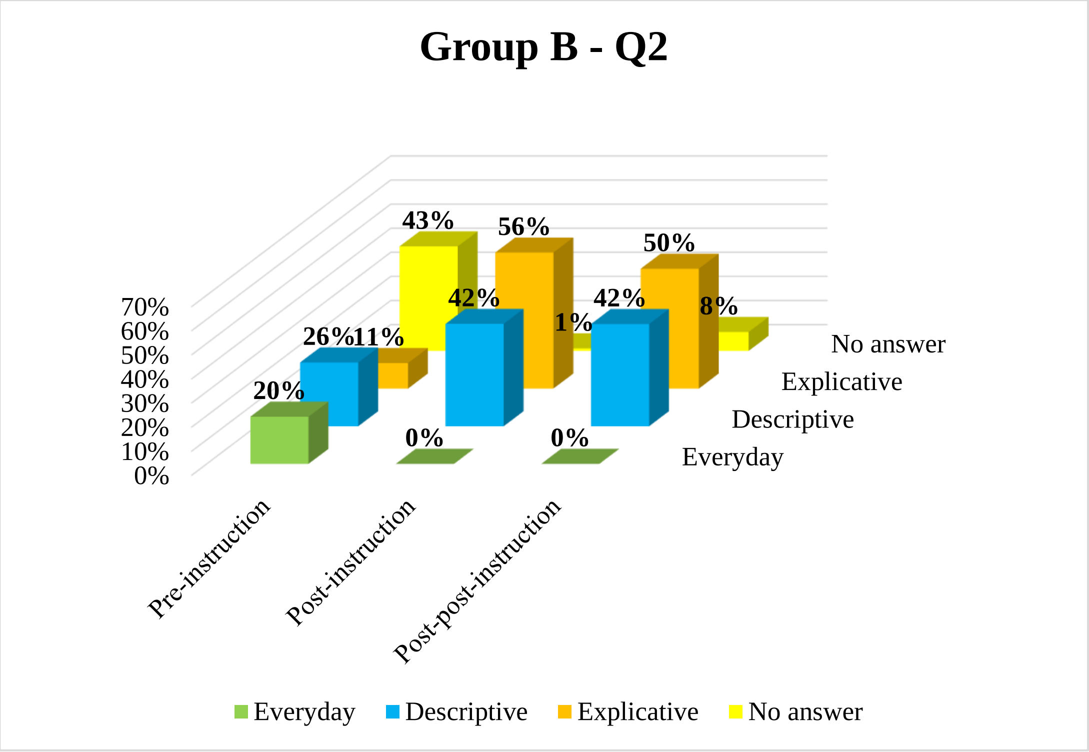


Fig. 31: Bar diagrams showing the percentages of answers given by Group A and Group B students, respectively, to questionnaire Q2 during the pre-, post-, and post-post-instruction administrations. The answers are categorized according to the "epistemological profiles" identified in our analysis.

Fig. 31 gives more detail about what happened in each group. Both show a sharp decrease in the percentage of not answered questions from the pre- to post-instruction administrations. Moreover, In the post-instruction administration, everyday-type answers are not significant in both groups. This behaviour is also maintained after the two-months break.

Both Group A and B highlight an increase in descriptive- and explicative-type answers. However, Group A highlights a 30% increase of descriptive answers and a 38% increase of explicative answers between pre- and post- instruction. Group B highlights a 16% increase in descriptive-type answers and a relevant (45%) increase in explicative answers from the pre- to post-instruction administration.

Looking to the results obtained after the two-months break, we can note that Group A students do not maintain the high percentage (49%) of explicative-type answers highlighted during the post-instruction administration of the questionnaire and highlight an increase of descriptive ones. On the other hand, Group B students maintain the level of descriptive-type answers. This can be evidence of a better persistence of explanation-based reasoning skills in Group B students than in Group A ones. On the other hand, the maintenance of descriptive reasoning skills in both Groups shows that the shift from common-sense reasoning to scientific-based one is stable after two months from the end of the pedagogical activities.

Summing up, both Group A and Group B show a decrease in the percentage of everyday-type answers and not-given answers from pre- to post-instruction questionnaire administration, for both Q1 and Q2. Moreover, for both groups an increase in the percentage of descriptive and explicative-type answers for both questionnaires Q1 and Q2 is highlighted from pre- to post-instruction questionnaire administration. The results appear reasonably stable after the two-months break, particularly for Group B.

Based on the results obtained through the analysis of the questionnaires Q1 and Q2, it emerges that the TLSs activities, and particularly both the modelling approaches, have contributed to the evolution of everyday-type answer strategy towards descriptive and explicative-type ones. However, our results allow us to say that students in Group B are, after instruction, more able to give answers based on explanation-based reasoning than students in Group A. This behaviour persists even after some time from the end of the TLSs activities. It may mean that mesoscopic modelling activities support the development of explanation-oriented reasoning lines more than the more traditional, macroscopic ones. In this sense, we can say that modelling activities based on mesoscopic approach can be considered useful to foster the development of scientific knowledge (variable 1.2), with respect to the use of reasoning skills aimed at explaining real-life situations and experiments (variable 2.2) more for Group B students than for Group A ones. The usefulness of these activities seems stable after a two-months break. On the other hand, the modelling activities based on macroscopic approach, although able to make students shift from common-sense reasoning to scientific ones, seems less efficient than the mesoscopic approach to foster the development of reasoning skills based on explanations and stable in time.

7.1.2 Variables 1.1 and 1.3

This part of the study of variable 1.1: Appropriation of concepts and forms of representation was done by means of a content analysis of the answers to questionnaire Q2 before, after instruction and after the two-months break (to investigate variable 1.3, i.e., long-time retention of concepts).

A further study of the variable was conducted on the other databases and will be discussed in section 7.2.2.

As the variable regards the appropriation of both concepts and forms of representations, we decided to analyse the student answers separately with respect to these two aspects.

Concepts

In section 4.2.1, we discussed some research literature evidences about appropriation of concepts and content. We saw that teachers can observe a first level of appropriation when personal signature ideas grounded in the discipline emerge in students, and they are able to correctly describe and discuss the contents. A second, deeper appropriation occurs when students are able to apply the contents to solve problems and face situations.

For this reason, we decided to analyse the answers given by students to questionnaire Q2 searching in each student answer for the evidence of 1) application of the concept to solve a problem or face a situation; 2) correct description of a concept; 3) incorrect description of a concept; 4) no answer.

Tab. 19 shows the results of that analysis for the whole group of students (Group A and Group B) in the three administration phases of the questionnaire. The values represent the number of answers that highlight a specific level of appropriation of concepts.

Tab. 19: $\chi^2 = 443{,}1, p < 1\%$.

All students - Q2	***Application***	***Correct description***	***Incorrect description***	***No answer***
Pre-instruction	5	90	95	219
Post-instruction	101	194	49	11
Post-post instruction	88	202	40	30

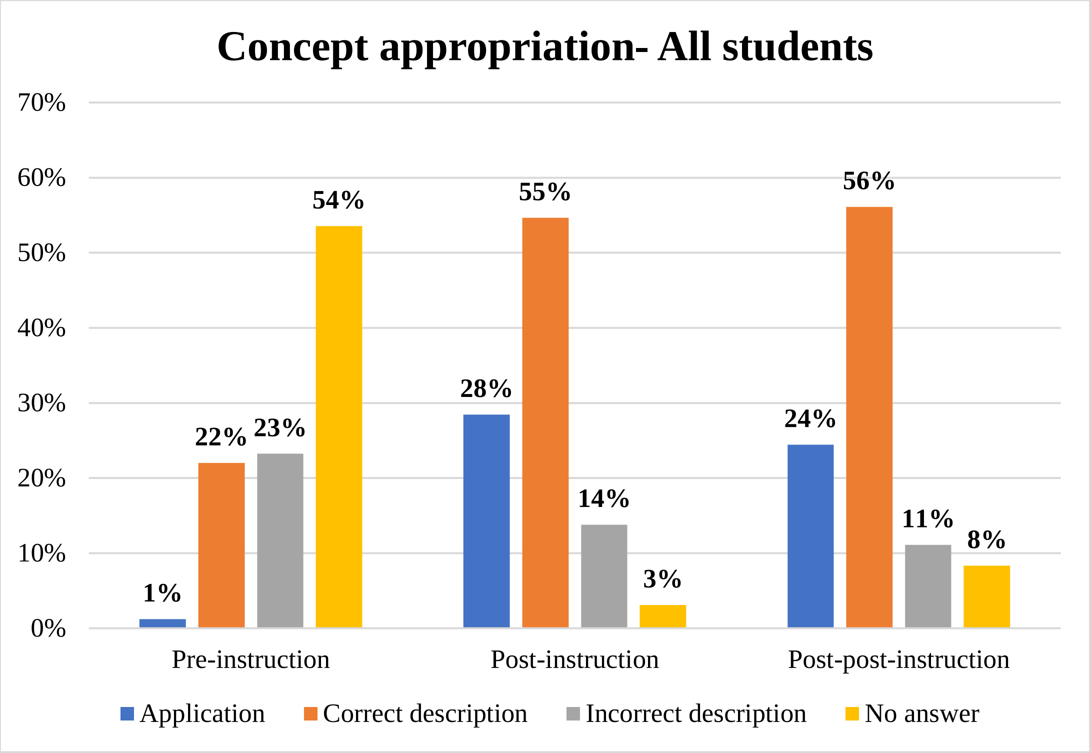


Fig. 32: Bar-diagrams showing the percentages of answers given by the entire sample of students (Group A + Group B) to questionnaire Q2 during the pre-, post-, and post-post-instruction administrations. The answers are categorized according to the different level of concept appropriation identified in our analysis.

As can be seen in the bar diagrams in Fig. 32, a drastic decrease in the number of students who do not answer the questions proposed is registered from the pre-instruction to the post-instruction questionnaire. Moreover, after instruction, parallel to a decrease in the number of incorrect descriptions, a significant increase in the number of correct description of concepts and their application to face problems is registered. These trends are confirmed in the post-post administration of the questionnaire, giving evidence of the persistence of concepts learned before.

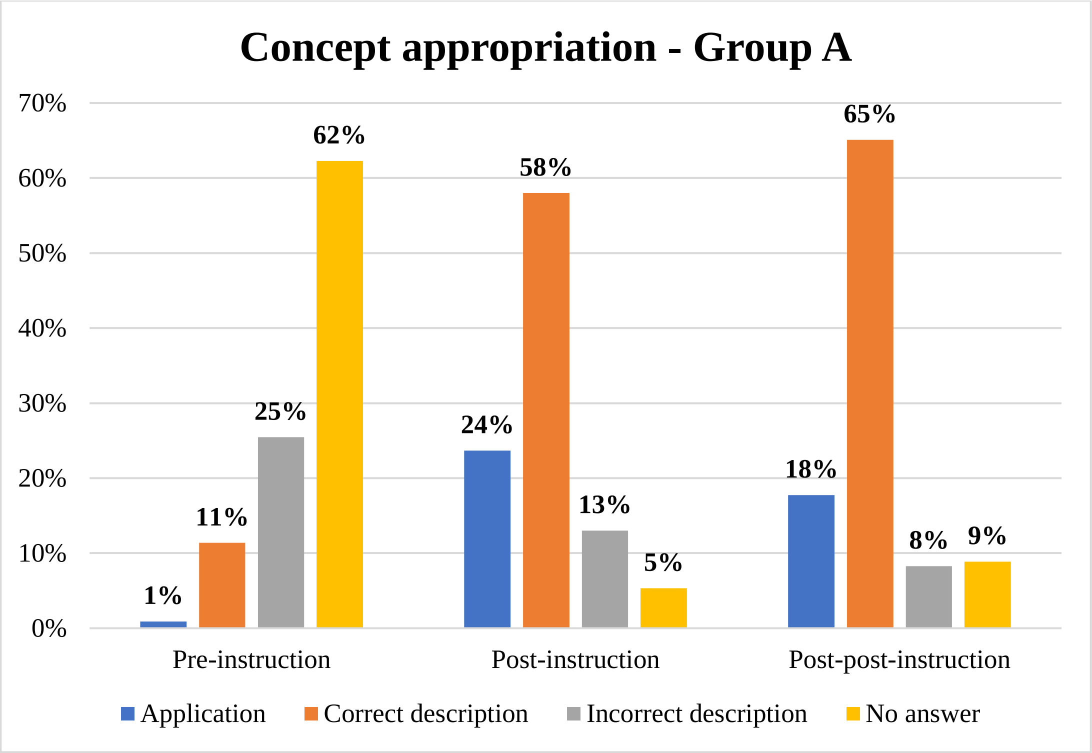
Tab. 20 and 21 show the contingency tables for the results of that analysis for Group A and Group B students, respectively, in the three administration phases of the questionnaire. The values represent the number of answers that highlight a specific level of appropriation of concepts.

Tab. 20: $\chi^2 = 284{,}0$, $p < 1\%$.

Group A - Q2	***Application***	***Correct description***	***Incorrect description***	***No answer***
Pre-instruction	2	25	56	137
Post-instruction	40	98	22	9
Post-post instruction	30	110	14	15

Tab. 21: $\chi^2 = 174{,}4$, $p < 1\%$.

Group B - Q2	***Application***	***Correct description***	***Incorrect description***	***No answer***
Pre-instruction	3	65	39	82
Post-instruction	61	96	27	2
Post-post instruction	58	92	26	15



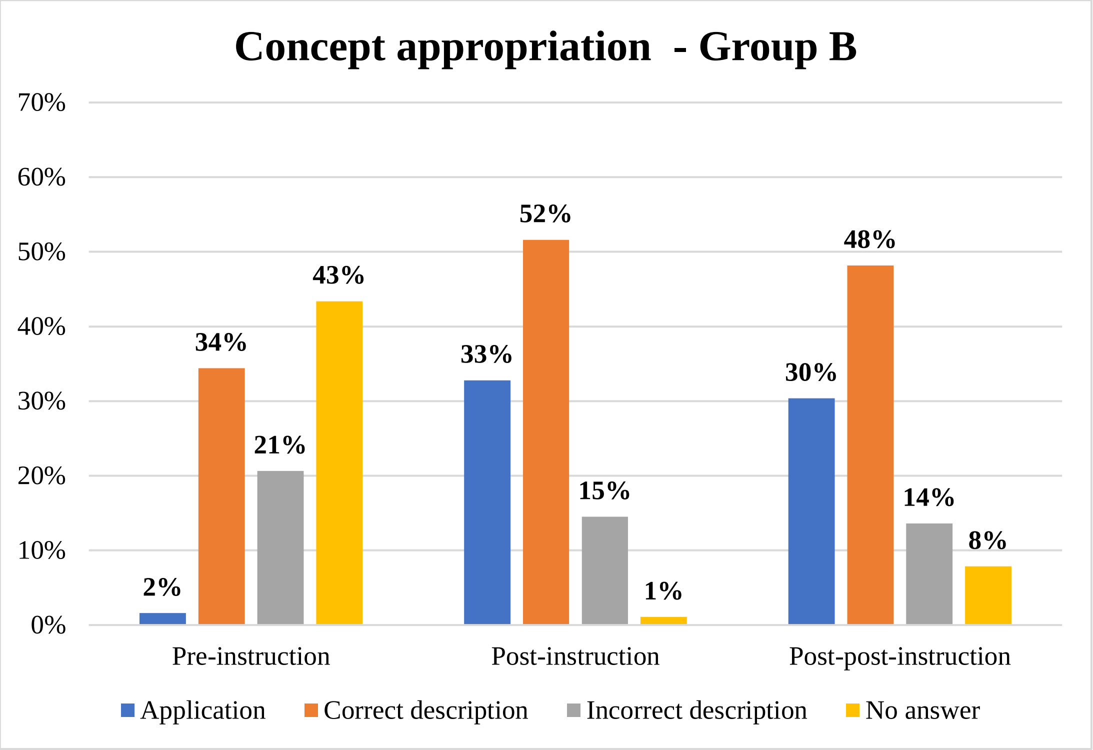


Fig. 33: Bar diagrams showing the percentages of answers given by Group A and Group B students, respectively, to questionnaire Q2 during the pre-, post-, and post-post-instruction administrations. The answers are categorized according to the different level of concept appropriation identified in our analysis.

As can be seen in Fig. 33, in the pre-instruction questionnaire, the percentage of application of concepts is significantly low for both groups, and the percentage of no answer is particularly high, especially for group A. From the pre to the post-instruction questionnaire administration, an increase in the percentage of application of concepts and correct descriptions is registered, especially in Group B. These results are confirmed in the post-post instruction administration of the questionnaire.

Forms of representation

For what regards the forms of representations, in Section 4.2.1 we identified verbal, iconic, tabular, graphic, analytical representations as the commonly used in science. So, we analysed the answers given to Q2 searching for the evidence of such kind of communication and representation channels in each student answer.

Tab. 22 shows the results of that analysis for the whole group of students (Group A and Group B) in the three administration phases of the questionnaire. The values represent the number of answers that highlight the use of one representation channel.

Tab. 22: $\chi^2 = 410{,}3, p < 1\%$.

All students - Q2	***Verbal***	***Iconic***	***Tabular***	***Graphical***	***Analytical***	***No representation***
Pre-instruction	93	40	22	27	8	219
Post-instruction	60	121	12	91	60	11
Post-post-instruction	80	103	16	81	50	30

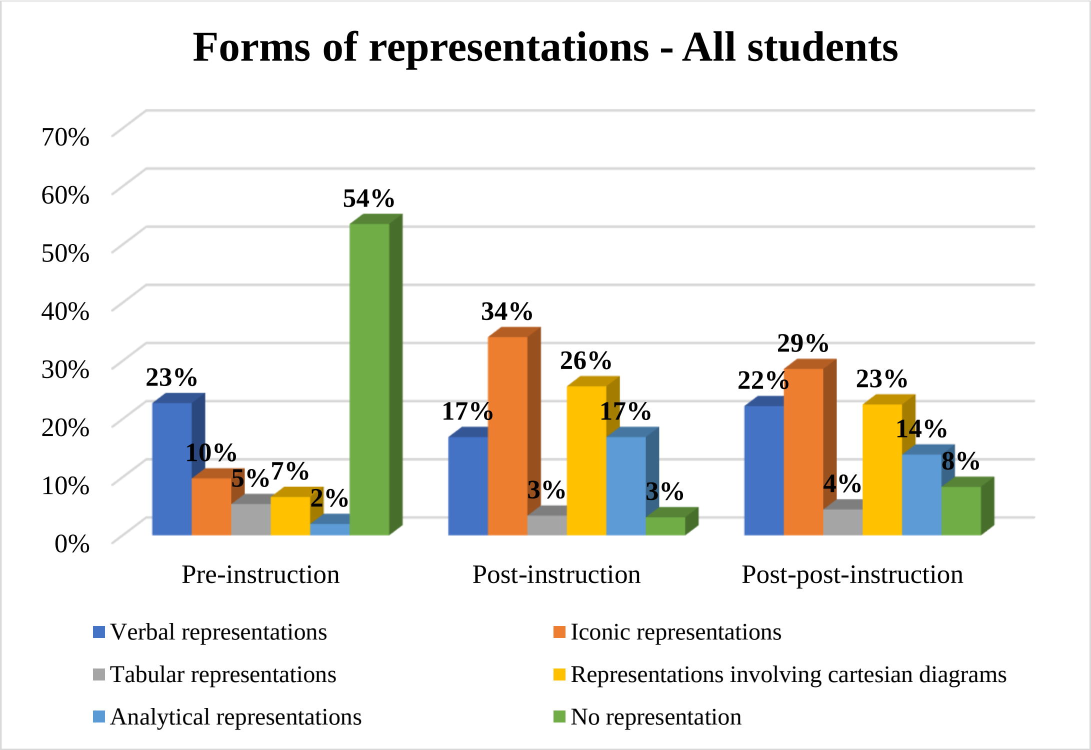


Fig. 34: Bar-diagrams showing the percentages of answers given by the entire sample of students (Group A + Group B) to questionnaire Q2 during the pre-, post-, and post-post-instruction administrations. The answers are categorized according to the different forms of representation used by the students.

As can be seen in the bar diagrams in Fig. 34, a drastic decrease in the number of students who do not use any form of representation to face the situations proposed is registered, from the pre-instruction to the post-instruction administration of the questionnaire. Moreover, after instruction, parallel to a decrease in the number of students who use verbal representation strategies, a significant increase in the number of students who use iconic and analytical forms of representation and representations involving cartesian diagrams is registered. Except for the percentage of students using verbal representations, the percentages of students using other forms of representation remain almost unchanged in the post-post instruction administration of the questionnaire. The percentage of students using tabular forms of representation is low and almost unchanged in both pre and post-instruction.

Tab. 23 and Tab. 24 show the contingency tables for the results of the analysis for Group A and Group B students, respectively, in the three administration phases of the questionnaire. The values represent the number of answers that highlight the use of one representation channel.

Tab. 23: $\chi^2 = 233{,}4, p < 1\%$.

Group A - Q2	***Verbal***	***Iconic***	***Tabular***	***Graphical***	***Analytical***	***No representation***
Pre-instruction	43	15	10	13	2	137
Post-instruction	30	50	8	32	40	9
Post-post-instruction	45	35	8	31	35	15

Tab. 24: $\chi^2 = 180{,}5, p < 1\%$.

Group B - Q2	***Verbal***	***Iconic***	***Tabular***	***Graphical***	***Analytical***	***No representation***
Pre-instruction	50	25	12	14	6	82
Post-instruction	30	71	4	59	20	2
Post-post-instruction	35	68	8	50	15	15

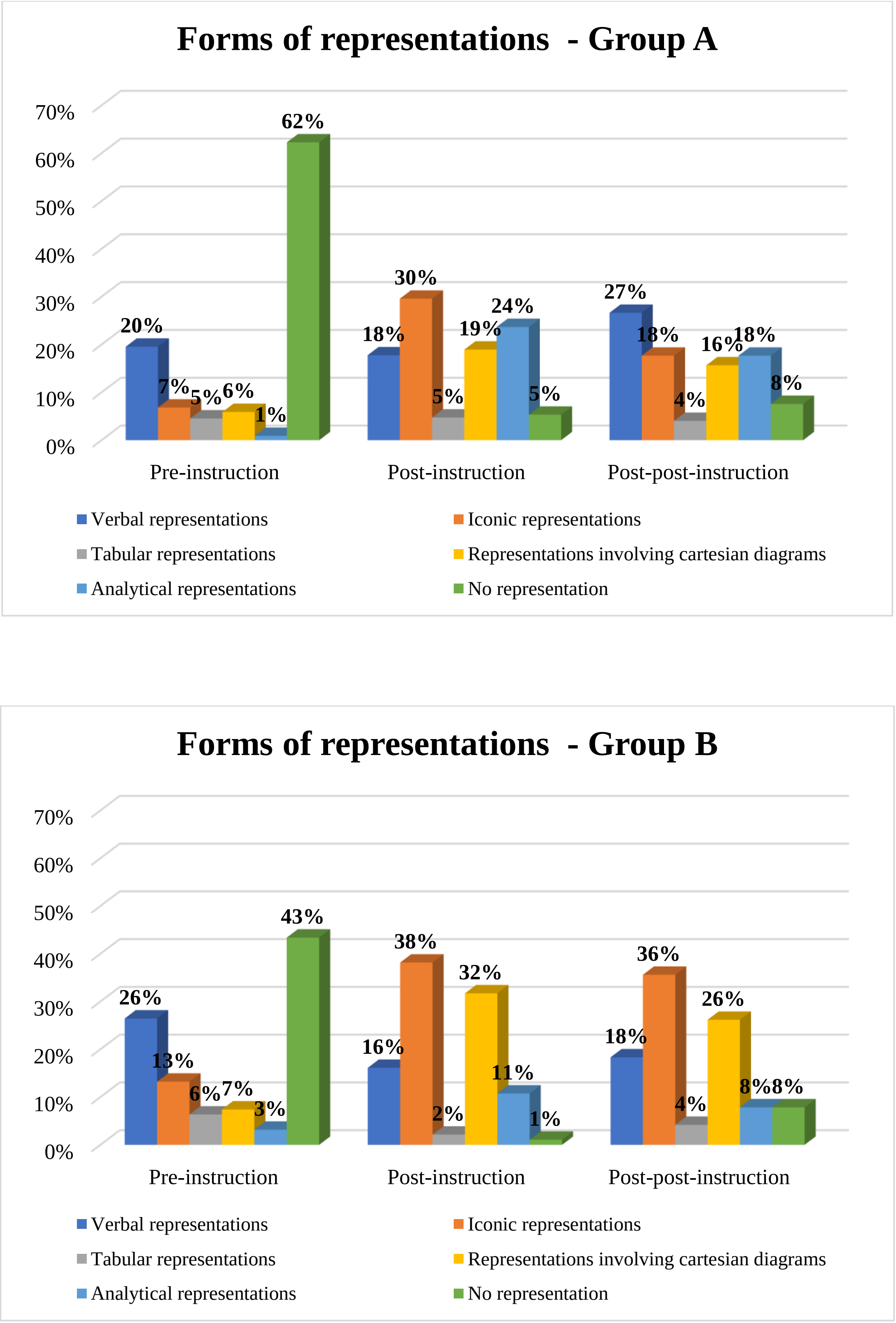


Fig. 35: Bar diagrams showing the percentages of answers given by Group A and Group B students, respectively, to questionnaire Q2 during the pre-, post-, and post-post-instruction administrations. The answers are categorized according to the different forms of representation used by the students.

