Interaction in the classroom based on typologies of experiments and mathematization in physics teaching

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Changing the traditional approach to experimentation in science teaching poses a significant challenge. This research discusses the characterization of physics experiments, not solely based on the topics they cover, or the materials used in their setups, but rather in terms of the opportunities they offer to enhance classroom interaction and, consequently, contribute to the development of scientific thinking skills. This study is an action-research intervention in the classroom, involving four groups of undergraduate physics students from a public university in Bogotá, Colombia. This process allowed us to categorize experiment typologies, including discrepant, homemade, illustrative, research-based, recreational, crucial, mental, and virtual experiments. The most relevant data were derived from students' productions and researchers' reports after each class. Through content analysis techniques, we were able to categorize the information and derive insights into the richness that each experiment typology brings to classroom interactions. The results reveal shifts in the perception of the role of new teachers, who are no longer seen as mere possessors and transmitters of truth. They now comprehend strategies for effectively engaging students as the class progresses, fostering the exchange of ideas, reflections, debates, and questions among students themselves, their peers, and the teacher.

Keywords: Physics teacher training; non-traditional experimentation; contextualized education; didactics of physics.

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1. Introduction

Training Physics teacher programs often exhibit shortcomings in preparing teachers for effective classroom interaction. It is a common misconception to assume that a deep mastery of Physics content automatically equips teachers to excel in their instructional role, because the reality is more intricate. Teachers must establish criteria to make professional decisions on various fronts, such as: how to explain and argue a topic in class, gauge its level of complexity, ensure contextualization, employ appropriate language, cultivate positive attitudes, and create conducive educational environments within the classroom, among other aspects. Each of these elements necessitates a specific and dedicated learning process.

Previous research around the world has explored the potential of using experimentation in various ways. Otero, Pollock, and Finkelstein [1] presented several strategies to inspire young people to pursue physics teaching as a profession, and one of these strategies involved the facilitation of non-traditional experimental approaches. Furthermore, in the reference [2], alternative methods of experimentation using simple and attractive materials were devised to encourage students' participation in discussions and at the same time foster their analytical, critical, and argumentative skills. Along the same lines, the article [3] suggests specific approaches to address various concepts in physics, delves into the demarcation between explanations rooted in common sense and those constructed through scientific principles. This approach requires students to use their creativity, imagination, and organizational skills to improve their reasoning skills.

Working by characterizing typologies of experimentation puts the subject at the center of the learning and teaching process. It does not mean focusing on designing or developing experimental assemblies that are striking or motivating but focusing on studying the possibilities that this experience offers for educating the teacher in new roles. In the same view, students modify their ways to participate in the class, and consequently, the treatments of scientific content and the discourses circulating in the classroom also will be different. Related previous considerations of these issues were published in the Refs. [4-7].

2. Research metodology

This qualitative research is focused on exploring the impacts of a methodological approach centered around experimentation typologies. The study delves into various strategies for training pre-service physics teachers with the goal of improving their grasp of alternative methods for teaching and learning physics, engaging students in a deep way. This research is conducted within the context of action research, from the perspective of Latorre [8], who emphasizes the classroom as a space for reflection and employs this method as a valuable tool for professional development. Brown [9] and Collins [10] discuss interventions in the classroom focused on creation for research purposes, especially in educational contexts.

The theoretical basis for this strategy is based on previous work by Castiblanco [11], which combines a doctoral thesis research with more than a decade of teaching experiences in preparing pre-service teachers for physics didactics, seen through a dimensional lens, in the disciplinary, sociocultural, and interactional. The approach to structure the development of the experiments comprises three moments in the class or set of classes. Initially, students learn to characterize the phenomenology under study. They then hone their skills in observing physical systems. Finally, they cultivate the ability to articulate their understanding through various forms of language to solidify an explanatory model, all around diverse experimental activities.

This work presents a synthesis of the results obtained from three work cycles centered around the same research question. The first cycle, conducted during the first semester of 2018, involved 20 students enrolled in the course "Didactics of Physics III." The second cycle included 25 students who participated in the "Introduction to Didactics of Physics" during the second semester of 2018. Finally, the third cycle was carried out with 25 students from the course "Didactics of Physics III" during the second semester of 2019. All these courses are part of an undergraduate teacher training program.