As we can see in Fig. 35, in answering the pre-instruction questionnaire the prevailing form of representation is the verbal one, for both Group A and Group B. In answering to the the post-instruction questionnaire Group A student show an increasing use of formulas (analytical representations) to address the proposed situations, while group B ones are more oriented to the use of schemes and graphs (iconic representations and representations involving cartesian diagrams). These trends are confirmed in the answers of post-post instruction questionnaire. In both groups the percentage of students using tabular forms of representation is low and almost unchanged either in pre- and post-instruction administration of the questionnaire.

7.1.3 Variable 2.3

This part of the study of variable 2.3: Generalization of what has been learned, was done by means of the analysis of the answers to questionnaire 2 before, after instruction and after the two-months break. A further study of the variables was conducted on the other databases and will be discussed in Section 7.2.2.

We have seen in Section 4.2.6 that the variable regards the use of contents and techniques learned in a given situation in similar or different, untrained circumstances, and a generalization gradient is commonly used to express the level of generalization. Therefore, we decided to content-analyse the student answers with respect to the following levels: 1) generalization to untrained situations; 2) generalization to similar situations; 3) no generalization/no answer.

Questionnaire Q2 includes questions related to both situations, similar to the ones dealt with during the TLSs phases, and situations that appear to an expert analogous to the TLSs ones but that cannot be perceptible by students as similar to the TLSs' ones. We report here also the results obtained from the analysis of the pre-instruction administration of the questionnaire, even if the information that can be obtained from that data does not regard the generalization skills due to the TLSs development. On the other hand, all the students have, as we had pointed out before, already fronted and studied some aspects of surface phenomena, during the chemistry lessons, at school. For that reason, we wanted to see what was their initial generalization level with respect to situations that they could have seen before.

Tab. 25 shows the results of that analysis for the whole group of students (Group A and Group B) in the three administration phases of the questionnaire. The values represent the number of answers that highlight a given generalization level.

Tab. 25: $\chi^2 = 448{,}6$, $p < 1\%$.

All students - Q2	***Untrained situations***	***Similar situatons***	***No generalization / no answer***
Pre-instruction	0	61	348
Post-instruction	104	183	68
Post-post-instruction	85	193	82

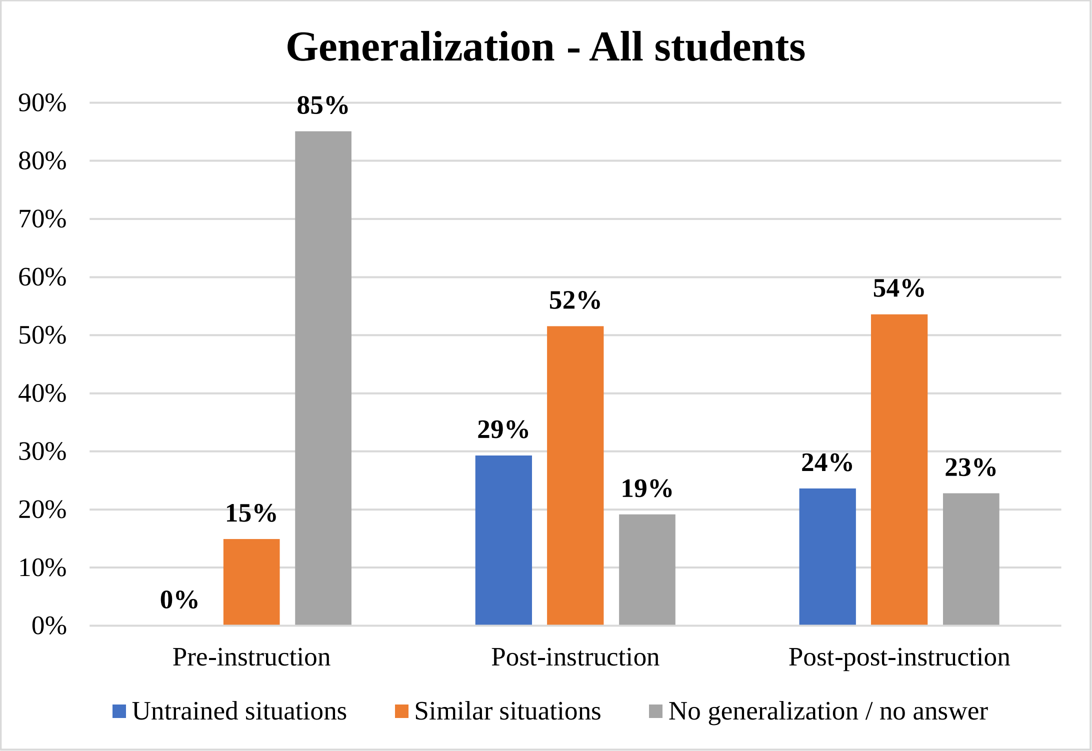


Fig. 36: Bar-diagrams showing the percentages of answers given by the entire sample of students (Group A + Group B) to questionnaire Q2 during the pre-, post-, and post-post-instruction administrations. The answers are categorized according to students' different levels of generalization.

As can be seen in the bar diagrams in Fig. 36 a drastic decrease in the number of students who do not generalize or not answer the question proposed is registered, from the pre-instruction to the post-instruction questionnaire. At the same time, after instruction a significant increase in the number of students who generalize in untrained situations and in situations similar with those with which they are familiar to is registered. These results are confirmed in the post-post instruction questionnaire.

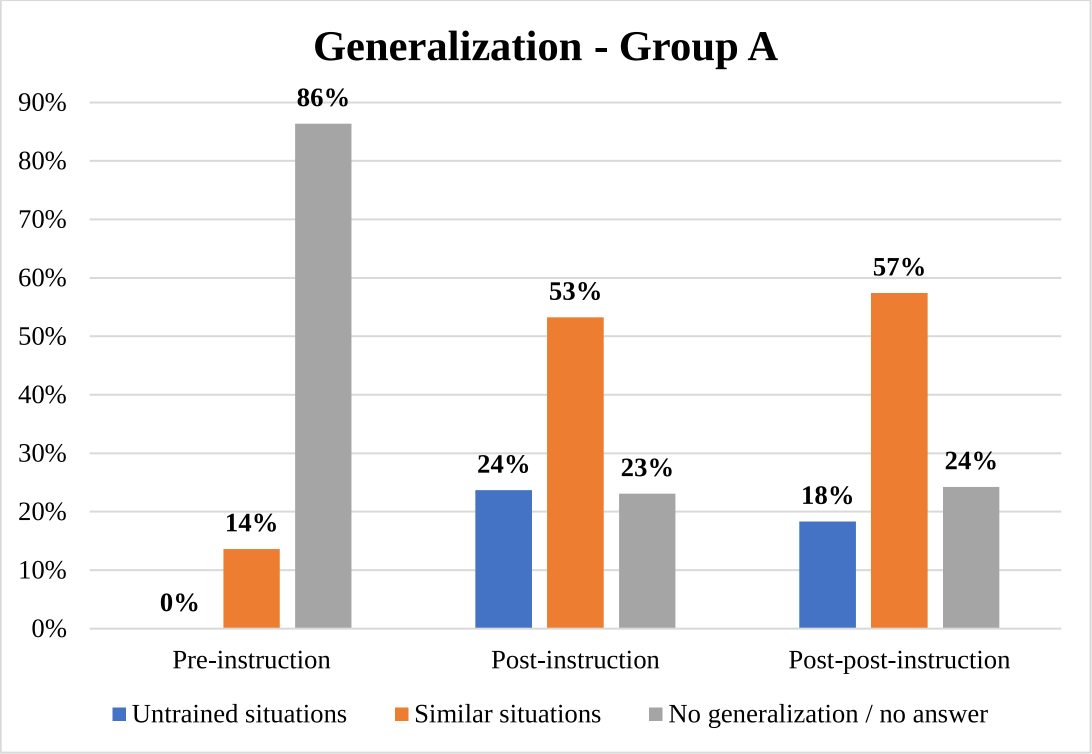
Tables 26 and 27 show the results of that analysis for Group A and Group B, respectively, in the three administration phases of the questionnaire. The values represent the number of answers that highlight a given generalization level.

Tab. 26: $\chi^2 = 216{,}3$, $p < 1\%$.

Group A - Q2	***Untrained situations***	***Similar situatons***	***No generalization / no answer***
Pre-instruction	0	30	190
Post-instruction	40	90	39
Post-post-instruction	31	97	41

Tab. 27: $\chi^2 = 230{,}7$, $p < 1\%$.

Group B - Q2	***Untrained situations***	***Similar situatons***	***No generalization / no answer***
Pre-instruction	0	31	158
Post-instruction	64	93	29
Post-post-instruction	54	96	41



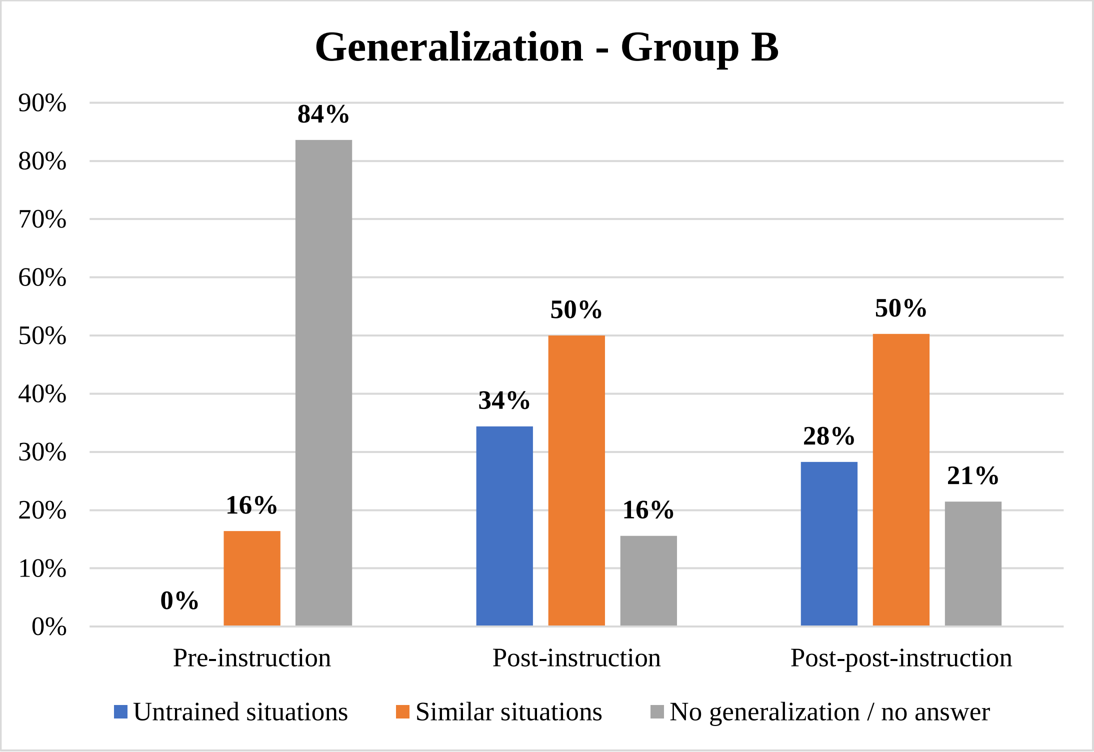


Fig. 37: Bar diagrams showing the percentages of answers given by Group A and Group B students, respectively, to questionnaire Q2 during the pre-, post-, and post-post-instruction administrations. The answers are categorized according to students' different levels of generalization.

As we see in Fig. 37, in the pre-instruction questionnaire, the percentage of generalization in untrained situations is equal to zero, and the percentage of no generalization/no answer is significantly high for both groups. Before instruction, only a small percentage of students seem capable to generalize in situations similar to those with which they are familiar with. In answering the post instruction questionnaire, an increase in the percentage of students who generalize in both untrained situations and situations similar to those with which they are familiar with is registered. In particular, group B students seem to be oriented towards generalization in untrained situations more than group A ones. It is worth noting that also after instruction, a percentage not negligible of students is still unable to generalize. This could be due to the small time spent on modelling activities.

A further analysis of questionnaires Q1 and Q2

From what we have seen before, it seems that, in general, both groups exhibit improved behaviour with respect to the variables studied by means of the analysis of answers to the questionnaire described so far (variables 1.1, 1.2, 1.3, 2.2, and 2.3). In order to give some more detail on the analysis, in Appendix I, we report some excerpts of the answers given by the students during the post-instruction administration of Q1 and Q2 questions.

7.2 Thematic-like analysis of the other databases

The analysis carried out on the data collected by means of the other instruments (students' worksheets, audio recordings of students group discussions at the end of each activity, students' feedback on the activities carried out during the TLSs, students' contributions during the final day brainstorming phase, and notes from researchers) was inspired by thematic analysis methods, and involved the following steps:

1. Repeated readings of the data in order to become familiar with them;
2. Identification of text segments useful for answering the research question;
3. Identification of codes that synthesize the information carried by the data;
4. Labelling of text segments of analytic interest (see step 2) through the codes identified in the step 3;
5. Construction of a table of code-variable correspondences;

6. Identification of text segments significative for the analysis of specific aspects of learning (sub-dimensions of learning introduced in the chapter 3) on the basis of the code-variable correspondences;

In the following section the specific processes involved in coding our databases and the role of the identified codes are described.

7.2.1 The coding process in our analysis

Codes have allowed us to synthesize the complexity of our data and to highlight how the variables, that give us information on the specific dimensions of learning, emerge from data. Labelling data segments by using codes allowed us to navigate more easily and intentionally within the datasets. We used an inductive coding. This means that we did not have a set codebook, but we created codes based on the qualitative data itself. Codes have been identified by researchers based on the information carried out by the data. In particular, the initial codes were roughly identified from the recurrences of words and sentences. The codes identified after the first reading of the databases are reported below. For each code, we give a brief description clarifying which aspects of data can be summarized by the code.

Procedures-methodologies understanding. Students report on activities, tools, situations etc., which promote or hamper the comprehension of specific topics addressed during the trialling.

Tools-skills. Students describe tools, materials, and skills acquired and/or used during the trialling.

Theory VS practice. Students point out the difference between theory and practice. Theory is what they are most used to, practice is something they are not yet familiar with.

Traditional lecture VS "innovative lecture". Students strongly perceive the difference between the traditional lectures they are used to at school and what they defined "innovative lectures" based on approaches they do not are familiar with. With traditional lectures, they refer to frontal lessons in which teachers explain, and students listen to.

Content understanding. Different levels of understanding of the topics emerge from the data. From students' answers to content questions, it emerges whether they have understood a content and/or its forms of representation consciously.

Debate. Students openly declare that the debate turns out to be an important tool to achieve a greater and better understanding of the topics.

Perspective. A given topic can be analysed from multiple perspectives and points of view. Students expand their learning perspective through the point of view of others through the use of new study methods and new learning tools.

Role: Different roles can be assumed by students in their learning process. For example, students can distinguish the learning contexts in which they have an active or passive role.

Language: The use of a specific lexicon, that is, scientific terminology used in a conscious way, is highlighted. Students recognize the role of mathematic language in the formalization of results obtained through experiments. The acquisition and use of a scientific vocabulary facilitate the communication of results among the students.

Reflection. Students reflect accurately on the activities carried out, on what they learned, on the skills they have acquired. They critically discuss the pros and cons of the activities they were involved in and reflect on how to apply models acquired in a given context to different situations.

Acknowledgement. Students declare they have acquired self-awareness by carrying out the activities proposed during the trialling. Students show to be aware of their strengths and weaknesses and acknowledge their progress.

Engagement-interest. Students talk about the activities they find most interesting and engaging. Many of them find computer-based simulations and hands-on experiments particularly challenging, while they get bored during more "traditional" activities similar to that they are used to at school.

Comfort. Students talk about the contexts in which they find themselves more comfortable during the learning process and those in which they do not feel comfortable.

Proactiveness. Students give us suggestions to modify and improve didactic activities, based on what they have experienced during the trialling. Some of them reproduce or propose to reproduce some of the experiments carried out by making changes and look for additional information on the topics addressed in the classroom.

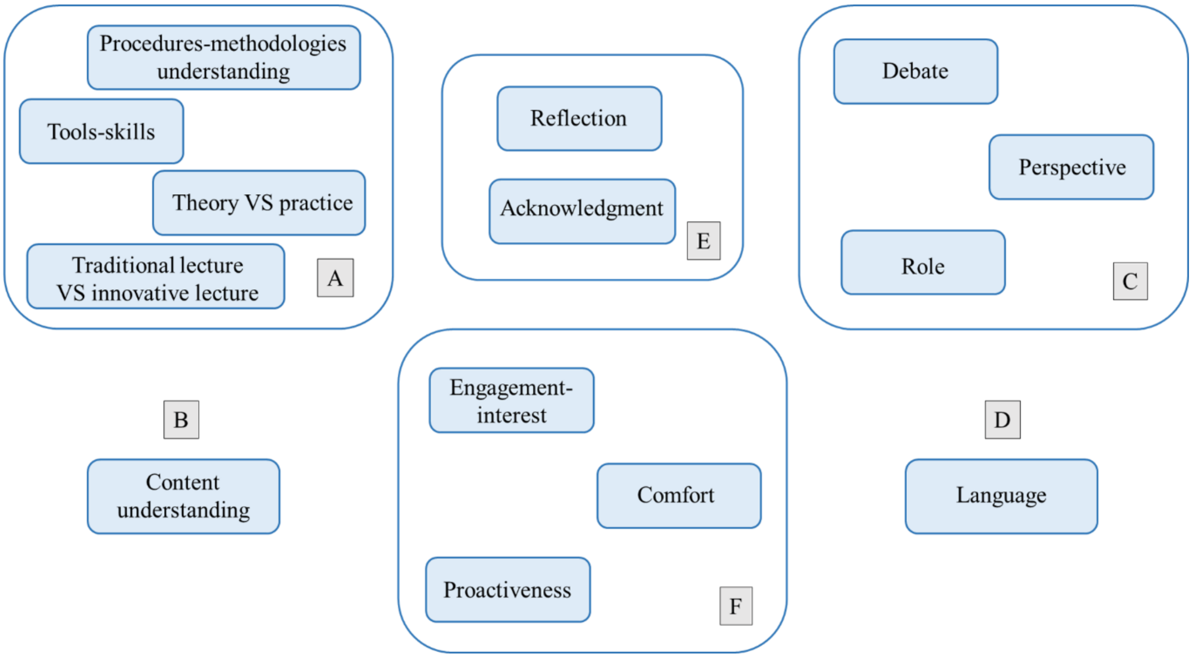


Fig. 38: Diagram showing the codes introduced in our analysis. The boxes contain the codes subtending to the same overarching code (A-F).

To improve the inter-rater reliability in conducting thematic analysis, three researchers were involved in the coding process. After five repeated phases involving readings and debating the texts, the researchers reached an agreement of about 95%.

The researchers also agreed that some codes could be merged with each other since they carry the same or similar information about the data. The codes ‘Procedures-Methodology understanding’, ‘Tools-skills’, ‘Theory VS practice’ and ‘Traditional lectures VS innovative lectures’ have been embedded into the overarching code A, the codes ‘Debate’, ‘Perspective’ and ‘Role’ into C, the codes ‘Engagement-interest’, ‘Comfort’ and ‘Proactiveness’ into F and finally, the codes ‘Reflection’ and ‘Acknowledgement’ into E.

The code-variable correspondence table (see Tab. 28) shows which variables, therefore which aspects of learning, emerge from the data labelled with a given code. For example, as can be seen in Fig. 38, data labelled with the code ‘A’ will hold information about aspects of learning related to intellectual growth (2.2, 2.3) and development of a mindset suited to science (3.2, 3.3, 3.5, 3.6). As can be seen from the table, each code can summarize information relating to one or more aspects of learning (i.e., Conceptual knowledge, Intellectual growth, Development of a mindset suited to learning Science). The overarching codes (A-F) reported in Tab. 28, are the codes that have been definitely used to conduct the qualitative analysis of our data. These codes incorporate and synthetise all the information carried by the codes that have merged to constitute them.

Tab. 28: Code-variable correspondence table showing what kind of information about the learning process is synthesized by each code. Codes composing each overarching code are reported.

	VARIABLES											
	Conceptual knowledge		**Intellectual growth**				**Development of a mindset suited to learning science**					
CODES	1.1	1.2	2.1	2.2	2.3	2.4	3.1	3.2	3.3	3.4	3.5	3.6
A				X	X			X	X		X	X
B	X	X		X	X							
C		X	X	X		X	X	X	X	X	X	X
D	X	X	X		X				X		X	
E				X	X	X	X	X	X			X
F								X		X		X

A	Procedures-methodology understanding/Tools-skills/Theory VS practice/Traditional lecture VS innovative lecture
B	Content understanding
C	Debate/Perspective/Role
D	Language
E	Reflection/Acknowledgment
F	Engagment-interest/Comfort/Proactiveness

Variable 1.3 is not mentioned, as we could obtain information on it only by means of the post-post-instruction administration of questionnaire Q2. It is worth noting that the code-variable correspondence table Tab. 28 is the result of a long negotiation process which led to the agreement among the researchers involved in the qualitative data analysis. In other words, the choice of “merging” two or more codes and the association of each code to one or more variables were discussed and agreed by the researchers.

7.2.2 Analysis of the databases

Here we present the results obtained through the analysis of the following databases:

- Students’ worksheets (Database 1)
- Audio recordings of students group discussions at the end of each activity (Database 2)
- Students’ contributions during the final day brainstorming phase (Database 3)
- Students’ feedback on the activities carried out during the TLSs (Database 4)

Through the qualitative analysis of these databases, we aim to study how much each of them has highlighted the involvement of the variables of interest in the processes experienced by the students.

A detailed analysis of Database 1 and Database 2 allowed us to identify which activities, and therefore which aspects of each approach (macroscopic and mesoscopic) were effective in promoting aspects of the learning process related to ‘conceptual knowledge’ and ‘intellectual growth’ (see Fig. 18). On the other hand, from Database 3 and Database 4, we extrapolated information on the learning dimensions ‘intellectual growth’ and ‘development of a mindset suited to learning Science’ (see Fig. 18).

None of the databases analysed in this section provided us with information on long time retention of the acquired knowledge and competencies. The analysis of the answers given by the students during the post-post-instruction administration of questionnaire Q2 and the comparison between students' answers in the previous administration phases allowed us to reflect on the long-term effectiveness of the proposed approaches, as described in Section 7.1.2.

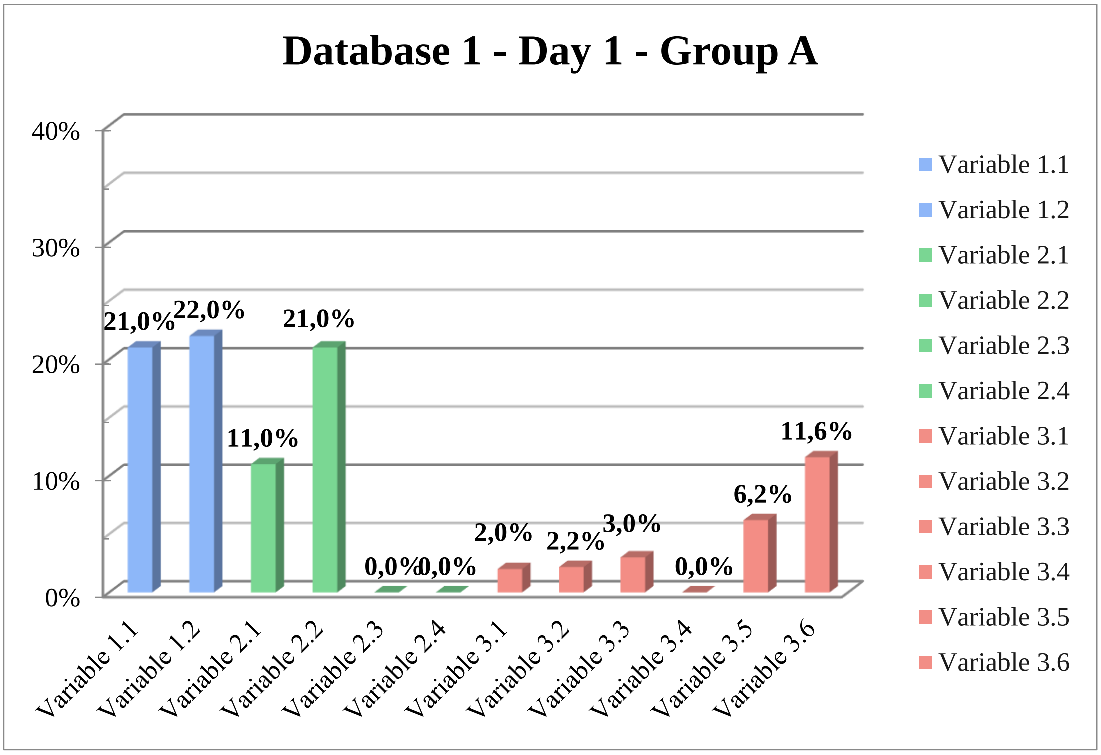
The results of the qualitative analysis of databases 1-4 are presented through bar diagrams obtained by counting the number of times a given variable (i.e., a sub-dimension of learning) emerges within a specific database. In particular, each graph shows the percentages of occurrence of a given variable within a given database. All graphs have been normalized.

The results obtained for Group A and Group B through the qualitative analysis of the aforementioned databases are presented in detail in the following section.

Database 1: Students’ worksheets – Day 1

The database analysed in this section consists of students’ worksheets filled during the first day of experimentation. This day was dedicated to qualitative experiments.

Qualitative experiments seem to promote the perception of self-efficacy (3.1), development of a growth mindset (3.2), and metacognition (3.3) in Group B students more than in Group A ones. In particular, the percentage of Group B students oriented towards the development of a growth mindset is higher of 7,1% than that of Group A students. Moreover, Group B students show a perception of self-efficacy double with respect to Group A students.



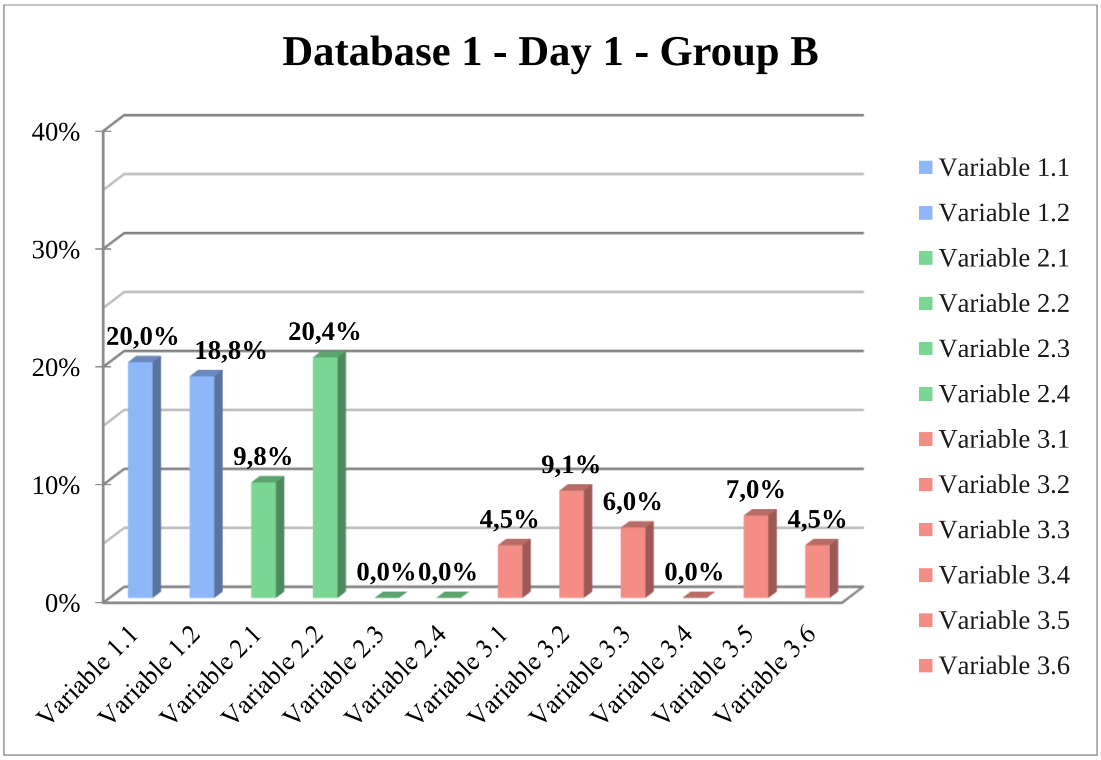


Fig. 39: Bar-diagrams showing the percentages of recurrence of each variable in Database 1 - Day 1 for Group A and Group B, respectively.

On the other hand, qualitative experiments seem to foster the willingness to extend studies and research (3.6) in Group A students more than in Group B ones. The percentage of Group A students showing a disposition towards these aspects of learning is higher by 7,1% with respect to that of Group B students.

At this stage, Group A and Group B do not show significant differences as regards the aspects of learning related to the appropriation of concepts and forms of representation (1.1) and evolutions of common-sense conceptions to scientific ones (1.2). This result is not surprising because the two groups carried out qualitative experiments before the introduction to modelling. Moreover, it seems that qualitative experiments had a similar impact on the two groups in promoting the enhancement of interpersonal and social skills (2.1) and the development of reasoning skills aimed at interpreting real-life situations and experiments (2.2).

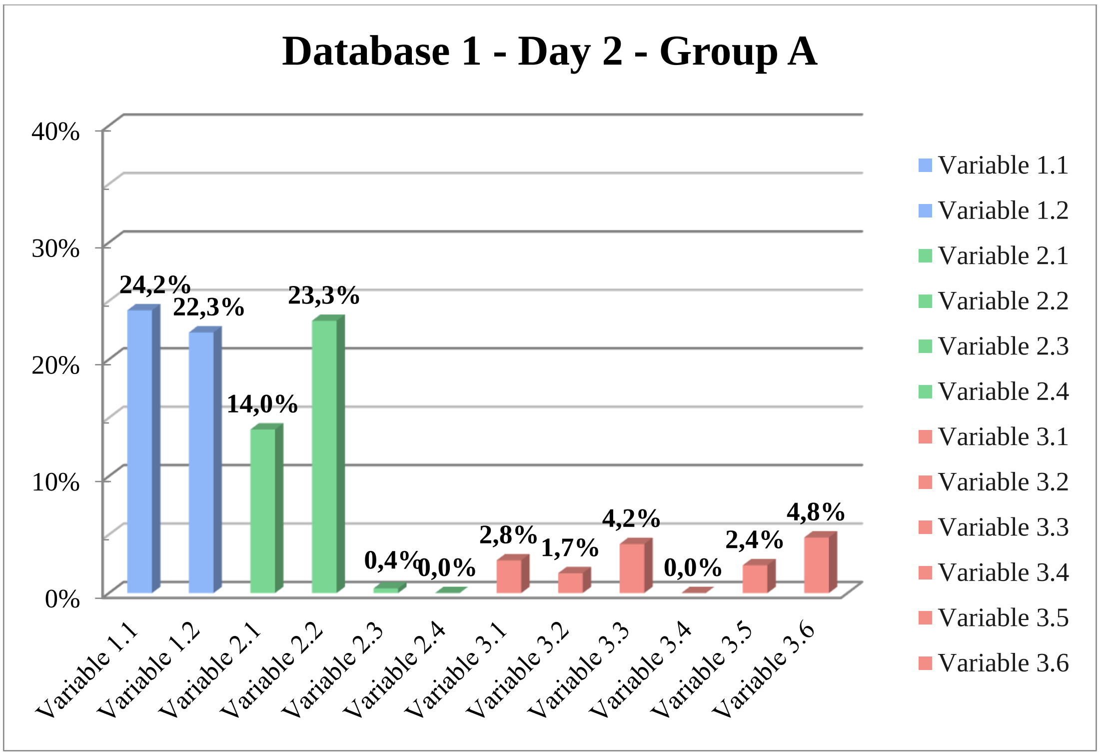
Database 1: Students' worksheets – Day 2

The database analysed in this section consists of students' worksheets filled during the second day of experimentation. During this day students carried out further qualitative experiments.

Qualitative experiments seem to promote aspects of learning related to the appropriation of concepts and forms of representation (1.1) and evolutions of common-sense conceptions to scientific ones (1.2) a little more in Group A students than in Group B ones.

Qualitative experiments confirm to be effective in promoting the perception of self-efficacy (3.1) and development of a growth mindset (3.2), in Group B students more than in Group A ones.

Also in this case, it seems that qualitative experiments did not produce significant differences between the two groups with respect to the enhancement of interpersonal and social skills (2.1) and the development of reasoning skills aimed at interpreting real-life situations and experiments (2.2).



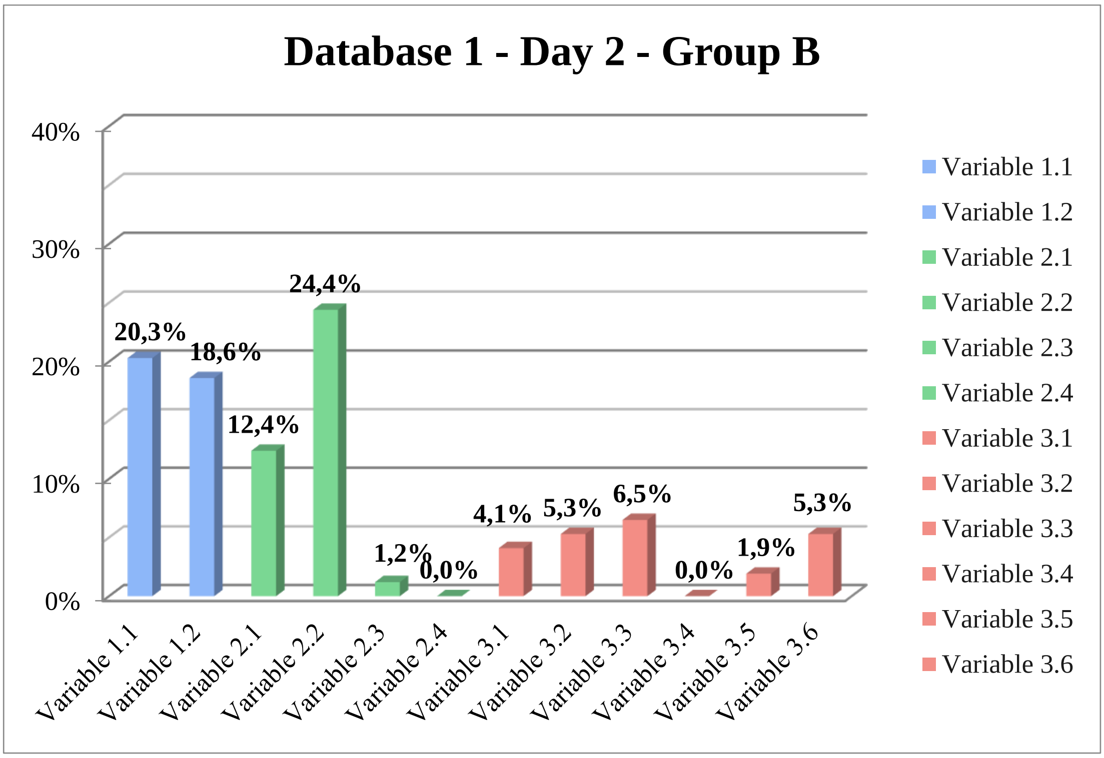


Fig. 40: Bar-diagrams showing the percentages of recurrence of each variable in Database 1 - Day 2 for Group A and Group B, respectively.

Database 1: Students’ worksheets – Day 3

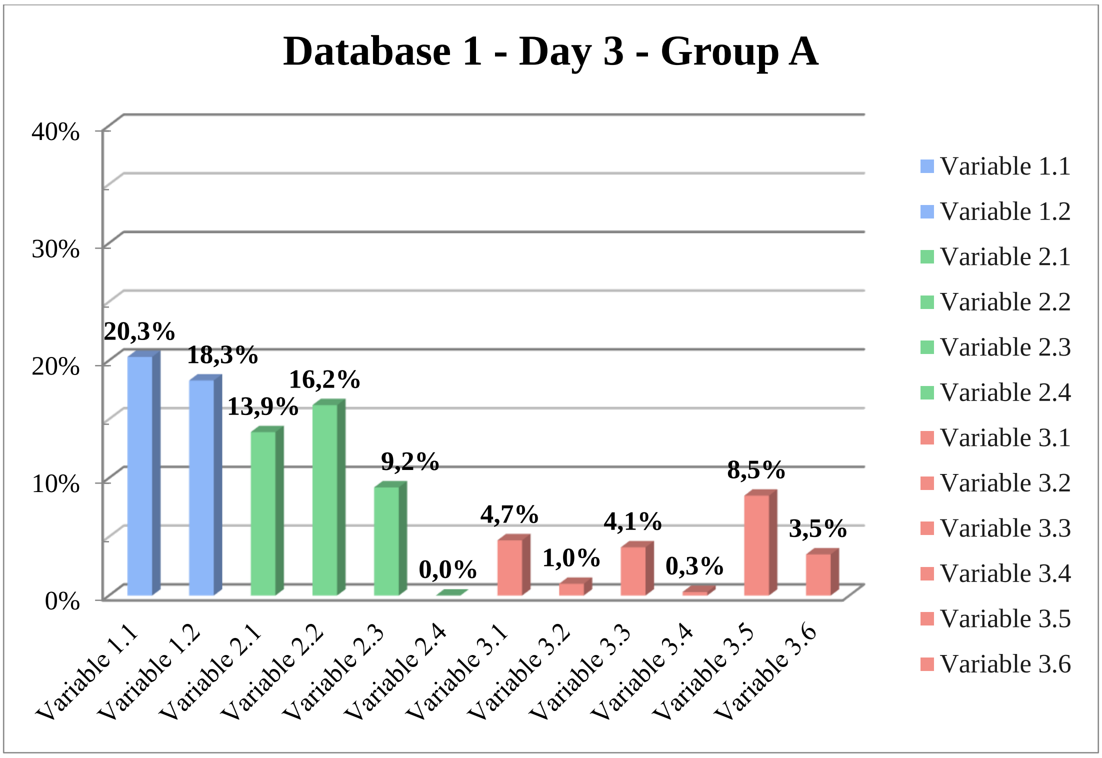
The database analysed in this section consists of students’ worksheets filled during the third day of experimentation. During this day students were introduced to modelling activity.

Modelling activities seem to promote the enhancement of interpersonal and social skills (2.1), the development of reasoning skills aimed at interpreting real-life situations and experiments (2.2), and the willingness to extend studies and research (3.6) in Group B students more than in Group A ones. This means that modelling activities based on the introduction of a mesoscopic model of liquid, implemented through computer simulations, are more effective in promoting the aforementioned aspects of learning with respect to modelling activities based on a macroscopic description of liquid.

On the other hand, modelling activities based on a macroscopic approach seem to promote generalization of what has been learned (2.3), perception of self-efficacy (3.1), and metacognition (3.3) more than ones based on a mesoscopic approach.

The two groups do not show significant differences as regards the aspects of learning related to the appropriation of concepts and forms of representation (1.1) and evolutions of common-sense conceptions to scientific ones (1.2). However, the mesoscopic modelling approach, followed by Group B, seems slightly more effective than the macroscopic one, followed by Group A, in promoting aspects of learning related to the appropriation of concepts and forms of representation (1.1) and evolutions of common-sense conceptions to scientific ones (1.2). This is confirmed by the results obtained by analysing the post-instruction questionnaires Q1 and Q2.

Moreover, during the modelling activities, Group B students seem to experience slightly higher well-being than Group A ones. However, more information on this aspect of learning emerges to a greater extent in other databases.



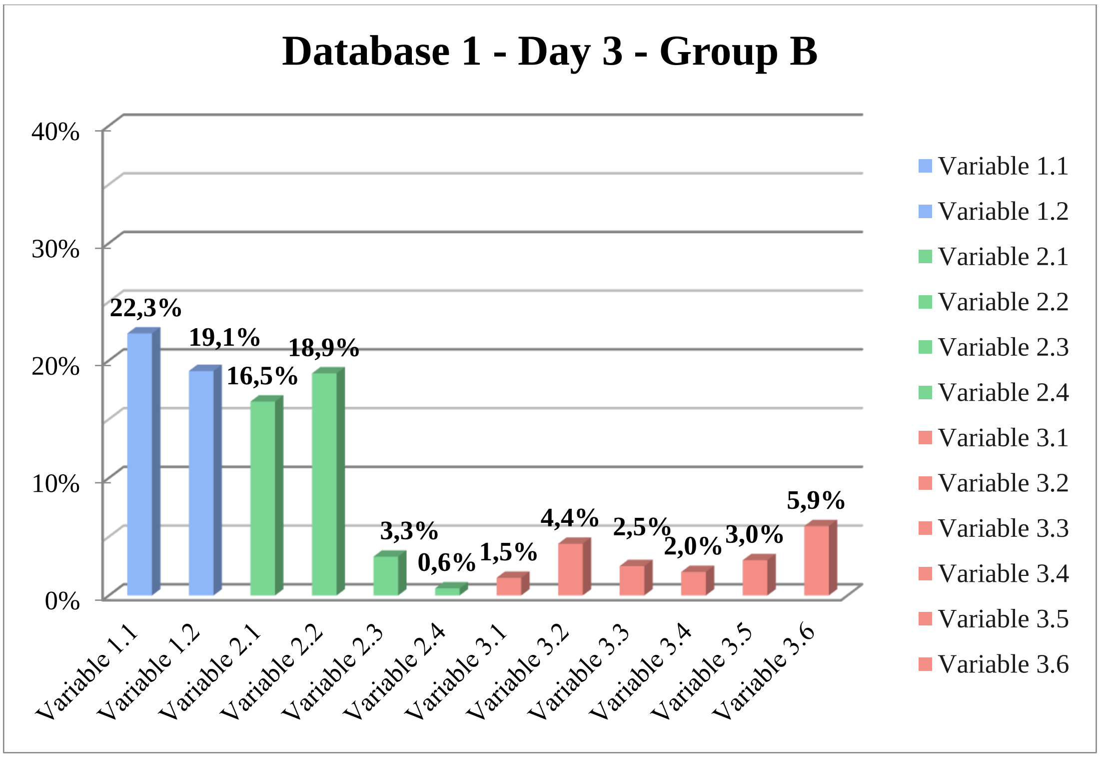


Fig. 41: Bar-diagrams showing the percentages of recurrence of each variable in Database 1 - Day 3 for Group A and Group B, respectively.

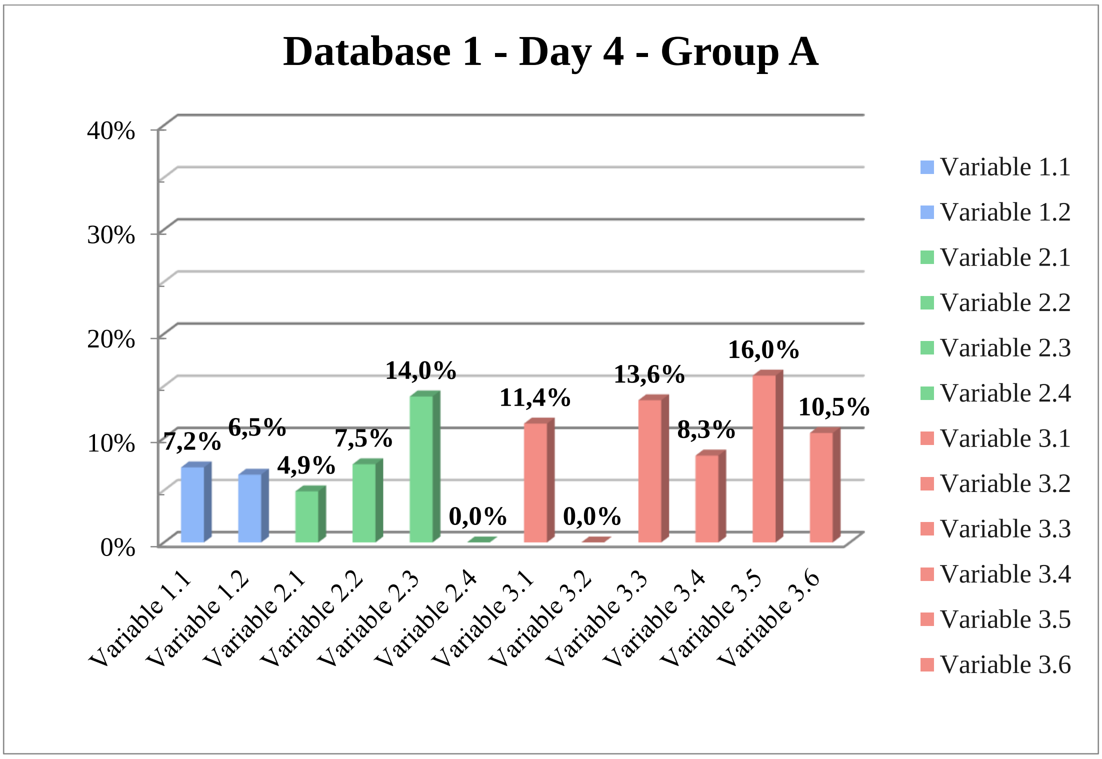
Database 1: Students' worksheets – Day 4

The database analysed in this section consists of students' worksheets filled during the fourth day of experimentation. This day was dedicated to quantitative experiments.