The primary objective was to raise awareness among pre-service teachers regarding the various experimentation experiences within the classroom and shift their perspectives on the mathematization process in a physics class. To achieve this, we guided them in reflecting on three key aspects:

1. Specificities of Experimental Setups.

   What unique characteristics are demanded by the experimental setups in each scenario?

2. Strengthening Scientific Thinking Skills.

   How does each typology contribute to the development of scientific thinking skills? and

3. Characterization of Teacher and Student Roles.

   How can we characterize the roles of both the teacher and the student in these contexts?

Data emerged concurrently with the development of the experimental activities. This implies that the researchers assumed the role of teachers and actively intervened throughout the process by facilitating activities explicitly designed to encourage engagement. Data analysis sought to uncover the levels of knowledge construction related to various non-traditional approaches to teaching physics through mathematization processes. It also aimed to provide evidence supporting a potential characterization of each experimentation typology.

The following codes are used to represent specific data in the presentation of the results. The letter G corresponds to a group of participants, with each group differentiated by a subsequent number. For instance, if three groups participated in an activity, we would use codes like $G1$, $G2$, and $G3$. The second number in the code signifies the cycle. Thus, we have codes like $G11, G21$, and $G31$, indicating the first, second, and third cycles, respectively. When presenting a textual sentence from a participant, it is denoted by the letter E, while the involvement of teachers is indicated by P.

3. Theoretical framework

3.1. Thinking the education of teachers from didactics of physics

According to the Refs. [1-3,12,13], there is a need to educate pre-service teachers to analyze aspects such as the construction of new languages for explanations, the meaning of "observing" a physics phenomenon, the importance of an in-depth analysis of the History, Philosophy, and Epistemology of Science to overcome naive visions and the real possibility of gaining autonomy for re-construction of his scientific knowledge.

When we learn to engage with physics independently, we gain awareness of our level of comprehension. We delve as profoundly as possible into our queries, striving for coherence and consistency. We draw upon knowledge from various domains to gain insights into our thought processes. We also become cognizant of our language usage, eliminating epistemological barriers, and constructing our unique perspective on the significance of science and the practice of scientific inquiry.

Delving into the sociocultural dimension of Didactics of Physics, proposes numerous considerations about the unique classroom challenges associated with teaching and learning physics. It drives us to explore strategies to adapt solutions to the specific educational context. Future teachers must recognize the importance of interweaving diverse knowledge of the social and human sciences. That process allows us to create a classroom environment that fosters the personal growth of all participants, transcending the simplistic notion that future teachers can only acquire the art of teaching through repetitive practical experience. To move on to an idea of the growth of the teaching professional from the construction of specific knowledge for the social and cultural context in which the teacher operates.

Addressing the interactional dimension implies providing teachers with the ability to perceive the classroom as a system or a complex network of interests. Consider, for example, situations in which students show a lack of motivation, indiscipline, disinterest, or other behavioral challenges, to which, in many cases, teachers are not sure how to respond, often assuming that these issues are not related to the subject they are teaching. These misconceptions can lead to feelings of insecurity. As a result, teachers may resort to ineffective approaches, such as trying to entertain students or resorting to punitive measures.

Hence, the importance of reflecting on classroom interaction as a differentiated field of knowledge, in which teachers must learn criteria to give meaning to the use of support resources to develop a genuine process of mathematization of physics in the classroom.

This perspective allows educators to discern the true potential of technology, literature, and laboratory resources to improve the dynamics of interaction within the classroom and ensure communicative action. When individuals participate in the collaborative construction of knowledge through interaction, they place great importance on teamwork. They strive to express themselves openly and construct coherent arguments to address challenges collectively. In addition, this process encourages the acquisition of important life skills, such as the ability to participate in debates with tolerance and the development of intellectual autonomy.

3.2. Typologies of experimentation to educate teacher skills

The transformation of a teacher's approach hinges on the establishment of new criteria to comprehend their teaching activity. It is impractical to explore fresh perspectives if they adhere to conventional notions regarding teaching and learning processes. For instance, experimentation just as an instrumental process impedes progress because the focus is on studying absolute truths instead of fostering the development of students' critical thinking.