Quantitative experiments seem to promote the development of reasoning skills aimed at interpreting real-life situations and experiments (2.2), the development of a growth mindset (3.2), and the willingness to extend studies and research (3.6) in Group B students more than in Group A ones. In particular, the percentage of Group B students oriented towards the development of reasoning skills aimed at interpreting real-life situations (2.2) and experiments, and towards the willingness to extend studies and research (3.6), is higher of 8,7% and 10,1%, respectively, than those of Group A students. It is worth noting that the process of growth mindset development taking place during quantitative experiments in Group B, does not occur in Group A. Since Group B students have never analysed the physical quantities involved in surface phenomena from a macroscopic point of view, they had to reason and engage themselves more than the students of Group A, in order to interpret the results obtained through quantitative experiments. At the end of the activities, Group B students, thanks to their commitment and perseverance were able to "solve" problems that initially seemed impossible to solve, and it contributed to reinforcing beliefs and behaviours characteristic of the so-called growth mindset.

On the other hand, quantitative experiments seem to promote the appropriation of concepts and forms of representation (1.1), the evolution of common-sense conceptions to scientific ones (1.2), the enhancement of interpersonal and social skills (2.1), the generalization of what has been learned (2.3), and the understanding of the nature of science (3.5) in Group A students more than in Group B ones. The percentage of Group A students showing a better understanding of the nature of science (3.5) is significantly higher than that of Group B students.

Moreover, it is interesting to reflect on the reasons why Group A seems oriented towards the appropriation of concepts and forms of representation (1.1), the evolution of common-sense conceptions to scientific ones (1.2), and the generalization of what has been learned (2.3) more than Group B. Group A students, after studying the macroscopic approach, interpreted the results obtained through quantitative experiments more easily respect to Group B students. This is due to the fact that the quantities involved in the experiments are those on which Group B previously reflected in the modelling phase. In this sense, Group B students were able to generalize, during the quantitative experiments, what they had learned through modelling activities.



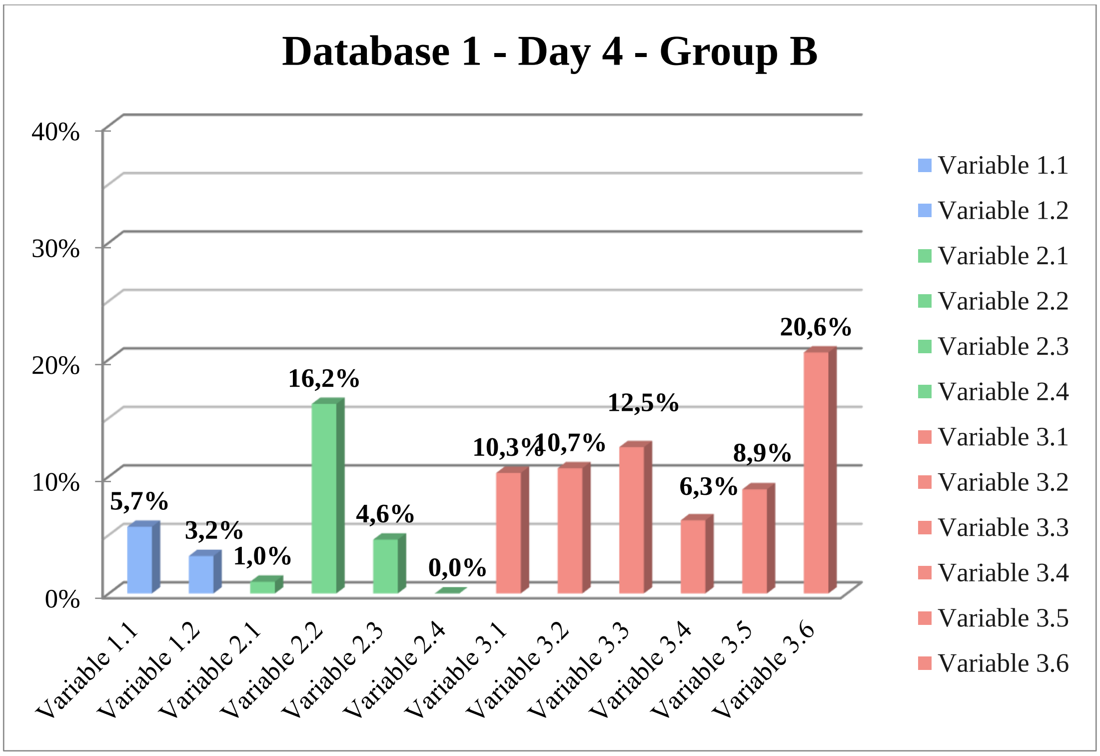


Fig. 42: Bar-diagrams showing the percentages of recurrence of each variable in Database 1 - Day 4 for Group A and Group B, respectively.

Database 2: Audio recordings of students group discussions at the end of each activity – Day 1

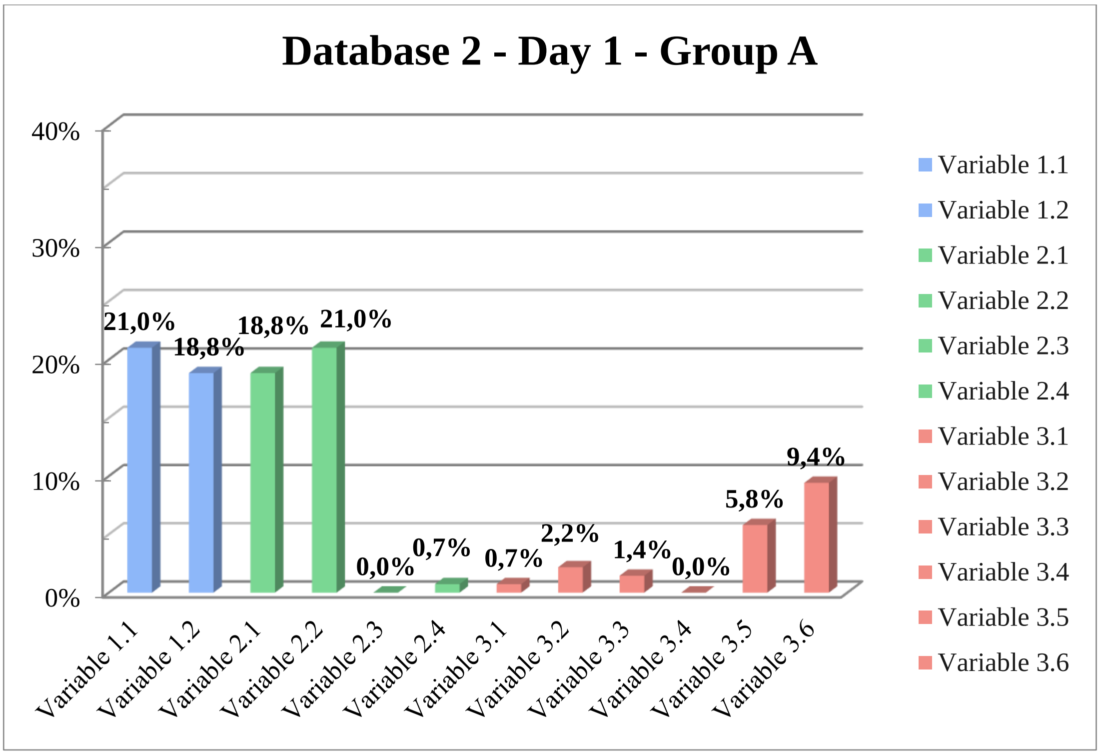
The database analysed in this section consists of the audio recordings of students' group discussions at the end of each activity carried out during the first day of experimentation. This day was dedicated to qualitative experiments.

Qualitative analysis of Database 2 - Day 1 produced results consistent with those obtained for Database 1- Day 1.

Qualitative experiments seem to promote the perception of self-efficacy (3.1), development of a growth mindset (3.2), and metacognition (3.3) in Group B students more than in Group A ones. In particular, the percentage of Group B students oriented towards the development of a growth mindset is higher of 7,5% than that of Group A students.

On the other hand, qualitative experiments seem to foster the understanding of the nature of science (3.5) and willingness to extend studies and research (3.6) in Group A students more than in Group B ones. The percentage of Group A students showing a disposition towards these aspects of learning is approximately double respect to that of Group B students.

As discussed before, it is not surprising that at this stage, Group A and Group B do not show significant differences as regards the aspects of learning related to the appropriation of concepts and forms of representation (1.1) and evolutions of common-sense conceptions to scientific ones (1.2). In fact, both groups carried out qualitative experiments before the introduction to modelling. Also in this case, it seems that qualitative experiments had a similar impact on the two groups in promoting the enhancement of interpersonal and social skills (2.1) and the development of reasoning skills aimed at interpreting real-life situations and experiments (2.2).



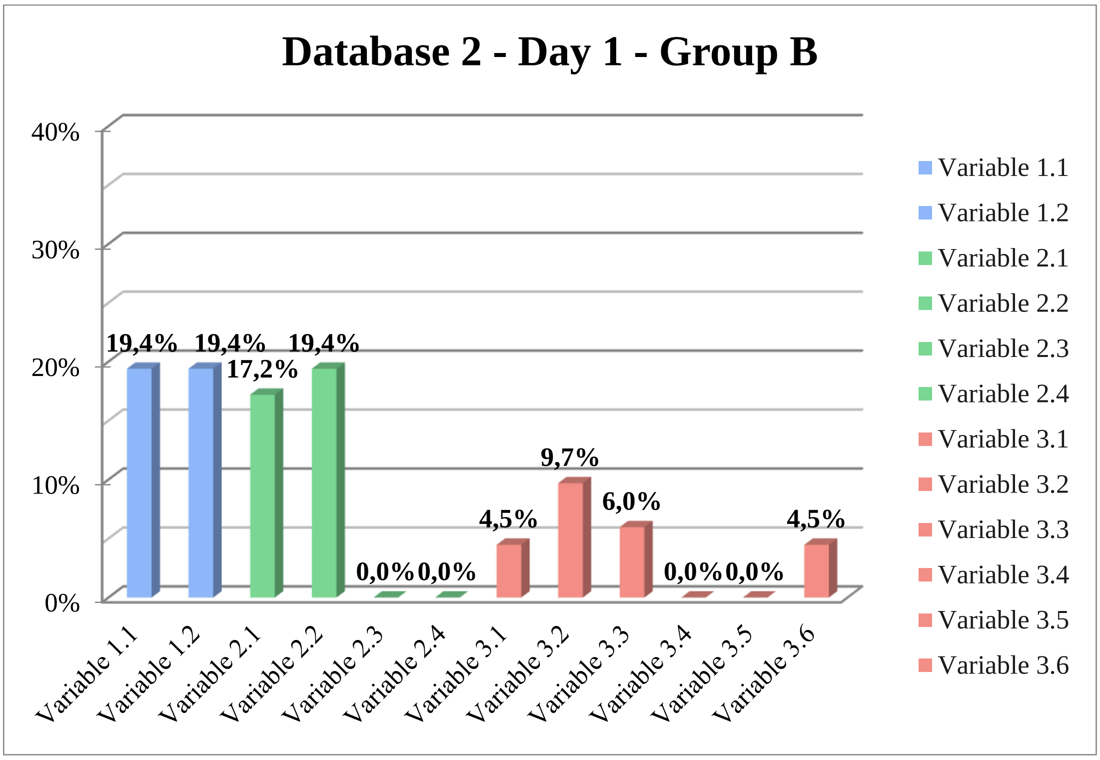


Fig. 43: Bar-diagrams showing the percentages of recurrence of each variable in Database 2 - Day 1 for Group A and Group B, respectively.

Database 2: Audio recordings of students group discussions at the end of each activity – Day 2

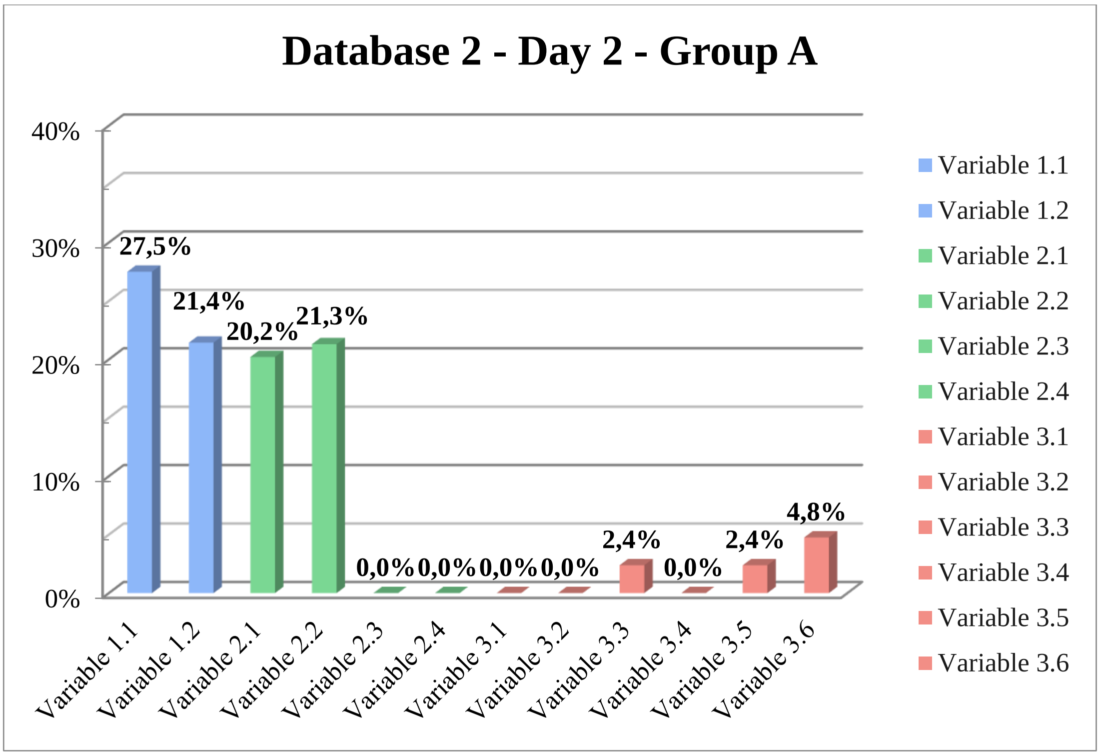
The database analysed in this section consists of the audio recordings of students' group discussions at the end of each activity carried out during the second day of experimentation. During this day students carried out further qualitative experiments.

Qualitative analysis of Database 2 - Day 2 produced results consistent with those obtained for Database 1- Day 2.

Also in this case, qualitative experiments seem to promote aspects of learning related to the appropriation of concepts and forms of representation (1.1) and evolutions of common-sense conceptions to scientific ones (1.2) a little more in Group A students than in Group B ones. In particular, the percentage of Group A students showing the development of appropriation of concepts and forms of representation (1.1) is higher of 5,4% with respect to that of Group B students.

Qualitative experiments confirm to be effective in promoting the perception of self-efficacy (3.1) and development of a growth mindset (3.2), in Group B students more than in Group A ones.

Also in this case, it seems that qualitative experiments did not produce significant differences between the two groups with respect to the enhancement of interpersonal and social skills (2.1) and the development of reasoning skills aimed at interpreting real-life situations and experiments (2.2).



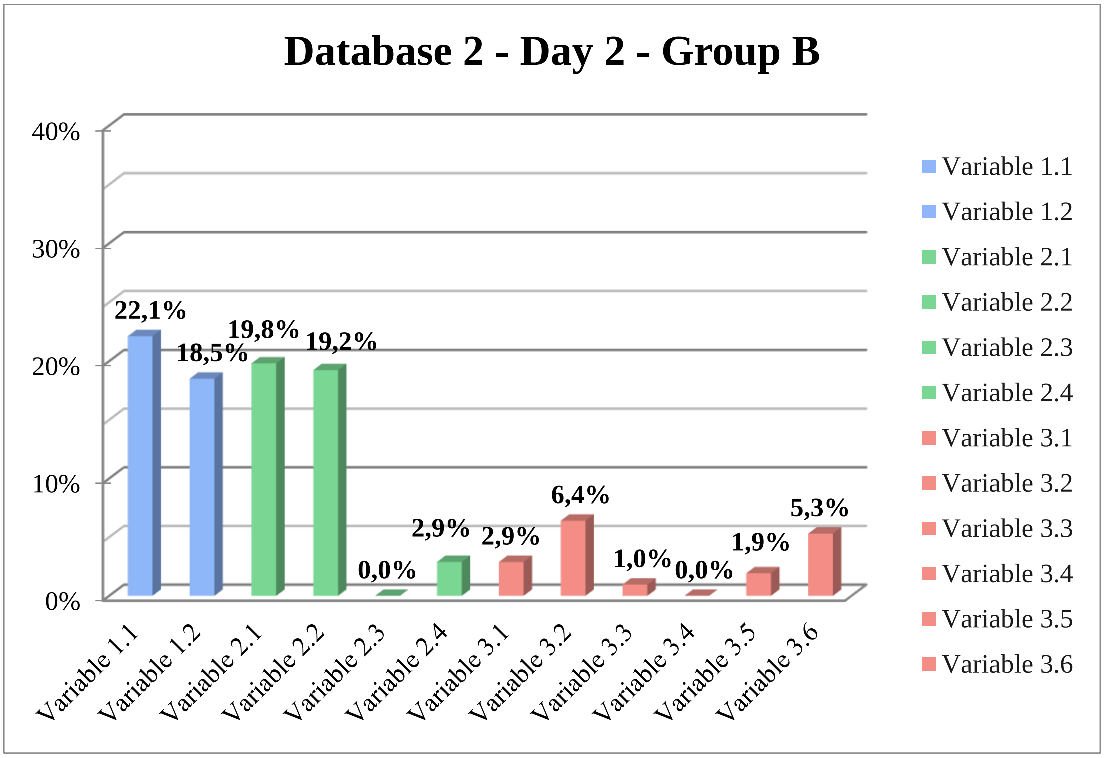


Fig. 44: Bar-diagrams showing the percentages of recurrence of each variable in Database 2 - Day 2 for Group A and Group B, respectively.

Database 2: Audio recordings of students group discussions at the end of each activity – Day 3

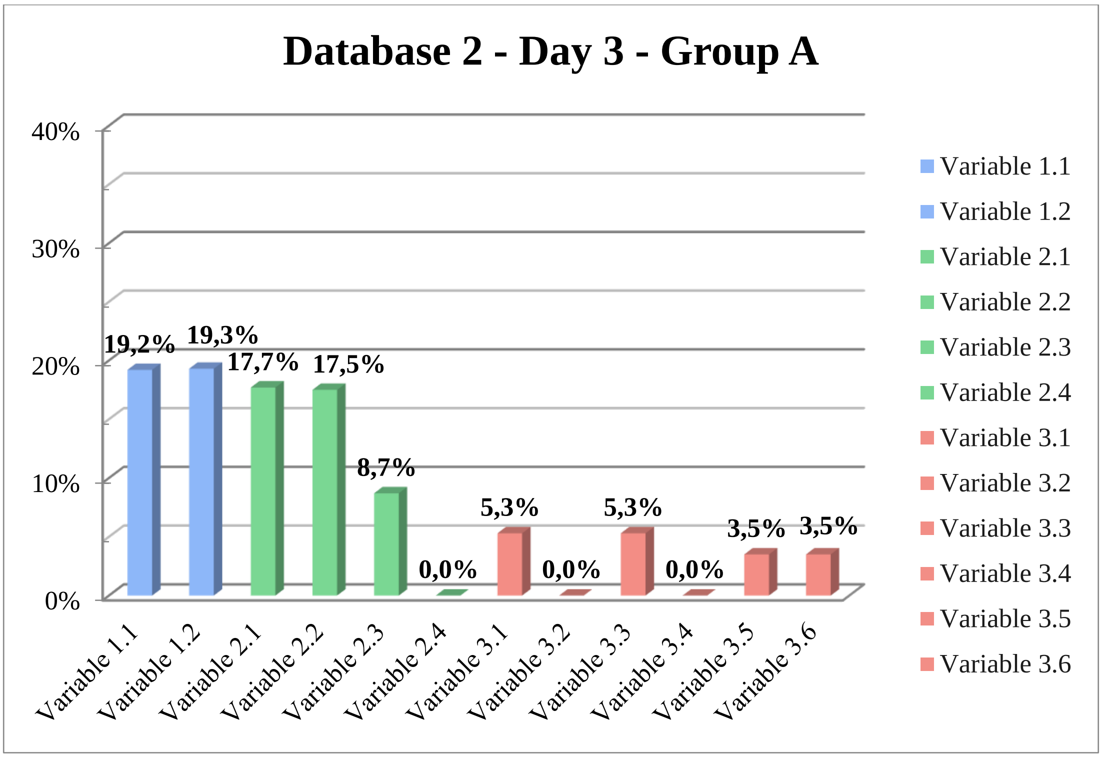
The database analysed in this section consists of the audio recordings of students' group discussions at the end of each activity carried out during the third day of experimentation. During this day students were introduced to modelling activity.

Qualitative analysis of Database 2 - Day 3 produced results consistent with those obtained for Database 1- Day 3.

Modelling activities seem to promote the enhancement of interpersonal and social skills (2.1), the development of reasoning skills aimed at interpreting real-life situations and experiments (2.2), and the willingness to extend studies and research (3.6) in Group B students more than in Group A ones. This means that modelling activities based on the introduction of a mesoscopic model of liquid, implemented through computer simulations, are more effective in promoting the aforementioned aspects of learning with respect to modelling activities based on a macroscopic description of liquid.

On the other hand, modelling activities based on a macroscopic approach seem to promote generalization of what has been learned (2.3), perception of self-efficacy (3.1), and metacognition (3.3) more than ones based on a mesoscopic approach.

The two groups do not show significant differences as regards the aspects of learning related to the appropriation of concepts and forms of representation (1.1) and evolutions of common-sense conceptions to scientific ones (1.2). However, as also noted in the analysis of Database 1- Day 3, the mesoscopic modelling approach, followed by Group B, seems slightly more effective than the macroscopic one, followed by Group A, in promoting aspects of learning related to the appropriation of concepts and forms of representation (1.1) and evolutions of common-sense conceptions to scientific ones (1.2). This is confirmed by the results obtained by analysing the post-instruction questionnaires Q1 and Q2.



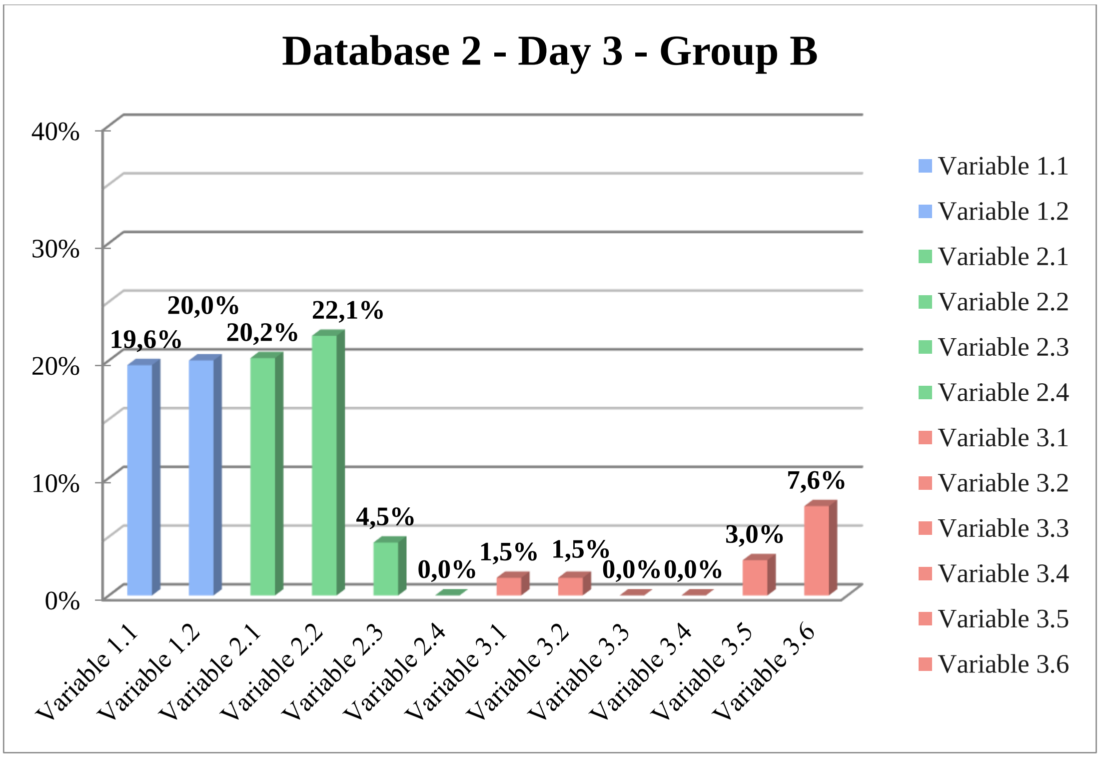


Fig. 45: Bar-diagrams showing the percentages of recurrence of each variable in Database 2 - Day 3 for Group A and Group B, respectively.

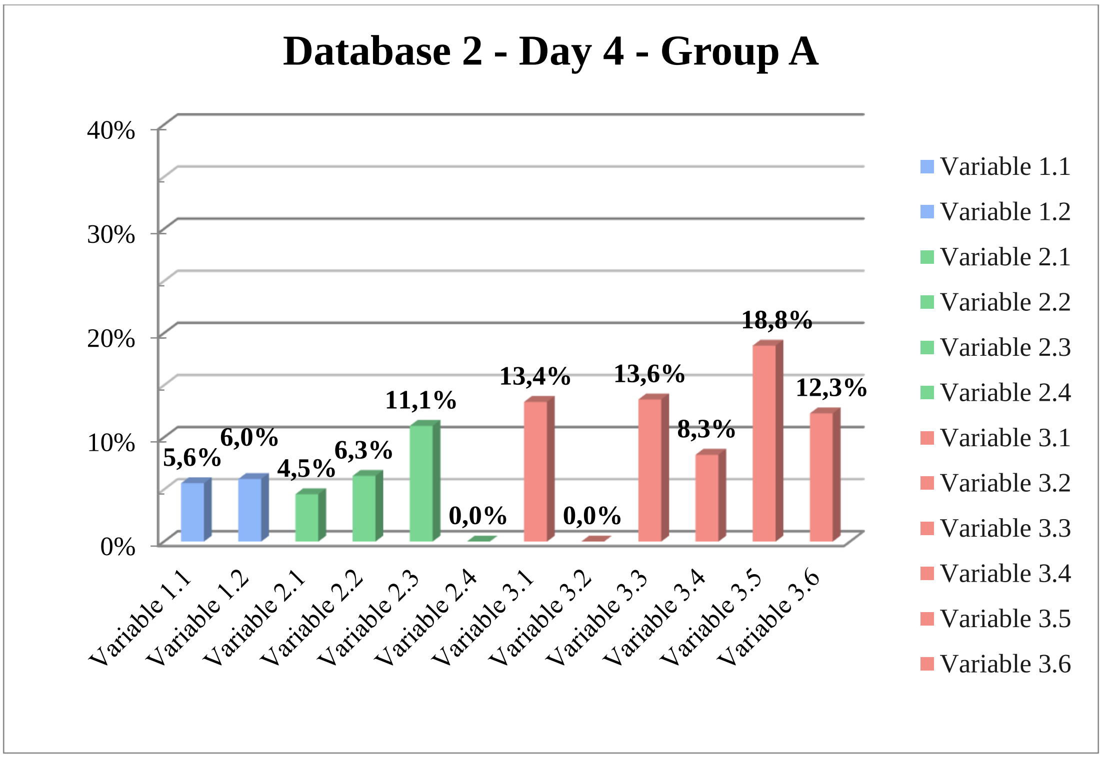
Database 2: Audio recordings of students group discussions at the end of each activity – Day 4

The database analysed in this section consists of the audio recordings of students' group discussions at the end of each activity carried out during the fourth day of experimentation. This day was dedicated to quantitative experiments.

Qualitative analysis of Database 2 - Day 4 produced results consistent with those obtained for Database 1- Day 4.

Quantitative experiments seem to promote the development of reasoning skills aimed at interpreting real-life situations and experiments (2.2), the development of a growth mindset (3.2), and the willingness to extend studies and research (3.6) in Group B students more than in Group A ones. In particular, the percentage of Group B students oriented towards the development of reasoning skills aimed at interpreting real-life situations and experiments and towards the willingness to extend studies and research is higher of 9,3% and 6,5%, respectively, than those of Group A students. It is worth noting that the process of growth mindset development taking place during quantitative experiments in Group B does not occur in Group A. Since Group B students have never analysed the physical quantities involved in surface phenomena from a macroscopic point of view, they had to reason and engage themselves more than the students of Group A in order to interpret the results obtained through quantitative experiments. At the end of the activities, Group B students, thanks to their commitment and perseverance, were able to "solve" problems that initially seemed impossible to solve, and it contributed to reinforcing beliefs and behaviours characteristic of the so-called growth mindset.

On the other hand, quantitative experiments seem to promote the appropriation of concepts and forms of representation (1.1), the evolution of common-sense conceptions to scientific ones (1.2), the enhancement of interpersonal and social skills (2.1), the generalization of what has been learned (2.3), and the understanding of the nature of science (3.5) in Group A students more than in Group B ones. The percentage of Group A students showing a better understanding of the nature of science is double respect to that of Group B students.



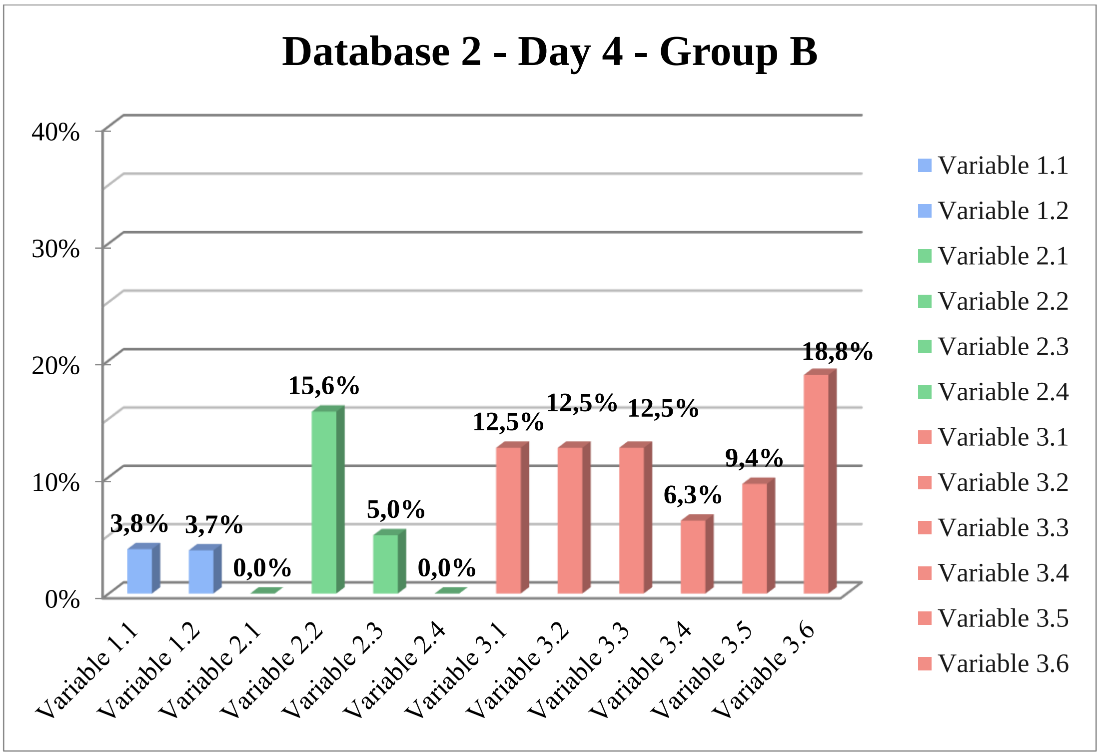


Fig. 46: Bar-diagrams showing the percentages of recurrence of each variable in Database 2 - Day 4 for Group A and Group B, respectively.

Moreover, it is interesting to reflect on the reasons why Group A seems oriented towards the appropriation of concepts and forms of representation (1.1), the evolution of common-sense conceptions to scientific ones (1.2), and the generalization of what has been learned more than Group B. Group A students, after studying the macroscopic approach, interpreted the results obtained through quantitative experiments more easily respect to Group B students. This is due to the fact that the quantities involved in the experiments are those on which Group B previously reflected in the modelling phase. In this sense, Group B students were able to generalize, during the quantitative experiments, what they had learned through modelling activities.

Database 3: Students' contributions during the final day brainstorming phase

The database analysed in this section consists of the audio recordings of students' contributions during the final day brainstorming phase. In this phase, researchers suggested to students some topics and aspects of the experimentation activities to think about and let the two groups discuss and compare their experiences.

The results of the analysis of this database show that Group B students, after the trialling, have developed metacognition (3.3), well-being in learning (3.4), and willingness to extend studies and research (3.6) more than Group A ones.

On the other hand, after the trialling, Group A students seem to have achieved an appropriation of concepts and forms of representation (1.1) higher than Group B ones. Moreover, at the end of the educational path, Group A show an enhancement of interpersonal and social skills (2.1) and the ability to recognize and recognize the evolution of personal cognitive styles (2.4) higher than Group B.

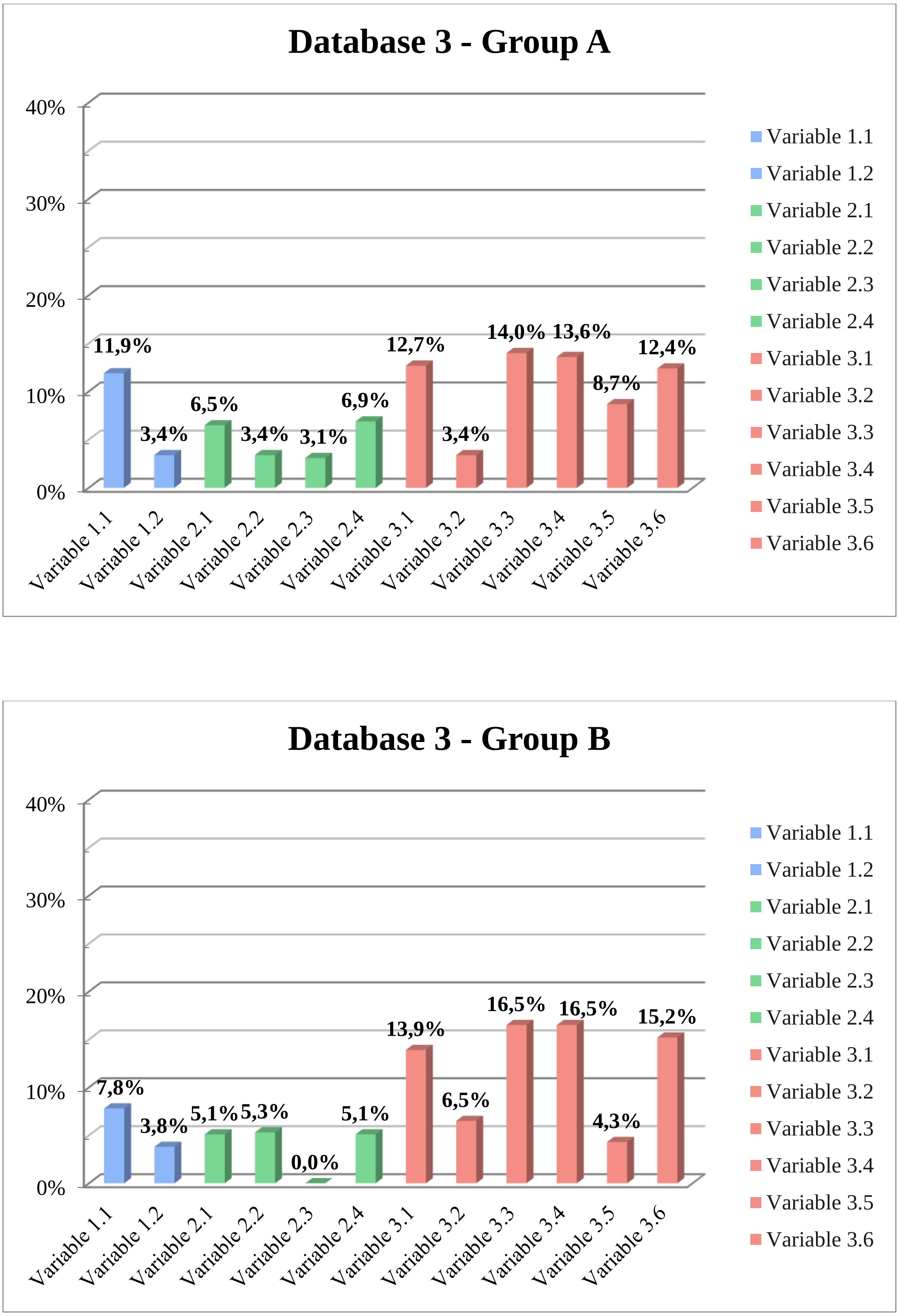


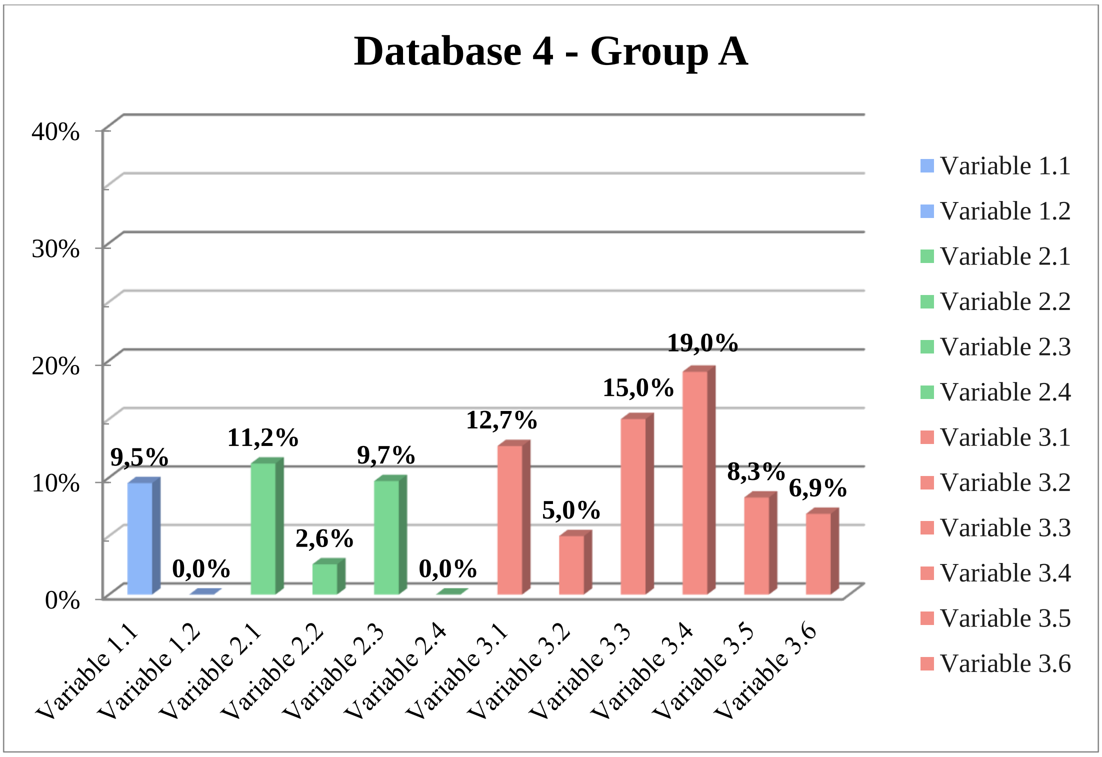
Fig. 47: Bar-diagrams showing the percentages of recurrence of each variable in the Database 3 for Group A and Group B, respectively.

Database 4: Students’ feedback on the activities carried out during the TLSs

Within the satisfaction questionnaire Q3, administrated at the end of the experimentation, a free section was left so that students could give feedback about their experiences during the experimentation and suggestion on how to improve the activities carried out in the context of the TLSs. The database analysed in this section consists of students’ feedback on these activities. As expected, this database allowed us to collect information on learning aspects mainly related to the ‘development of a mindset suited to learning Science’ (see Fig. 18)

From the students' feedback, it emerges that the activities carried out during the trialling foster the enhancement of interpersonal and social skills (2.1) and the acquisition of reasoning skills aimed at interpreting real-life situations and experiments (2.2). From the analysis of this database, it emerges that Group B students seem to have develop beliefs and behaviours characteristic of a growth mindset (3.2) and metacognition skills (3.3), more than Group A ones. Moreover, Group B declare to have experienced higher well-being with respect Group A.

On the other hand, Group A students have achieved an appropriation of concepts and forms of representation (1.1) and the ability of generalization of what has been learned (2.3) more than Group B ones. The enhancement of these two aspects of learning results in a better understanding of the nature of science (3.5) from Group A students.



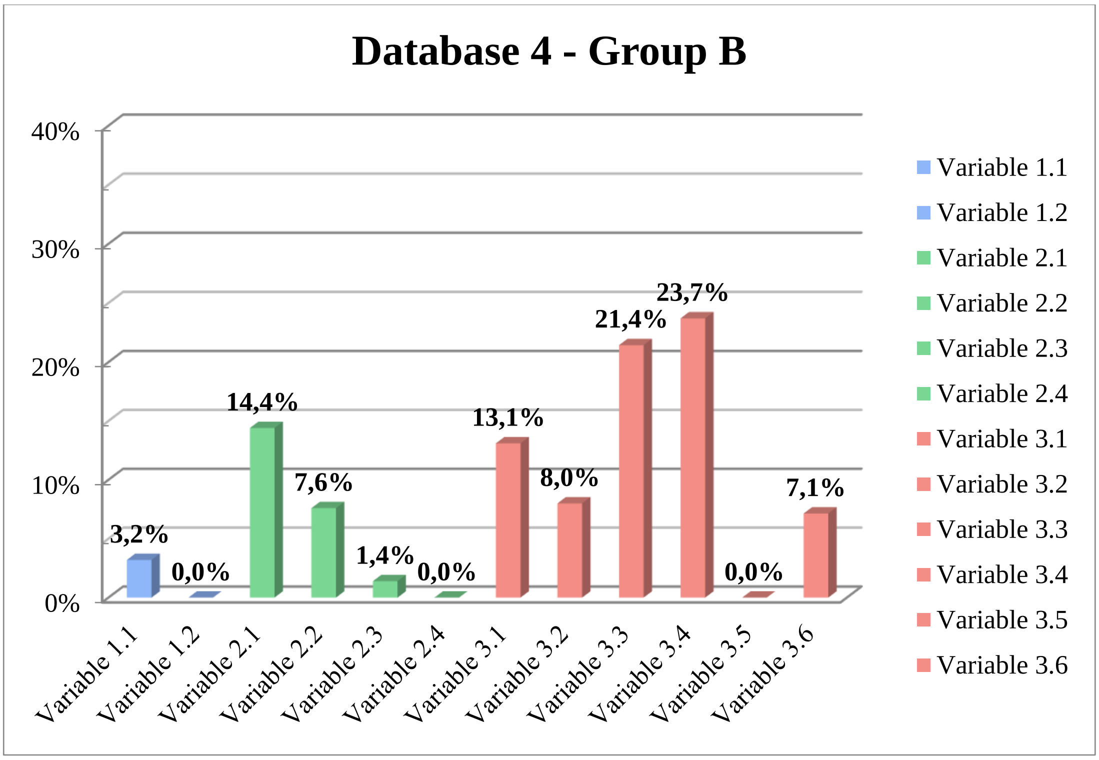


Fig. 48: Bar-diagrams showing the percentages of recurrence of each variable in Database 4 for Group A and Group B, respectively.

A further analysis of the databases

In order to give some more detail on the analysis, in Appendix L we report some excerpts of students' sentences that allowed us to study the variables of interest.

7.2.3 Conclusions

Group B students, through the mesoscopic approach, have developed and reinforced reasoning skills aimed at interpreting real-life situations and experiments (variable 2.2) more than Group A students. Group B students have developed the willingness to extend studies and research (variable 3.6) more than Group A students. This led Group B students to reinforce beliefs and acquire behaviours characteristic of a growth mindset. (variable 3.2).

It is interesting to note that Group B students seem to show a greater enhancement of interpersonal and social skills (variable 2.1) during modelling activities with respect to Group A students. On the contrary, during quantitative experiments Group A students are oriented towards the enhancement of interpersonal and social skills more than Group B ones.

The fact that Group A students experience an enhancement of interpersonal and social skills during the quantitative experiments, leads them to understand the nature of science (variable 3.5) aspects related to social interactions and sharing of information better than Group B students.

In general, Group A and Group B show comparable levels of well-being in learning (variable 3.4). This indicates that the inquiry-type approach proposed through the two TLSs has been welcomed by both groups. However, it is worth noting that, during modelling activities, Group A students experience well-being slightly high than that of Group B students.

This is probably due to the fact that modelling activities based on the macroscopic approach proposed to Group A are activities they are familiar with, a sort of consolidating activity of what they have already studied previously. On the other end, modelling activities based on the mesoscopic approach involve computer-based simulations that are new for the high school student sample we analysed. Although these kinds of activities can create a significant engagement of the students, it is understandable that some of them may feel insecure and not completely at ease when faced with "something new".

Through the macroscopic approach, Group A seems to have developed the ability of generalization of what has been learned (variable 2.3) more than Group B.

7.3 Analysis of questionnaire Q3

In this section the results obtained through the analysis of students' responses to the questionnaire Q3 are reported.

This questionnaire is divided in the following sections:

- **PART I:** expectations and previous knowledge
- **PART II:** organization
- **PART III:** self-assessment and impacts on curricular learning
- **PART IV:** evaluation of educational proposals - relational climate and motivation
- **PART V:** overall satisfaction
- **PART VI:** final comments

The score options based on a Likert scale were converted in a number scale from 0 to 4, as follows:

- 0 = not at all
- 1 = a little
- 2 = enough
- 3 = a lot
- 4 = very much

For each question the weighted mean value of the scores assigned by the students $\bar{x} = \sum_{i=1}^{N} \frac{x_i N_i}{N}$, where N_i is the number of students who assigned the score x_i, and N in the total number of students, was determined. We report the results in Fig. 49.