At present, a community of researchers, as evidenced by the publications [14,15], is dedicated to exploring new facets of experimentation. Their investigations extend the use of the lab beyond the mere validation of theoretical models or the demonstration of scientific laws. They encompass the development of observation and research. For instance, Araujo and Abib [16] presents an array of innovative experimentation possibilities. Their objectives span from analyzing physics laws through the design of experimental setups, studying everyday situations, and explorations within virtual environments, to endeavors aimed at accentuating reflective processes concerning physics phenomena through the reformulation of students' explanatory models.

The thesis defended in this work affirms that it is feasible to classify experiments into typologies based on the potential they offer to promote various thinking skills. Consequently, when teachers master the recognition of these typologies of experiments, they can improve their ability to organize new teaching methodologies through alternative interaction dynamics for the class.

4. Results

4.1. Characterization of experiment typologies

It is possible to delineate the distinguishing features that set one type of experimentation apart from another, contingent upon the potential they offer to cultivate scientific thinking. It's important to clarify that we are not referring to the experiments themselves but rather to various methodologies for incorporating experimentation within the classroom. Additionally, through the characterization of each typology, we have initiated a process of mathematization of physics within the teaching process. This concept signifies the culmination of previous research undertaken by our research group, as elaborated in the publications [17,18]. Table I provides a synthesis of this characterization, where the first column designates the typology's name along with its primary objectives in class, and the second one clarifies the roles of both the teacher and students, while also highlighting the key aspects to be considered when evaluating the process.

4.2. The phases of mathematization physics for teaching

4.2.1. The phenomenological approach

It involves guiding students to become aware of the existence of natural phenomena, moving beyond the mere act of in-

TABLE I. Synthesis of characterisation of experiment typologies based on their potential to enrich interaction process in the classroom [6].

Type of experiment	Aplication criteria
Illustrative. Phenomenological analysis, stimulus to doubt.	The professor's role involves describing and explaining a physics phenomenon, fostering doubt in the student's mind, providing resources for testing scientific discourse, stimulating imagination, and enhancing scientific language. In turn, the student is encouraged to question ideas and explanations, modify conditions of occurrence, engage in interdisciplinary thinking, and collaborate effectively within a team. Evaluation in this context focuses on assessing the capacity for doubt, creativity, procedure design, and decision-making skills.
Mental. Representations of language, debate, tolerance.	The teacher's role encompasses contextualizing the thought experiment, providing instruction to students in various forms of representation (pictorial, graphic, algorithmic, literary, experimental, conceptual, etc.), and ensuring the coherence of the language used to describe and explain paradoxes or dilemmas arising from the experiment. Students are motivated to create their own interpretation of the experiment using a variety of representations, to engage in socialization, and to articulate their own discourse about it. The evaluation process centers on assessing the collective construction of knowledge and the enhancement of both scientific and interactive language skills for effective communication of ideas and consensus-building.