In general, students who took part to the TLSs seem satisfied by the quality of the activities proposed (PART V). They found the TLSs interesting (PART I) and they appreciated the general organization of the activities, the materials and tools at their disposal (PART II and PART IV). Moreover, students found the activities they were involved in useful for acquiring new learning methodologies and skills, which they also applied in the school context (PART III), feeling more confident in dealing with scientific topics (PART IV).

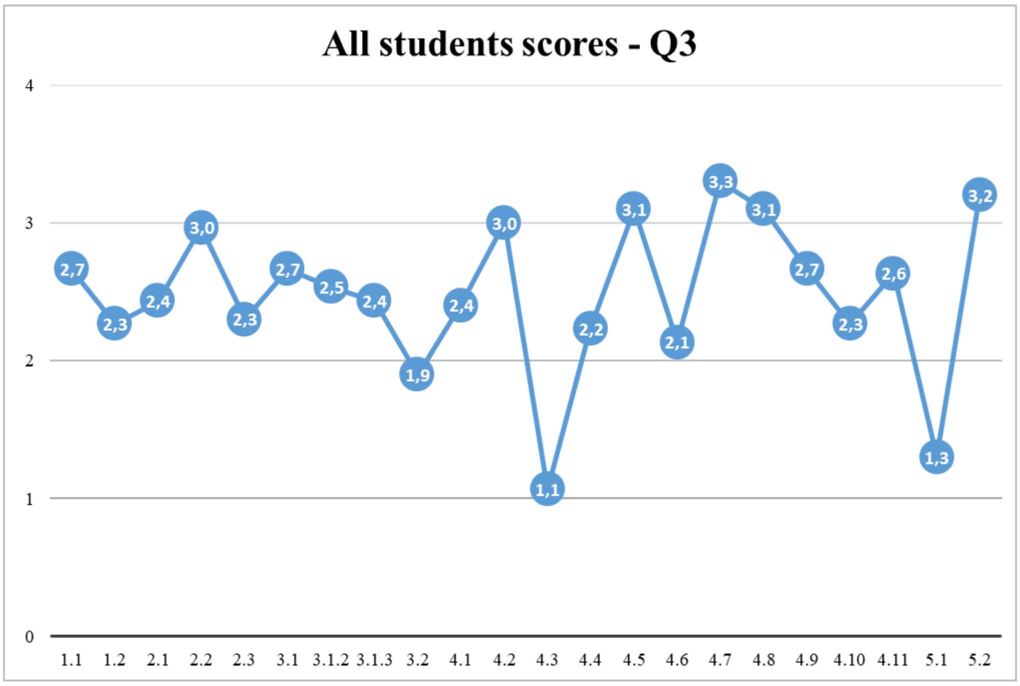


Fig. 49: Weighted mean values of the scores for each question. In the x-axis the labels of the questions are reported, while the y-axis refers to the scores in the Likert scale.

All these information emerge by the general trend of the scores (above the value 2) shown in Fig. 49. The only scores lower than 2 are those assigned to the questions 4.3 and 5.1 in which students are asked to answer about the difficulty level of the proposed activities. This means that, they encountered no major difficulties in facing the situations of interest.

The PART VI of the questionnaire has been analysed in Section 7.2.2, where is indicated as Database 4.

CHAPTER 8

DISCUSSION

8.1 Summary of the results

As we discussed in Chapter 1, from the teaching/learning perspective, it can be relevant to think about the explanatory power of the different scales that can be used to model phenomena, like the surface ones. Therefore, from a research point of view, it is relevant planning and trialling Teaching Learning Sequences recognizing the relevance of the modelling scales in fostering student understanding of the physical contents.

In the research described in this thesis, we started from the hypothesis that choosing an appropriate modelling scale to introduce this topic would appreciably enhance the teaching/learning processes at both school and university levels.

On the basis of this research hypothesis, we decided to study how and to what extent different didactical approaches based on macroscopic and mesoscopic description, respectively, can foster the teaching and learning of surface phenomena, starting from the secondary school level. We designed two teaching-learning sequences (TLSs) on surface phenomena, one based on macroscopic modelling and the other on mesoscopic modelling, which were trialled each with a group of upper secondary school students.

The planning and implementation phases of the two TLSs, based on macroscopic and mesoscopic approaches, respectively, were guided by the general research question, “Which aspects of each approach can be considered relevant in promoting students’ scientific learning?”.

In trying to answer this question, we tried to also answer an overarching question: “what does ‘promoting learning’ actually mean?”. To address this issue, we conducted literature research on all the features of learning the researchers and the teachers focus on when they investigate issues related to the concept of learning, finding that “promotion of student learning” is quite a complex concept to study. Thus, the reflection on this general idea, and a subsequent extensive literature review on the topic, led us to build a conceptual map highlighting three main aspects of learning that can be considered relevant for our research field in the light of the research literature.

According to the literature (see references in chapter 4), among the learning dimensions useful to characterize the promotion of learning, with specific reference to scientific one, there are:

1. Acquisition of conceptual knowledge,

2. Intellectual growth,

3. Development of a mindset suited to learning Science.

We investigated each of these dimensions at a finer grain level. In particular, we identified 13 sub-dimensions of learning (see Fig. 18), named ‘study variables’ (or, simply, ‘variables’), that we found useful to study in this research to inspect the effectiveness of our TLSs with respect to the general aim of promoting learning. The study of these variables was carried out by analysing all the data collected by means of the methods described in Section 6.1.

8.1.1 Results of the questionnaire analysis

As discussed in Section 6.1.1, questionnaires Q1 and Q2 were designed mainly to get information on the study variables: 1.1: appropriation of concepts and forms of representation, 1.2: evolution of common-sense conceptions to scientific ones, 1.3: long-time retention of concepts, 2.2: development of reasoning skills aimed at interpreting real-life situations and experiments, and 2.3: generalization of what has been learned.

The analysis of students’ answers to the questionnaires with respect to variables 1.2 and 2.2 was performed by first using phenomenographic methods (Marton, 1986) and then refined by using a content analysis (Krippendorff, 2018) approach. As shown in Section 7.1.1, students’ answers were classified on the basis of three “epistemological profiles”, related to three different ways of reasoning when dealing with problems and situations proposed in the questions (study variable 2.2), also related to the use of common-sense and scientific knowledge (study variable 1.2).

We here give an example of answers, classified in the three categories, given by the students by answering two questions of Q1 during the post-instruction administration.

Question 4: What do we observe if we place a dry sponge on a surface covered with water? Explain.

Everyday-type answer example

Student 7:*"The sponge absorbs water and changes colour."*

Descriptive-type answer example

Student 19: *"The sponge absorbs water due to the capillary rise."*

Explicative-type answer example

Student 2:*"The sponge will absorb water thanks to the bonds among the water particles. The phenomenon involved is that of capillarity in which the adhesive forces among the liquid and the walls of the solid capillary and cohesive forces of the liquid act."*

Question 5: Why is it preferable to add soap to the water to wash our clothes?

Everyday-type answer example

Student 23:*" Because the soap washes away the dirt and gives a good smell to clothes. This always happens to me when I wash my hands."*

Descriptive-type answer example

Student 19: "Because the soap weakens the bonds among the dirt particles. I remember that I studied this in my chemistry lessons."

Explicative-type answer example

Student 3:*"Because the soap breaks the cohesive forces that are responsible for the surface tension of the water, also facilitating the removal of dirt particles."*

The answers given by the students during the pre- and post-instruction administration of the questionnaires (and also during the re-administration of questionnaire Q2 two months after the end of the pedagogical activities) were used to build contingency tables, useful to see if differences could be found in answers given during the different administration phases. The p-values obtained by running chi squared tests in all the contingency tables (always less than

1%) show that there are significant differences in the distributions of answers in the three epistemological categories used for the analysis among pre-, post-instruction testing and post-post instruction.

The bar-diagrams in Fig. 28 (see Section 7) resume the results of the analysis of the answers given to questionnaire Q1 during pre-and post-instruction administration for the entire sample of students (Group A + Group B), respectively. As can be seen in Fig. 28, a general decrease in everyday-type answers from the pre-instruction questionnaire to the post-instruction is registered. After instruction, everyday-type answers are still present, but descriptive- and explicative-type answers are prevalent. Moreover, a decrease in the number of not-answered questions in the post-instruction questionnaire with respect to the pre-instruction one is highlighted. It is worth noting that the most significant variations between the pre-instruction administration of the questionnaire and the post-instruction one regard the percentages of everyday- and explicative-type answers. Everyday-type answers decreased by 18% from the pre- to post-instruction questionnaire administration, while explicative-type answers increase by 20%.

Fig. 29 gives more detail about what happened in each group. It is again clear that in the post-instruction questionnaire, both groups still give everyday-type answers, but to a lesser extent than before. Both groups also show a decrease in the percentage of not answered questions from the pre- to post-instruction questionnaire administration. In particular, Group A highlights an increase of 16% in descriptive-type answers. Moreover, a decrease of 12% in the number of not-answered questions from the pre- to post-instruction questionnaire is highlighted. On the other hand, Group B maintains the percentage of descriptive-type answers and highlights a significant increase (31%) in explicative-type answers. Everyday-type answers show a clear decrease (25%) from the pre- to post-instruction questionnaire.

We continue with an analysis of answers to questionnaire Q2 with respect to the study variables 1.2 and 2.2. Questionnaire Q2 is based on content dealt with during the activities of the TLSs, which is usually not dealt with during traditional physics lessons in Italian high schools. We chose to administer it before instruction because students of the research sample had already heard about surface phenomena at school, in chemistry classes. However, in that context, several concepts typical of the topic, like surface tension, cohesion and adhesion forces, energy, etc., were introduced only superficially. Particularly, the interactions involved in surface phenomena had not been clarified and presented only in theoretical form.

For that reason, we wanted to have information on content understanding and approaches followed by the students when trying to make sense of situations/questions related to surface phenomena. We, first of all, compare the results of the analysis of students' answers for the entire sample of students (Group A + Group B). As can be seen in Fig. 30, a general and sharp decrease in everyday-type answers from the pre-instruction questionnaire to the post-instruction (from 15% to 0%) is registered. The decrease is also confirmed after the two-months break. Furthermore, a huge decrease (from 54% to 3%) of not-answered questions between the pre- and post-instruction administrations is highlighted. It is worth noting that significant variations from the pre-instruction administration of the questionnaire to the post-instruction one also regard descriptive- and explicative-type answers. Descriptive answers increase by 23% from the pre- to post-instruction questionnaire, while explicative-type answers increase of 42%. The results obtained after the two-month pause show that the epistemological profiles highlighted by the students change a bit, with a 5% increase of descriptive approaches and a 11% decrease of explicative ones.

Fig. 31 gives more detail about what happened in each group. Both show a sharp decrease in the percentage of not answered questions from the pre- to post-instruction administrations. Moreover, In the post-instruction administration, everyday-type answers are not significant in both groups. This behaviour is maintained also after the two-months break. Both Group A and B highlight an increase in descriptive- and explicative-type answers. However, Group A highlights a 30% increase of descriptive answers and a 38% increase of explicative answers between pre- and post-instruction. Group B highlights a 16% increase of descriptive-type answers and a relevant (45%) increase of explicative answers from the pre- to post-instruction administration.

In the following we give an example of explicative-type answers given by a Group A student and a Group B student, to a question of Q2 during the post-instruction administration of the questionnaire.

Question 3: Consider a boat floating on the surface of the water contained in a tank. After dropping a few drops of soap in the water with a dropper, it is observed that the boat starts to move. Why? Explain in terms of the forces acting on the boat.

Explicative-type answer example

Student 14:*"This is because surface tension is an elastic force that holds the surface of the liquid in tension. When the tension is broken due to surfactants, the water molecules bounce back and in doing so move the boat."*

Student 24:*"Because soap is able to weaken surface tension. Therefore, the interaction between the water particles and the soap ones creates an interparticle force directed forward that allows the boat to start moving."*

The examples show that both answers can be considered explicative, as we said. However, the Group A student focuses mainly on a macroscopic explanation. He references molecules but then continues to use terms related to macroscopic results: he explains in terms of an elastic force that acts on the molecules and makes the boat move. The Group B student, on the other hand, bases all his answers on a micro/mesoscopic explanation focused on interaction among particles.

Looking at the results obtained after the two-months break, we can note that Group A students do not maintain the high percentage (49%) of explicative-type answers highlighted during the post-instruction administration of the questionnaire and highlight an increase of descriptive ones. On the other hand, Group B students maintain the level of descriptive-type answers and only slightly decrease the percentage of explicative-type ones. This can be evidence of a better persistence of explanation-based reasoning skills in Group B students than in Group A ones. On the other hand, the maintenance of descriptive reasoning skills in both Groups shows that the shift from common-sense reasoning to scientific-based one is stable after two months from the end of the pedagogical activities.

In the following, we give an example of answers given after the two-months break to question 3 of Q2 by the same Group A and Group B students seen above.

Question 3: Consider a boat floating on the surface of the water contained in a tank. After dropping a few drops of soap in the water with a dropper, it is observed that the boat starts to move. Why? Explain in terms of the forces acting on the boat.

Explicative-type answer example

Student 14:*"This is due to an elastic force acting on the liquid that pushes the boat when the surfactant breaks the surface tension."*

Student 24:*"Because the soap weakens the interactions between the liquid particles and so the boat starts moving as it is now freer to do so."*

From these answers we can see that the group A student directly relates the movement of the boat to an elastic force and does not refer anymore to molecular forces. On the other hand, the Group B students continues to refer to particle interaction even if his answer is less precise than one given during the post-instruction administration of the questionnaire.

Summing up, both Group A and Group B show a decrease in the percentage of everyday-type answers and not-given answers from pre- to post-instruction questionnaire administration, for both Q1 and Q2. Moreover, for both groups an increase in the percentage of descriptive and explicative-type answers, for both questionnaires Q1 and Q2 is highlighted from pre- to post-instruction questionnaire administration. The results appear reasonably stable after the two-months break, particularly for Group B.

Based on the results obtained through the analysis of the questionnaires Q1 and Q2, it emerges that the TLSs activities, and particularly both the modelling approaches, have contributed to the evolution of everyday-type answer strategy towards descriptive and explicative-type ones. However, our results allow us to say that students in Group B are, after instruction, more able to give answers based on explanation-based reasoning than students in Group A. This behaviour persists even after some time from the end of the TLSs activities. It may mean that mesoscopic modelling activities support the development of explanation-oriented reasoning lines more than the more traditional, macroscopic ones. In this sense, we can say that modelling activities based on mesoscopic approach can be considered useful to foster the development of scientific knowledge (variable 1.2), with respect to the use of reasoning skills aimed at explaining real-life situations and experiments (variable 2.2) more for Group B students than for Group A ones. The usefulness of these activities seems stable after a two-months break. On the other hand, the modelling activities based on macroscopic approach, although able to make students shift from common-sense reasoning to scientific ones, seems less efficient than the mesoscopic approach to foster the development of reasoning skills based on explanations and stable in time.

A further analysis of Q2 answers, discussed in sections 7.1.2 and 7.1.3, gave us insights on the development of conceptual knowledge and forms of representation (study variable 1.1), on long-time retention of concepts (study variable 1.3), and on generalization skills of what has been learned (study variable 2.3).

The part of the study of variable appropriation of concepts and forms of representation (1.1) was done by means of a content analysis of the answers to questionnaire Q2 before, after instruction and after the two-months break (to investigate variable 1.3, i.e., long-time retention of concepts). As the variable regards the appropriation of both concepts and forms of representations, we decided to analyse the student answers separately with respect to these two aspects.

When we discussed some research literature evidences about appropriation of concepts and content, we saw that teachers can observe a first level of appropriation when personal signature ideas grounded in the discipline emerge in students, and they are able to correctly describe and discuss the contents. A second, deeper appropriation occurs when students are able to apply the contents to solve problems and face situations. For this reason, we decided to analyse the answers given by students to questionnaire Q2 searching in each student answer for the evidence of: 1) application of the concept to solve a problem or face a situation; 2) correct description of a concept; 3) incorrect description of a concept; 4) no answer.

As can be seen in the bar diagrams in Fig. 32 a drastic decrease in the number of students who do not answer the questions proposed is registered from the pre-instruction to the post-instruction questionnaire. Moreover, after instruction, parallel to a decrease in the number of incorrect descriptions, a significant increase in the number of correct description of concepts and their application to face problems is registered. These trends are confirmed in the post-post administration of the questionnaire, giving evidence of a persistence of concepts learned before.

As can be seen in Fig. 33, in the pre-instruction questionnaire the percentage of application of concepts is significantly low for both groups, and the percentage of no answer is particularly high, especially for Group A. From the pre to the post-instruction questionnaire administration, an increase in the percentage of application of concepts and correct descriptions is registered, especially in Group B. These results are confirmed in the post-post instruction administration of the questionnaire.

For what regards the forms of representations, in Section 4.2.1 we identified verbal, iconic, tabular, graphic, analytical representations as the commonly used one in science. So, we analysed the answers given to Q2 searching for the evidence of such kind of communication and representation channels in each student answer.

As can be seen in the bar diagrams in Fig. 34, a drastic decrease in the number of students who do not use any form of representation to face the situations proposed is registered, from the pre-instruction to the post-instruction administration of the questionnaire. Moreover, after instruction, parallel to a decrease in the number of students who use verbal representation strategies, a significant increase in the number of students who use iconic and analytical forms of representation and representations involving cartesian diagrams is registered. Except for the percentage of students using verbal representations, the percentages of students using other forms of representation remain almost unchanged in the post-post instruction administration of the questionnaire. The percentage of students using tabular forms of representation is low and almost unchanged in both pre- and post-instruction.

As we can see in Fig. 35, in answering the pre-instruction questionnaire the prevailing form of representation is the verbal one for both Group A and Group B. In answering to the post-instruction questionnaire, Group A students show increasing use of formulas (analytical representations) to address the proposed situations, while Group B ones are more oriented to the use of schemes and graphs (iconic representations and representations involving cartesian diagrams). These trends are confirmed in the answers of the post-post instruction questionnaire. In both groups, the percentage of students using tabular forms of representation is low and almost unchanged either in pre- and post-instruction administration of the questionnaire.

The study of the variable 2.3: generalization of what has been learned was done by means of the analysis of the answers to questionnaire 2 before, after instruction and after the two-months break.

We have seen in Section 4.2.6 that the variable regards the use of contents and techniques learned in a given situation in similar or different, untrained circumstances. Therefore, we decided to content-analyse the student answers with respect to the following levels: 1) generalization to untrained situations; 2) generalization to similar situations; 3) no generalization/no answer.

Questionnaire Q2 includes questions related to both situations, similar to the ones dealt with during the TLSs phases, and situations that appear to an expert analogous to the TLSs ones but that cannot be perceptible by students as similar to the TLSs' ones.

As can be seen in the bar diagrams in Fig. 36, a drastic decrease in the number of students who do not generalize or not answer the question proposed is registered from the pre-instruction to the post-instruction questionnaire. At the same time, after instruction, a significant increase in the number of students who generalize in untrained situations and in situations similar to those with which they are familiar to is registered. These results are confirmed in the post-post instruction questionnaire.

As we see in Fig. 37, in the pre-instruction questionnaire, the percentage of generalization in untrained situations is equal to zero, and the percentage of no generalization/no answer is significantly high for both groups. Before instruction, only a small percentage of students seem capable to generalize in situations similar to those with which they are familiar with. In answering the post instruction questionnaire, an increase in the percentage of students who generalize in both untrained situations and situations similar to those with which they are familiar with is registered. In particular, Group B students seem to be oriented towards generalization in untrained situations more than Group A ones. It is worth noting that also after instruction, a percentage not negligible of students is still unable to generalize. This could be due to the small time spent on modelling activities.

In order to give some more detail on the analysis, in Appendixes I-L we report some excerpts of students' sentences that allowed us to study the variables of interest.

8.1.2 Results of thematic analysis

The analysis carried out on the data collected by means of students' worksheets (Database 1), audio-recordings of students group discussions at the end of each activity (Database 2), students' contributions during the final day brainstorming phase (Database 3), students' feedback on the activities carried out during the TLSs (Database 4) was inspired by thematic analysis methods.

Through the qualitative analysis of these databases, we aimed to study how much each of them has highlighted the involvement of the variables of interest in the processes experienced by the students.

The detailed analysis of Database 1 and Database 2 performed in Section 7.2.2 allowed us to identify which activities, and therefore which aspects of each approach (macroscopic and mesoscopic) were effective in promoting aspects of the learning process related to the learning dimensions ‘conceptual knowledge’ and ‘intellectual growth’ (see Fig. 18). On the other hand, from Database 3 and Database 4, we extrapolated information on the learning dimensions ‘intellectual growth’ and ‘development of a mindset suited to learning Science’ (see Fig. 18).

The results of the qualitative analysis of databases 1-4 are presented through bar diagrams obtained by counting the number of times a given variable (i.e., a sub-dimension of learning) emerges within a specific database. In particular, each graph shows the percentages of occurrence of a given variable within a given database. All graphs have been normalized.

From the results presented in Section 7.2.2 we can say that Group B students, through the mesoscopic approach, have developed and reinforced reasoning skills aimed at interpreting real-life situations and experiments (variable 2.2) more than Group A students. Group B students have developed the willingness to extend studies and research (variable 3.6) more than Group A students. This led Group B students to reinforce beliefs and acquire behaviours characteristic of a growth mindset. (variable 3.2).

It is interesting to note that Group B students seem to show a greater enhancement of interpersonal and social skills (variable 2.1) during modelling activities with respect to Group A students. On the contrary, during quantitative experiments, Group A students are oriented towards the enhancement of interpersonal and social skills more than Group B ones.

The fact that Group A students experience an enhancement of interpersonal and social skills during the quantitative experiments leads them to understand the nature of science (variable 3.5) aspects related to social interaction and sharing of information better than Group B students.

In general, Group A and Group B show comparable levels of well-being in learning (variable 3.4). This indicates that the inquiry-type approach proposed through the two TLSs has been welcomed by both groups. However, it is worth noting that, during modelling activities, Group A students experience a well-being slightly higher than that of Group B students.

This is probably due to the fact that modelling activities based on the macroscopic approach proposed to Group A are activities they are familiar with, a sort of consolidating activity of what they have already studied previously. On the other end, modelling activities based on the mesoscopic approach involve computer-based simulations that are new for the high school student sample we analysed. Although these kinds of activities can create a significant engagement of the students, it is understandable that some of them may feel insecure and not completely at ease when faced with “something new”.

Through the macroscopic approach, Group A seems to have developed the ability of generalization of what has been learned (variable 2.3) more than Group B.

The analysis of the satisfaction questionnaire Q3 (see Section 7.3) reveals that in general, students who took part to the TLSs is satisfied by the quality of the activities proposed. They found the TLSs interesting, and they appreciated the general organization of the activities, the materials and tools at their disposal. Moreover, students found the activities they were involved in useful for acquiring new learning methodologies and skills which they applied also in the school context feeling more confident in dealing with scientific topics.

All these information emerge by the general trend of the scores (above the value 2) shown in Fig. 49. The only scores lower than 2 are those assigned to the questions 4.3 and 5.1, in which students are asked to answer about the difficulty level of the proposed activities. This means that, they encountered no major difficulties in facing the situations of interest.

8.2 Implications for teaching and limitations of the study

Based on the results of our analysis, we believe that to deal with surface phenomena effectively, it should be useful to build a TLS embedding aspects of both the approaches trialled.

The strong experimental connotation common to both TLSs, which in several cases required the active involvement of the students in designing experiments and collecting and analysing data, the importance given to the continuous interaction of the students within the small and large groups, and the constant request to the students to express their agreement with the conclusions reached by the group, represented a characterising aspect of the approach followed during the development of the two TLSs. All the students showed appreciable improvements in relation to many of the study variables. On the other hand, the different modelling approaches and the related differences in student learning showed that mesoscopic modelling seems to provide students with more effective tools for developing explanatory reasoning models with respect to the more traditional macroscopic modelling.

We also believe that presenting a topic through a multiple perspective, involving students in a complex and variegated learning environment can really help them to achieve a deep understanding and awareness of themselves. All this also fosters students' acquisition of ways of reasoning and attitude towards problem-solving that represent transversal tools crucial in everyday life beyond the didactic experience. In particular, we believe that in a future trialling of this TLS it will worth dedicating more time to the mesoscopic approach as this, despite the limited time available during the first trialling, clearly shown particular effectiveness in promoting students' understanding of the functioning mechanisms underlying the physical phenomena explained, which is essential for the achievement of scientific knowledge.

Another aspect worth of consideration regards the issues related to the preparation of physics teachers to design, implement and evaluate TLSs on surface phenomena, like the ones we described in this research, and, more generally, the preparation of teachers in effectively designing, implementing and evaluating pedagogical approaches based on active learning methodologies and investigation/inquiry-based approaches. The two teachers that participated in our research are both graduated in physics and interested in innovation in teaching and learning the subject. They were able to not only actively support the researchers in the design and implementation phases of the TLSs, but were also willing to transfer the pedagogical methods used during the trialling to their daily teaching practice. This undoubtedly facilitated the development of the research, as we could count on the fact that the activities carried out in the classroom were systematically resumed and extended during the normal classroom activities. Unfortunately, this is not a common situation in Italian schools, where many teachers are not graduated in physics and/or do not always consider the use of active learning methodologies as feasible and useful, mainly because of time constraints with the school programs and the commitment that is required to effectively involve students in laboratory and modelling activities based on investigation/inquiry.

The study presented in this thesis is affected by some limitations related to the number and nature of the research sample. Since the TLSs designed were tested on a sample of 40 students, all of them attending the upper secondary school, the results of our study are not easily generalizable. We plan to design a single TLS embedding the most effective aspects and tools characteristics of the macroscopic and mesoscopic approaches on surface phenomena experimented in the context of the two TLSs described in this work. On the basis of the results obtained and of the 'lesson learnt', we plan to trial this upgraded TLS on a more extended sample composed of upper secondary school students (once again). A further trial of the upgraded TLS is also planned with undergraduate students (first year of Engineering degree courses) in order to get information on the influence of age and content understanding background on the improvements due to the investigative/modelling approach that can be observed with respect to the study variables.

Appendix A

Questionnaire Q1

1. Imagine to dip a small portion of a cookie in a cup of milk. What happens to the liquid?

   ____

2. What do you think happens to the cookie?

   ____

3. Explain what you observed previously.

   ____

4. What do we observe if we place a dry sponge on a surface covered with water? Explain.

   ____

5. Why is it preferable to add soap to the water to wash our clothes?

   ____

6. Let's imagine to fix a grid on the top of a glass. We gently put some water into the glass through the grid, then we put a cardboard on the grid in order to plug the glass. After turning the glass upside down and removing the cardboard, the water does not fall. Why?



   ____

7. During a rainy day, you can wear clothes of different materials. As you may have noticed, water behaves differently in contact with different materials. Do you think

there is a difference in the behavior of the water in the two cases indicated in the figure?

8. Explain what these differences are due to.

9. Why, if we put some oil in a pan, there is no formation of drops as it happens in the case of water? How does the oil behave? Explain.

10. Why is it preferable to use hot water to remove stains from our clothes?

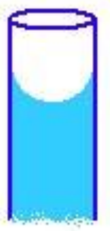
11. Why does the insect in the picture walk on water without "sinking"?

12. How does water go up from the roots to the leaves of a tree?

Appendix B

Questionnaire Q2

1. The liquid inside a glass capillary tube has a concave meniscus (see the figure). Why? Explain in terms of forces.



____

2. A liquid does not wet the glass it is in contact with. Why? Explain in terms of forces.

____

3. Consider a boat floating on the surface of the water contained in a tank. After dropping a few drops of soap in the water with a dropper, it is observed that the boat starts to move. Why? Explain in terms of the forces acting on the boat.

____

4. What are the units of measurement of surface tension? How is it possible to obtain them?

____

5. The number of water droplets required to completely cover the surface of a coin is greater than the number of seed oil droplets required to cover the surface of a coin identical to the first one. Explain what this phenomenon might be related to.

____

6. Consider three capillary tubes of the same material and of the same diameter each dipped in three tanks containing water, mercury and oil, respectively. Represent how each liquid will be arranged inside the capillary tubes graphically. Explain in terms of forces.

____

7. What do you think are the "adhesive forces" and "cohesive forces"? Give some examples of contexts in which these forces are present.

8. What difference do you think there is between these two types of forces?

9. Which quantities influence the rise of a liquid inside a capillary tube? Explain.

10. Do you think the soap modifies water properties? If yes, which ones?

11. If you put some soap into water and deposit a drop of this mixture on a horizontal plane, you will notice that the water is evenly distributed on the surface not forming a real drop. Explain this phenomenon.

Appendix C

Questionnaire Q3

You are: ☐ male ☐ female ☐ I prefer not to answer

PART I: EXPECTATIONS AND PREVIOUS KNOWLEDGE

1.1 Did this course turn out to be interesting/useful, based on your previous expectations?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

1.2 Were the knowledge you had before starting the course useful for carrying out the activities?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

PART II: ORGANIZATION

2.1 Do you think the duration of the course (overall hours) was adequate?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

2.2 Were you able to reconcile the effort required by the project with the study dedicated to the disciplinary subjects?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

2.3 Do you find the environments (classrooms, laboratories, etc.) offered comfortable?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

PART III: SELF-ASSESSMENT AND IMPACTS ON CURRICULAR LEARNING

3.1 By attending this project you have acquired new knowledge:

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

3.1.2 a new working method:

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

3.1.3 new operational skills:

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

3.2 Were there things you learned during the project that were useful to you in the study of the school subjects or that you think could be?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

PART IV: EVALUATION OF EDUCATIONAL PROPOSALS

4.1 Do you positively judge the materials and tools used (photocopies, equipment, computers, etc.)?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

4.2 Were the activities (experiments, simulations, exercises, discussions, ...) carried out during the course interesting?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

4.3 Did you encounter difficulties in tackling the proposed activities?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

4.4 Do you think it is useful to have moments of personal reflection before carrying out group work?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

4.5 Do you find the team-work mode useful?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

4.6 After attending the course, how much do you feel able to describe a studied phenomenon?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

4.7 Do you think it is useful to use tools other than the textbook (internet, other books, scientific articles, videos, etc.) to search for information on the topic of interest?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

4.8 Do you think it is useful to arrive at the construction of descriptions and explanations in a cooperative way and by carrying out experiments and discussions, rather than immediately listening to a complete presentation by the teacher (traditional lesson)?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

PART IV: RELATIONAL CLIMATE AND MOTIVATION

4.9 Has a positive climate of participation been created in the group?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

4.10 After attending the course, do you feel more confident in dealing with scientific topics?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

4.11 After attending the course, do you think you have an aptitude for scientific subjects?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

PART V: OVERALL SATISFACTION

5.1 How hard did you find the course?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

5.2 How satisfied are you with the course in general?

☐ not at all ☐ a little ☐ enough ☐ a lot ☐ very much

PART VI: FINAL COMMENTS

If you want to add some final comments, you can do so below

Appendix D

Qualitative experiments

Qualitative experiment n.1

Observation (video: https://www.youtube.com/watch?v=4CU8gYYkwSw)

Prediction of the individual student

A video showing an insect sitting on the water will be presented. Do you think it will be able to move on it? And how?

Prediction of the small group

Discuss as a group what you think happens to the insect and report your shared prediction.

VIDEO WATCHING

Observation of the individual student

Report what in the video impressed you the most and why.

Observation of the small group

After discussing with your group, write down what impressed you in the video and why.

Observations and conclusions of the large group

After discussing with the large group, report below the aspect of the video that the group believes is most relevant in relation to the motion of the water strider on the surface of the water.

Comparison between the conclusions of the large group and the predictions of the individual student and the small group

Are the conclusions reached through the large group discussions compatible with your predictions? And with those of the small group?

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.

<u>Activity</u>

You have the following materials at your disposal:

- tray
- water
- paper clips, needles, safety pins

Individual activity

1. How would you use the available material to better study the previously observed phenomenon? The aim is to describe a water behavior similar to what is observed in the video.

2. Can you think of another possible experiment useful to show the same behavior of water even using different materials than those at your disposal here?

Small group activity

3. Taking turns explaining within the group which experiment you have thought of carrying out and briefly describe it.

4. After searching for information, for example online, all agree together which experiment to carry out with the materials at your disposal. Describe the experiment.

5. Report what results you expect from the experiment you have chosen to perform.

6. Report what you actually observed during the experiment.

7. Discuss whether or not what you observed in the previous point coincides with what you expected individually and as a group.

Observations and conclusions of the large group

After discussing with the large group, report below what you consider to be the elements of particular relevance that emerged and report the conclusions reached.

Comparison between the conclusions of the large group and the predictions of the individual student and the small group

Are the conclusions reached through the large group discussions compatible with your predictions? And with those of the small group?

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.

Qualitative experiment n.2

Observation (video: https://www.youtube.com/watch?v=WsksFbFZeeU)

Prediction of the individual student

You will be shown a video showing the following phenomenon: water is placed inside a glass and a card is placed on the top of the glass in order to plug it. What do you imagine happens to the water once the glass is turned upside down and the card removed?

Prediction of the small group

Discuss as a group what you think happens to the water when the glass is turned upside down and report your shared prediction.

VIDEO WATCHING

Observation of the individual student

Report what in the video impressed you the most and why.

Observation of the small group

After discussing with your group, write down what impressed you in the video and why.

Observations and conclusions of the large group

After discussing with the large group, report below the aspect of the video that the group believes is most relevant in relation to the behaviour of the water once the glass is turned upside down and the card removed.

Comparison between the conclusions of the large group and the predictions of the individual student and the small group

Are the conclusions reached through the large group discussions compatible with your predictions? And with those of the small group?

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.

Activity

You have the following materials at your disposal:

- tray
- water
- soap
- metal frame n.1/metal frame n.2

Individual activity

1. How would you use the available material to better study the previously observed phenomenon? The aim is to describe a water behavior similar to what is observed in the video.

---

2. Can you think of another possible experiment useful to show the same behavior of water even using different materials than those at your disposal here?

Small group activity

3. Taking turns explaining within the group which experiment you have thought of carrying out and briefly describe it.

---

4. After searching for information, for example online, all agree together which experiment to carry out with the materials at your disposal. Describe the experiment.

---

5. Report what results you expect from the experiment you have chosen to perform.

---

6. Report what you actually observed during the experiment.

---

7. Discuss whether or not what you observed in the previous point coincides with what you expected individually and as a group.

Observations and conclusions of the large group

After discussing with the large group, report below what you consider to be the elements of particular relevance that emerged and report the conclusions reached.

Comparison between the conclusions of the large group and the predictions of the individual student and the small group

Are the conclusions reached through the large group discussions compatible with your predictions? And with those of the small group?

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.

Qualitative experiment n.3

<u>Observation</u> (video: https://www.youtube.com/watch?v=11n5g1QE-Nk)

Prediction of the individual student

You will be shown a video showing a stalk of celery dipped inside a glass filled with colored water. What do you imagine will happen to the celery stalk? And to the water?

Prediction of the small group

Discuss as a group what you think happens to the celery stick and the water and report your shared prediction.

VIDEO WATCHING

Observation of the individual student

Report what in the video impressed you the most and why.

Observation of the small group

After discussing with your group, write down what impressed you in the video and why.

Observations and conclusions of the large group

After discussing with the large group, report below the aspect of the video that the group believes is the most relevant in relation to what happens to the celery stick and the water.

Comparison between the conclusions of the large group and the predictions of the individual student and the small group

Are the conclusions reached through the large group discussions compatible with your predictions? And with those of the small group?

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.

<u>Activity</u>

You have the following materials at your disposal:

- tray
- water
- sheets of paper, blotting paper
- scissors
- food coloring

Individual activity

1. How would you use the available material to better study the previously observed phenomenon? The aim is to describe a water behavior similar to what is observed in the video.

---

2. Can you think of another possible experiment useful to show the same behavior of water even using different materials than those at your disposal here?

Small group activity

3. Taking turns explaining within the group which experiment you have thought of carrying out and briefly describe it.

4. After searching for information, for example online, all agree together which experiment to carry out with the materials at your disposal. Describe the experiment.

5. Report what results you expect from the experiment you have chosen to perform.

6. Report what you actually observed during the experiment.

7. Discuss whether or not what you observed in the previous point coincides with what you expected individually and as a group.

Observations and conclusions of the large group

After discussing with the large group, report below what you consider to be the elements of particular relevance that emerged and report the conclusions reached.

Comparison between the conclusions of the large group and the predictions of the individual student and the small group

Are the conclusions reached through the large group discussions compatible with your predictions? And with those of the small group?

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.

Activity

You have the following materials at your disposal:

- capillary tube set/ communicating vessel set
- water
- food coloring

Individual activity

1. How would you use the available material to better study the previously observed phenomenon? The aim is to describe a water behaviour similar to what is observed in the video.

---

2. Can you think of another possible experiment useful to show the same behavior of water even using different materials than those at your disposal here?

Small group activity

3. Taking turns explain with the group which experiment you have thought of carrying out and briefly describe them.

---

4. After searching for information, for example online, all agree together which experiment to carry out with the materials at your disposal. Describe the experiment.

---

5. Report how you expect the system you have chosen to analyse to behave.

---

6. Report what you observed during the experiment.

---

7. Discuss whether or not what you observed in the previous point coincides with what you expected individually and as a group.

Observations and conclusions of the large group

After discussing with the large group, report below what you consider to be the elements of particular relevance that emerged and report the conclusions reached.

Comparison between the conclusions of the large group and the predictions of the individual student and the small group

Are the conclusions reached through the large group discussions compatible with your predictions? And with those of the small group?

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.

Qualitative experiment n.4

Observation (video: https://www.youtube.com/watch?v=PFZsMe4Vr58)

Prediction of the individual student

A video showing drops of different liquids in contact with the same surface will be presented. How do you think the various liquids will behave?

Prediction of the small group

Discuss as a group what you think happens to the various liquids and write your shared prediction below.

VIDEO WATCHING

Observation of the individual student

Report what in the video impressed you the most and why.

Observation of the small group

After discussing with your group, write down what impressed you in the video and why.

Observations and conclusions of the large group

After discussing with the large group, report the aspect of the video that the group believes is most relevant in relation to the behaviour of the drops of the various liquids is reported below.

Comparison between the conclusions of the large group and the predictions of the individual student and the small group

Are the conclusions reached through the large group discussions compatible with your predictions? And with those of the small group?

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.

Activity

You have the following materials at your disposal:

- water, oil, glycerin, soap, alcohol
- glass plates
- plexiglass plates
- baking paper
- tinfoil
- pipettes

Individual activity

1. How would you use the available material to better study the previously observed phenomenon? The aim is to describe a water behaviour similar to what is observed in the video.

2. Can you think of another possible experiment useful to show the same behavior of water even using different materials than those at your disposal here?

Small group activity

3. Taking turns explaining within the group which experiment you have thought of carrying out and briefly describe it.

4. After searching for information, for example online, all agree together which experiment to carry out. Describe the experiment.

5. Report what results you expect from the experiment you have chosen to perform.

6. Report what you actually observed during the experiment.

7. Discuss whether or not what you observed in the previous point coincides with what you expected individually and as a group.

Observations and conclusions of the large group

After discussing with the large group, report below what you consider to be the elements of particular relevance that emerged and report the conclusions reached.

Comparison between the conclusions of the large group and the predictions of the individual student and the small group

Are the conclusions reached through the large group discussions compatible with your predictions? And with those of the small group?

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.

Qualitative experiment n.5

<u>Observation</u> (video: https://www.youtube.com/watch?v=miWlDVOhrSE)

Prediction of the individual student

A video showing a paper boat placed on the surface of the water will be presented. At one point a drop of soap is deposited behind the boat. What do you imagine will happen to the boat and the water?

Prediction of the small group

Discuss as a group what you think happens to the boat and the water and report your shared prediction.

VIDEO WATCHING

Observation of the individual student

Report what in the video impressed you the most and why.

Observation of the small group

After discussing with your group, write down what impressed you in the video and why.

Observations and conclusions of the large group

After discussing with the large group, report below the aspect of the video that the group believes is most relevant in relation to the behaviour of the paper boat and the water.

Comparison between the conclusions of the large group and the predictions of the individual student and the small group

Are the conclusions reached through the large group discussions compatible with your predictions? And with those of the small group?

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.

Activity

You have the following materials at your disposal:

- tray
- water
- soap
- paper clips, needles, talcum powder, pepper, toothpicks

Individual activity

1. How would you use the available material to better study the previously observed phenomenon? The aim is to describe a water behaviour similar to what is observed in the video.

---

2. Can you think of another possible experiment useful to show the same behavior of water even using different materials than those at your disposal here?

Small group activity

3. Taking turns explaining within the group which experiment you have thought of carrying out and briefly describe it.

---

4. After searching for information, for example online, all agree together which experiment to carry out. Describe the experiment.

---

5. Report what results you expect from the experiment you have chosen to perform.

---

6. Report what you actually observed during the experiment.

---

7. Discuss whether or not what you observed in the previous point coincides with what you expected individually and as a group.

Observations and conclusions of the large group

After discussing with the large group, report below what you consider to be the elements of particular relevance that emerged and report the conclusions reached.

Comparison between the conclusions of the large group and the predictions of the individual student and the small group

Are the conclusions reached through the large group discussions compatible with your predictions? And with those of the small group?

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

Pre-modelling questions – Conceptual pit stop

Question1

How do you imagine a liquid is made?

Question2

Try to give a description of the liquid in terms of particles/molecules and give a graphical representation of it.

Question3

What do you think are the main forces that determine the behaviour of the liquid in the analysed physical situations? Try to describe how the forces act.

Question4

Draw the forces acting on a liquid molecule that is located

- on the surface of the liquid contained in the glass
- inside the liquid contained in the glass.

Appendix F

Simulated experiments

Simulated experiment n.1

Thought experiment

Consider a square distribution of particles in equilibrium. What do you imagine happens to the distribution of particles if, in addition to the pressure force, we also introduce the interparticle force described above? What shape will the system of particles take?

VIDEO

Analyze the behavior of the simulated liquid for a liquid-liquid interaction value of 3.0.

Prediction of the individual student

Describe how you expect the forces act on a particle of liquid at the surface of the drop and a particle of liquid at the edge of the drop when it reaches equilibrium.

Prediction of the small group

Describe how you expect the forces act on a particle of liquid at the surface of the drop and a particle of liquid at the edge of the drop when it reaches equilibrium.

In the space below, report what you observed at the end of the simulated experiment.

Give an explanation of what you observed in terms of forces by referring to what we discussed earlier.

Observations and conclusions of the large group

After discussing with the large group, report the conclusions.

Comparison between the conclusions of the large group and the predictions of the individual student and the small group

Are the conclusions reached by the large group discussions compatible with your predictions? And with those of the small group?

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.

Simulated experiment n.2

Thought experiment

Consider a rectangular distribution of particles deposited on a layer of stationary particles. What do you imagine happens to the rectangular distribution of particles if, in addition to the force of gravity and the pressure force, we also introduce the interparticle force described above? What shape will the system of particles take?

VIDEO

Analyze the behavior of the simulated liquid for a liquid-liquid interaction value of 3.0.

Prediction of the individual student

Describe how you expect the forces act on a particle of liquid at the surface of the drop and a particle of liquid at the edge of the drop when it reaches equilibrium.

Prediction of the small group

Describe how you expect the forces act on a particle of liquid at the surface of the drop and a particle of liquid at the edge of the drop when it reaches equilibrium.

In the space below, report what you observed at the end of the simulated experiment.

Give an explanation of what you observed in terms of forces by referring to what we discussed earlier.

Observations and conclusions of the large group

After discussing with the large group, report the conclusions.

Comparison between the conclusions of the large group and the predictions of the individual student and the small group

Are the conclusions reached by the large group discussions compatible with your predictions? And with those of the small group?

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.

Simulated experiment n.3

Thought experiment

Consider a distribution of particles in non-equilibrium conditions contained within a tank whose walls are simulated through the introduction of fixed particles. What do you imagine happens to the distribution of particles if, in addition to the force of gravity and the pressure force, we also introduce the interparticle force described above? What shape will the system of particles take?

VIDEO

Reasoning of the individual student

What kind of relationship do you think there should be between liquid-liquid and liquid-solid interaction forces in case you want to simulate a water-like and mercury-like liquid?

Reasoning of the small group

What kind of relationship do you think there should be between liquid-liquid and liquid-solid interaction forces if you want to simulate a water-like and mercury-like liquid?

Discussion of the large group

After the discussion of the large group what kind of relationship do you think there should be between liquid-liquid and liquid-solid interaction forces in case you want to simulate a water-like and mercury-like liquid?

Given the liquid-liquid interaction (= 3.0), analyze the following cases:

a) Solido-liquid interaction = 1.85
b) Solido-liquid interaction = 2.6

Prediction of the individual student

Describe how you expect the forces act on a particle placed on the surface of the liquid, on a particle placed inside the liquid and on a particle placed in contact with the solid, when the system reaches equilibrium, in cases a) and b).

Prediction of the small group

Describe how you expect the forces act on a particle placed on the surface of the liquid, on a particle placed inside the liquid and on a particle placed in contact with the solid, when the system reaches equilibrium, in cases a) and b).

In the space below, report what you observed at the end of the simulated experiment nei casi a) e b).

Give an explanation of what you observed in terms of forces by referring to what we discussed earlier in cases a) and b).

Observations and conclusions of the large group

After discussing with the large group, report the conclusions reached in relation to cases a) and b) below.

Comparison between the conclusions of the large group and the predictions of the individual student and the small group

Are the conclusions reached regarding cases a) and b) through the discussions of the large group compatible with your predictions? And with those of the small group?

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.

<u>Simulated experiment n.4</u>

VIDEO

Reasoning of the individual student

What kind of relationship do you think there should be between the liquid-liquid and liquid-solid interaction forces if you want to simulate the behavior of a solid object resting on the surface of a liquid?

Reasoning of the small group

What kind of relationship do you think there should be between liquid-liquid and liquid-solid interaction forces if you want to simulate the behaviour of a solid object resting on the surface of a liquid?

Discussion of the large group

After discussing with the large group what kind of relationship do you think there should be between the liquid-liquid and liquid-solid interaction forces if you want to simulate the behaviour of a solid object resting on the surface of a liquid?

Given the liquid-liquid interaction (= 3.0), analyse the following cases:

a) Solido-liquid interaction = 1.85
b) Solido-liquid interaction = 2.5
c) Solido-liquid interaction = 0.1

What do you imagine happens to the solid in cases a), b) and c)?

In the space below, report what you observed at the end of the simulated experiment nei casi a), b), c).

Give an explanation of what you observed in terms of forces by referring to what we discussed earlier in cases a), b), c).

Observations and conclusions of the large group

After discussing with the large group, report the conclusions reached in relation to cases a), b), c) below.

Comparison between the conclusions of the large group and the predictions of the individual student and the small group

Are the conclusions reached regarding cases a), b), c) through the discussions of the large group compatible with your predictions? And with those of the small group?

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.

Simulated experiment n.5

VIDEO

Reasoning of the individual student

What kind of relationship do you think there should be between liquid-liquid and liquid-solid interaction forces in case you want to simulate a water-like and mercury-like liquid?

Reasoning of the small group

What kind of relationship do you think there should be between liquid-liquid and liquid-solid interaction forces in case you want to simulate a water-like and mercury-like liquid?

Discussion of the large group

After the discussion of the large group what kind of relationship do you think there should be between liquid-liquid and liquid-solid interaction forces in case you want to simulate a water-like and mercury-like liquid?

Given the liquid-liquid interaction (= 3.0), analyse the following cases:

a) Solid-liquid interaction = 1.85

b) Solid-liquid interaction = 2.7

What do you imagine happens to the liquid in cases a) and b)?

In the space below, report what you observed at the end of the simulated experiment in cases a) and b).

Give an explanation of what you observed in terms of forces by referring to what we discussed earlier in cases a) and b).

Observations and conclusions of the large group

After discussing with the large group, report the conclusions reached in relation to cases a) and b) below.

Comparison between the conclusions of the large group and the predictions of the individual student and the small group

Are the conclusions reached regarding cases a) and b) through the discussions of the large group compatible with your predictions? And with those of the small group?

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.

Analyze the behavior of the simulated liquid for a liquid-liquid interaction value of 0.0.

What do you imagine happens to the liquid?

In the space below, report what you observed at the end of the simulated experiment.

Give an explanation of what you observed in terms of forces by referring to what we discussed earlier.

Observations and conclusions of the large group

After discussing with the large group, report the conclusions.

Comparison between the conclusions of the large group and the predictions of the individual student and the small group

Are the conclusions reached by the large group discussions compatible with your predictions? And with those of the small group?

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 G

Web links to videos:

https://www.youtube.com/watch?v=IjD5e33FnP0

https://www.youtube.com/watch?v=iBvKJyT5Jww

https://www.youtube.com/watch?v=tZrI-5gTv9o

https://www.youtube.com/watch?v=7Who8EpbvCY

https://www.youtube.com/watch?v=pmagWO-kQ0M

https://www.youtube.com/watch?v=5NCOnr3VSAY

Questions on the macroscopic model

Question n. 1

Observation of the individual student

With reference to what was previously discussed, do you think that the resultant force acting on a molecule placed on the surface of the liquid contained inside a tank is equal to the force per unit length that we have called the surface tension of the liquid? Argue your answer.

Observations and conclusions of the large group

After discussing with the large group, report the conclusions below.

Comparison between the observations of the large group and the observations of the single student and the small group

Are the conclusions reached by the large group compatible with your predictions? And with those of the small group?

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.

Question n. 2

Observation of the individual student

Let's consider a liquid in a capillary, in the case where the cohesion forces are greater than the adhesion forces. What shape does the liquid assume at the point of contact with the solid?

Draw the forces acting on the liquid at this point.

Observations and conclusions of the large group

After discussing with the large group, report the conclusions below.

Comparison between the observations of the large group and the observations of the single student and the small group

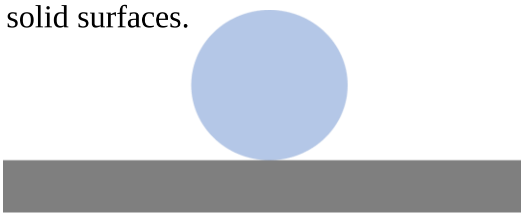
Are the conclusions reached by the large group compatible with your predictions? And with those of the small group?

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.

Question n. 3

Observation of the individual student

The figures schematize two liquids in contact with solid surfaces.



What is the relationship between the adhesion and cohesion forces in the two cases shown in the figure? Draw on the images above reported the forces of adhesion and cohesion.

Observations and conclusions of the large group

After discussing with the large group, report the conclusions below.

Comparison between the observations of the large group and the observations of the single student and the small group

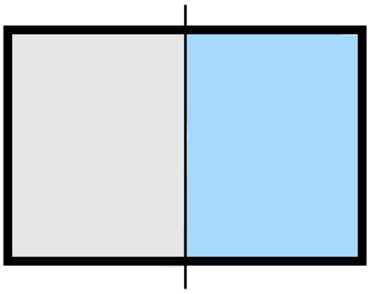
Are the conclusions reached by the large group compatible with your predictions? And with those of the small group?

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.

Question n. 4

Observation of the small group

Let’s consider a rectangular frame divided into two parts by a metal rod placed on the frame and movable on it.



On the sides of the rod there are two films of different liquids.
If the rod moves in a given direction, what can you tell about the surface tension of the two liquids?

Comparison between the observations of the large group and the observations of the single student and the small group

Are the conclusions reached by the large group compatible with your predictions? And with those of the small group?

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.

Question n. 5

Observation of the small group

Let's onsider a soap bubble in the air. Draw the surface tension.

Comparison between the observations of the large group and the observations of the single student and the small group

Are the conclusions reached by the large group compatible with your predictions? And with those of the small group?

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 H

Quantitative experiments

<u>Quantitative experiment n.1</u> (https://www.youtube.com/watch?v=J9Jh6_v72Lk)

You have the following material at your disposal:

- tray
- aluminum ring
- becker
- waterfall
- digital laboratory balance
- table with adjustable height
- mobile phone
- caliber

Question 1

Which quantities do you think it is necessary to measure to determine the surface tension of water with this method?

Below you will find a description of an experiment you can perform to determine the surface tension of a liquid.

Suggested experiment steps

1. Fill the tank 2/3 full with water
2. Gently place the tray filled with water on the adjustable table
3. Make sure the scale is level (on the plane)
4. Measure the diameter of the ring with the caliper and report the value ________________
5. Hang the metal ring to the scale
6. Raise the adjustable stage until the ring is fully submerged. The ring should not touch the bottom of the tank

7. Start a video recording of the balance display. Slowly lower the adjustable stage until the ring comes out of the water. End video recording
8. Determine the maximum force value recorded and report it ________________

Now carry out the experiment following the steps above.

Describe what you observed in steps 7. and 8. of the proposed description.

Try to provide an explanation of what you observed.

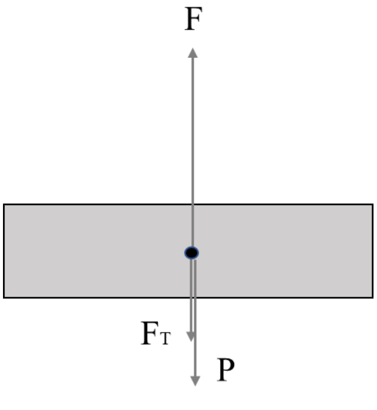
How would you use the measured quantities to determine the surface tension of water?

Small group discussion

The following diagram represents the forces acting on the ring at the moment of detachment.

Write the relationship between these forces at the equilibrium.

____



The force F_T can be written as $F_T = \gamma 4\pi R$, where γ is the surface tension of the water and R is the radius of the ring. The maximum force measured with the scale is in modulus equal to F, P is the weight of the ring.

The relation you wrote above should look like this:

$$F - \gamma 4\pi R - P = 0$$

Compare this relation with the one you wrote earlier.

Determine from the relation the value of the surface tension of the water γ, specifying whether the value obtained is compatible with the results reported in the literature (do a search on the web).

If the surface tension value obtained for water is not compatible with the value reported in the literature, what could be the reason for this result?

Large group discussion

Are the results obtained by the small group comparable with those obtained during the large group discussion? If they are not, do you understand what causes the difference between the results?

Quantitative experiment n.2

You have the following material at your disposal:

- tray
- dropper pipette
- Becker
- water
- digital laboratory balance
- Petri dish lid
- caliber

Question 1

Which quantities do you think it is necessary to measure to determine the surface tension of water with this method?

Below you will find a description of an experiment you can perform to determine the surface tension of a liquid.

Suggested experiment steps

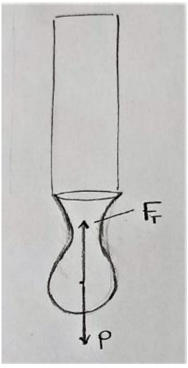
1. Measure the diameter of the "beak" of the dropper pipette and write the value below
   ____
2. Drop 20-30 drops of liquid onto the lid of the Petri dish placed on the balance
   Record the mass M of the drops deposited on the Petri dish lid and the corresponding number of drops N
   M = ____ N = ____, M = ____ N = ____, M = ____ N = ____
3. Calcolare la massa media di una goccia $m_p = M_p$/N = ____, $m_p = M_p$/N = ____, $m_p = M_p$/N = ____
4. Repeat the previous three steps three/four times

Now carry out the experiment following the steps above.

How would you use the measured quantities to determine the surface tension of water?

Small group discussion

The following diagram represents the forces acting on the neck of the droplet at the moment of detachment.



Write the relationship between these forces at the equilibrium.

The relationship you should have written earlier is the following:

$F_T - P = 0$

F_T can be written as $2\pi r\gamma_p$, where r represents the radius of the pipette's "beak", g is the gravity acceleration, and m_p is the average mass of a drop of water.

Thus.

$$2\pi r\gamma_p = m_p g$$

Determine from the relation the value of the surface tension of the water γ, specifying whether the value obtained is compatible with the results reported in the literature (do a search on the web).

If the surface tension value obtained for water is not compatible with the value reported in the literature, what could be the reason for this result?

Large group discussion

Are the results obtained by the small group comparable with those obtained during the large group discussion? If they are not, do you understand what causes the difference between the results?

Appendix I

Some data examples (Group A – Q1)

Imagine to dip a small portion of a cookie in a cup of milk. What happens to the liquid? What do you think happens to the cookie? Explain what you observed previously.

Student 1: *"What is observed happens thanks to the frictional forces between the particles. In addition, the biscuit gets soaked thanks to the adhesion forces between the milk and the biscuit material. The liquid rises through the pores of the biscuit, so thanks to the properties of the material of which it is made"*

Let's imagine to fix a grid on the top of a glass. We gently put some water into the glass through the grid, then we put a cardboard on the grid in order to plug the glass. After turning the glass upside down and removing the cardboard, the water does not fall. Why?

Student 4:*"Because the water has been distributed evenly among the empty spaces of the tulle and thanks to the forces of cohesion but above all of adhesion of the water to the parts of the tulle, the water will not fall. This behavior is also due to the very small pore size of the tulle material."*

Why, if we put some oil in a pan, there is no formation of drops as it happens in the case of water? How does the oil behave? Explain.

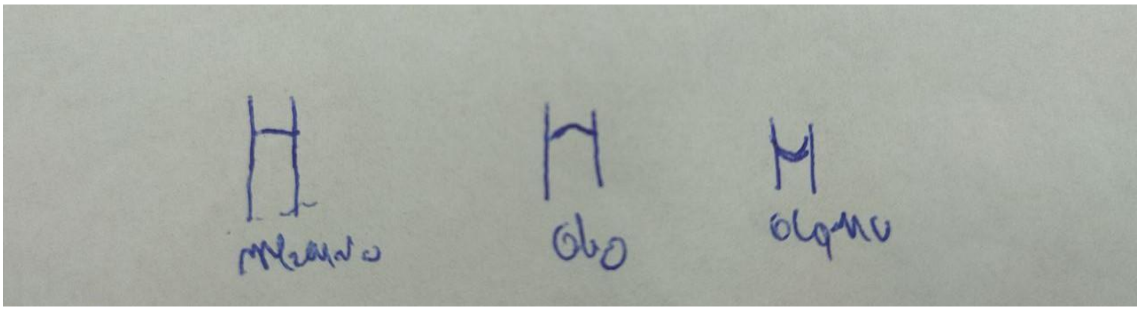
Student 5:*"The behavior of oil on a nonstick pan will be different from that of water due to the surface tension of the liquid. The oil has more cohesive particles. The cohesion forces between the oil particles and the adhesion forces between the oil particles and those of the solid surface are different from those that would exist for water."*

Some data examples (Group A – Q2)

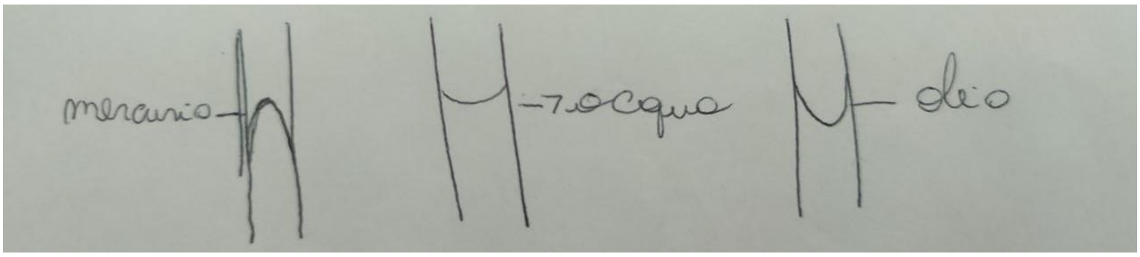
The number of water droplets required to completely cover the surface of a coin is greater than the number of seed oil droplets required to cover the surface of a coin identical to the first one. Explain what this phenomenon might be related to.

Student 4:*"It could depend on the nature of the two substances. One is polar, the other is apolar. In addition, the adhesion forces between oil and money are greater than those between water and money, so less oil is required to cover it."*

Consider three capillary tubes of the same material and of the same diameter each dipped in three tanks containing water, mercury and oil, respectively. Represent how each liquid will be arranged inside the capillary tubes graphically. Explain in terms of forces.



Student 7:*"Water having more intense adhesion forces with the material than other liquids will have this shape. Mercury, on the other hand, will have more intense cohesion forces than those of adhesion compared to other liquids, so it will have the shape in the figure. The oil has adhesion forces and cohesion with values intermediate between water and mercury and will have this shape."*



Student 6:*"Due to the forces of cohesion and adhesion, the behaviours of liquids change. In the case of mercury, the adhesion forces are lower than in the case of cohesion. In the case of water they are more or less equal to each other. In the case of oil, those of adhesion are greater than those of cohesion."*

If you put some soap into water and deposit a drop of this mixture on a horizontal plane, you will notice that the water is evenly distributed on the surface not forming a real drop. Explain this phenomenon.

Student 9:*"I believe that soap breaks and/or modifies the bonds among water particles and consequently its cohesion forces. If the cohesion forces change, the behavior of the water changes."*

Some data examples (Group B - Q1)

Imagine to dip a small portion of a cookie in a cup of milk. What happens to the liquid? What do you think happens to the cookie? Explain what you observed previously.

Student 19:*"The liquid level increases in the biscuit thanks to the action of the intermolecular forces acting in the liquid. The liquid rises through the biscuit as it happens inside a capillary tube"*

Why is it preferable to add soap to the water to wash our clothes?

Student 20:*"Because soap weakens the interactions between water molecules and dirt molecules."*

Let's imagine to fix a grid on the top of a glass. We gently put some water into the glass through the grid, then we put a cardboard on the grid in order to plug the glass. After turning the glass upside down and removing the cardboard, the water does not fall. Why?

Student 21:*"It does not fall thanks to the interactions that are created between the liquid molecules within the various portions of liquid in the tulle. This behavior is also due to the interactions between liquid molecules and tulle molecules."*

Some data examples (Group B – Q2)

The liquid inside a glass capillary tube has a concave meniscus (see the figure). Why? Explain in terms of forces.

Student 20:*"Because the liquid tends to adhere to the walls of the tube: the forces of adhesion to the material of the walls are greater than those of bond between the molecules of the liquid itself."*

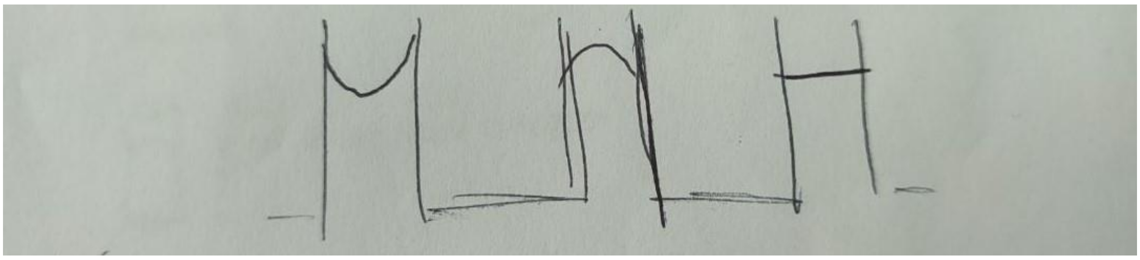
A liquid does not wet the glass it is in contact with. Why? Explain in terms of forces.

Student 23:*"Because it does not create bonds with the glass but the forces of the surface on the liquid are directed towards the molecules of the underlying liquid, as if there were a membrane separating the liquid from the glass (surface tension)"*

The number of water droplets required to completely cover the surface of a coin is greater than the number of seed oil droplets required to cover the surface of a coin identical to the first one. Explain what this phenomenon might be related to.

Student 26:*"This happens because the molecules composing the water droplets have stronger intermolecular bonds than there are between the oil molecules. In the case of water, the drops are more compact and occupy a smaller area of coin."*

Consider three capillary tubes of the same material and of the same diameter each dipped in three tanks containing water, mercury and oil, respectively. Represent how each liquid will be arranged inside the capillary tubes graphically. Explain in terms of forces.



Student 27:*"Water tends to adhere to walls. In mercury, on the other hand, the molecules of the surface take on a convex shape because they are attracted to the underlying molecules, so they exert a force inward, not towards the walls. In oil, on the other hand, the forces take on the same value."*

If you put some soap into water and deposit a drop of this mixture on a horizontal plane, you will notice that the water is evenly distributed on the surface not forming a real drop. Explain this phenomenon.

Student 28:*"Because by adding soap the water loses some of its properties by losing the surface tension the liquid no longer tends to take the shape of a drop and therefore to remain compact assuming the least possible shape."*

Appendix L

Some data examples

Student 16: *"The insect floats. Thanks to its small weight it does not break the bonds of the water. Paws distribute weight equally on the water surface. The insect skates because there is no friction. Each pair of legs has its own role."*

Student 32: *"The insect moves and floats thanks to surface tension. It skates and glides nimbly. It stands on the water surface thanks to its long legs which occupy a large surface and break the bonds of the water. The friction allows the insect to push itself on the water surface."*

Student 33: *"At the beginning we tried to put the clip, without changing its shape, and the needle on the water surface and we noticed how much easier it is do it, with the help of the absorbent paper. We verified that both objects stand on the surface of the liquid. On the other hand, the clip with an irregular shape does not stand on top of the membrane formed by the water on its surface. We have also seen how the clip behaves as if it were placed on an elastic membrane since the walls of the water around the clip are slightly concave, i.e., slightly raised with respect to the plane of the clip. It is as if the clip sinks inside this liquid membrane."*

Student 2: *"We have confirmed that the physical phenomenon of interest is not buoyancy but surface tension. When we gave the clip an irregular shape, in particular a wavy shape and we managed to make it float, we noticed that in the points where the clip was higher respect to the water surface, there was this membrane which was the surface tension of the water that bent and followed the shape of the paper clip. So, effectively the clip did not float because it did not enter the water. The surface of the water, thanks to the cohesive forces, followed the shape of the clip."*

Student 23: *"Through the simulation we have seen that the water drop, initially square in shape, was becoming less and less extensive over time. This confirms what we had assumed, which is that it would assume just this circular shape with all the points of the circumference equidistant from its centre."*

Student 27: *"We have seen that as soon as the forces acting among the particles are introduced in the simulation, since these are of equal intensity for each particle, the particles* *tend to approach each other and arrange themselves in positions more or less equidistant from each other and we say that the geometric shape which allows this particles configuration is the spherical one. Then, we also noticed that by increasing the forces, i.e., the intensity of the forces, the drop reaches the spherical shape much faster."*

Student 35: Response from another student: *"We disagree that over time, as the drop becomes more spherical, the distance between the particles decreased."*

Student 24: Answer from another student: *"If the inter-particle distance decreases as they say, we would arrive at an impossible situation in which the particles overlap each other, and this is not physically possible."*

Student 30: *"The two interaction forces act differently. The greater the difference between liquid-liquid interaction and liquid-solid interaction, the more spherical the drop will be, and therefore the liquid would be of the mercury type. The smaller the difference between liquid-liquid interaction and liquid-solid interaction, the more the drop will be more crushed, and therefore the liquid will be of water type. Furthermore, to confirm the differences in behaviour between the two liquids, we looked for videos on YouTube that showed the behaviour of different liquids. We have seen that mercury, placed in a small diameter tube, has a convex meniscus while water has a concave meniscus, therefore the two liquids behave differently on the surface. By doing the simulations we have also seen that if the liquid-liquid interaction were zero, the drop would not form, the liquid particles would no longer be linked to each other and would wander without interacting with each other. If, on the other hand, the liquid-solid interaction was zero, the drop would be perfectly spherical."*

Student 19: *"We observed the same liquid* behaviours observed by the other group. *Furthermore, we were curious to understand what happened by increasing the simulation time. So, we saw what happened running the simulation for 1, 2 and 3 seconds and we noticed that between 2 and 3 seconds nothing changed. Furthermore, when we analysed the case with liquid-liquid interaction equal to zero, we too saw that the liquid drop did not form. We also tried changing the liquid-solid interaction to see if it changed anything, but nothing changed."*

Student 27: *"This project was interesting and helped me a lot in school lessons. In particular, I realized that now I feel much more confident in addressing science subjects. For example, I tried to reproduce some simple physics experiments during the interviews by* *using materials I had at home, following the example of what we had done during the project."*

Student 13: *"This course gave me the idea of the university method and I think it is very useful for my future. I think I found it difficult to carry out the experiments without some theoretical basis because at school we are used to study a given subject in theory and only then do the experiment. At school we carry out experiments rarely."*

Student 7: *"Participating in these activities was interesting and stimulating and even if I encountered some difficulties in improvising and implementing the experiments without theoretical basis, since at school we are not used to doing experiments but only theory*."

Student 19: "*My attitude towards scientific disciplines has always been positive. But let's say that now I feel more confident of being able to understand even more difficult topics if I work hard to study and analyse them better, if I talk about them with others and look at them from various perspectives, such as that of experiment or simulation and not just that of mathematical calculation.*"

Student 18: "*Now I'm also starting to like subjects that I used to find trickier, like Physics. The attitude towards scientific subjects depends a lot on how we deal with them. For example, I used to have an approach that made me believe that if I didn't understand something right away, then I didn't want to waste time figuring it out. Moreover, I convinced myself that I didn't care. Now I see that that approach was wrong. Now I think that with commitment, talking to other classmates or doing different experiments, even a complicated topic, not necessarily physics, can be understood and turns out to be interesting.*"

Student 24: *"Working in a group dividing tasks and collaborating to find an explanation for the phenomena studied was very useful, as it allowed me to acquire a method that can also be applied to school subjects. Furthermore, the experimental part, besides being interesting, was very useful for achieve a better understanding of phenomena studied theoretically."*

Student 6: "*Traditional lectures are more comfortable than innovative lectures, but if you want to understand really the studied topics, an experiment/simulation-based approach is definitely better and more effective.*"

Student 30: "*Looking only at the formulas on the blackboard or at the textbooks, who thinks he/she is not good at Math, just cannot change his/her mind. However, activities such that* *experimented during the course, can help psychologically to increase one's self-esteem and to open one's mind.*"

Student 21: *"We do not share the results obtained by you. We may believe you, but we think it is strange that you observe this thing. Could you repeat the experiment in front of us so we can reason together on the experimental evidence?"*

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