By Research. Formulation of questions, construction of answers and socialization.	The teacher assumes a guiding role in a process that transitions from individual to collective reflection, prompting students to articulate their own concerns regarding a physics topic. This involves grouping students based on shared interests and offering guidance in formulating a research question that is coherent to them and amenable to experimental study within the available conditions. Meanwhile, the student takes on the responsibility of tackling a research question, devising procedures, conducting research for information and resources, participating in debates, analyzing findings, drawing, and socializing conclusions. In the evaluation process, the emphasis is placed on assessing the internal coherence of the proposed process, the generation of new knowledge, and reflection on the practice of scientific inquiry.
Home. Teamwork, creativity, analysis.	The teacher takes on the role of designing, demonstrating, and explaining a setup constructed by themself, addressing any inquiries from students regarding its operation, and presenting a challenge to be resolved based on teamwork. The student's task is to successfully navigate the assembly in accordance with the challenge. This involves documenting the decision-making process in a log, which should include the identification of dependent and independent variables, assumed parameters, and universal constants affecting the system. This record aids in developing decision-making criteria and effectively conveying the results. In the evaluation process, the emphasis is placed on assessing the processes of argumentation, formulation of decision-making criteria, and, notably, teamwork.
Discrepant. Conceptual imbalance, questioning of common sense.	The teacher arranges experiments designed to challenge existing notions, solicits hypotheses about anticipated outcomes, fosters metacognition, and facilitates guided discussions. In response, students are tasked with formulating hypotheses, developing explanatory models, subjecting the experimental setup to testing, engaging in debates, presenting arguments, and reaching consensus. Evaluation in this context centers on assessing students' capacity for description (what they observe), explanation (why observed phenomena occur), argumentation (why a particular model is superior to others), and their ability for reflection and in-depth analysis.
Virtual. Modeling of phenomena. Identification of epistemological obstacles.	The teacher engages in the analysis of the explanatory model, questions its relevance, and provides suggestions for its enhancement in terms of both use and design. The student, on the other hand, is responsible for producing analogies, fostering creativity, and overcoming epistemological obstacles. In the evaluation process, the focus is on observing critical and reflexive analysis, the construction of analogies, and the demonstration of creativity.
Crucial. The non-linearity and the non-bias of science. An alternative way to talk about the physics history.	The teacher recreates a crucial experiment using a variety of explanatory resources (model, assemble, simulator, reading, video, etc.), inciting reflection on the diverse social, political, cultural, and scientific contexts in which these experiments originally took place. Then, provides a list of crucial experiments, each with its description, and assigns groups to select and recreate an experiment from the list, with the option to follow the teacher's lead or go further. The teacher actively supports and guides each group during their preparation. Subsequently, a socialization phase occurs and a timeline is built to integrate these concepts and discuss the non-linearity and non-bias of science. The evaluation process mainly assesses the capacity for reflective criticism, participation in debates and the ability to construct explanations and arguments about historical events.
Recreational. It amuses, stimulates the question, and enriches the language.	The teacher presents the class with a series of experiments with unique configurations that are attractive and provoke questions. Next, the teacher guides the process of formulating questions and answers about the experiment. Afterward, he/she organizes groups of students to prepare and present one experiment at a recreational fair, where they must explain the phenomenon in less than 5 minutes. This approach helps students learn to ask specific questions, provide quick and concise answers, interact effectively with their peers, and seek information and resources to improve their discourse. The evaluation focuses on assessing the empowerment of students, their deepening of the topic, the level of interaction with their peers, and the development of their scientific language.

informing them about the phenomenon's existence. In this phase, the approach is to design activities that align with students' thought processes and their capacity to conceptualize the world. These activities are crafted to stimulate reflection, observation, the challenge to common sense, exploration of the relationship between sensory experiences and our mental constructs, and the need for precise language to establish consensus regarding observed phenomena, among other considerations.

This phase should culminate in a qualitative and quantitative analysis of diverse methods for demonstrating the occurrence of natural phenomena. Such analysis facilitates the identification of relevant variables and the development of a coherent description of the phenomenon for the student's comprehension.

4.2.2. The observation of a physical system

This phase fosters the development of skills that enable differentiation between the "observer," the "observed," and the "observable." The first pertains to the qualities of an individual intentionally studying something while acknowledging its limitations and potential. The second relates to the organization of a system under study, including the identification of dependent and independent variables, parameters, constants, the range of values, and real versus ideal conditions of occurrence. The third concerns the establishment of shared definitions constructed through consensus and communicated within a community, thereby collectively shaping their meaning and coherence. This ensures that everyone is referring to the same phenomenon.

Additionally, this phase stimulates the formulation of hypotheses, the planning of processes to compare, validate or disprove different explanations, and the ability to structure ideas for describing both the observed and the observables.

4.2.3. The phenomenon modelling

In this phase, the misconception that the mathematical model alone provides a complete explanation of the physical phenomenon is addressed. Instead, the focus is on guiding the students through the process of constructing explanatory models. The activities chosen should facilitate the synthesis of information gathered in the preceding phases, utilizing various forms of scientific language representation, such as graphs, drawings, diagrams, tables, definitions, equations, experimentations, considerations of occurrence, and limitations in explanations related to the studied phenomenon. These activities should encourage students to explore diverse methods of organizing information, fostering a sense of active participation in the construction of scientific knowledge.

4.3. Examples of activities developed in each type of experimentation, in the case of physics teacher training

4.3.1. Home experiment

4.3.1.1 General characteristics

This setup is presented by the teacher in a detailed manner and is designed to challenge students immediately. It should be created using low-cost and readily available materials. Furthermore, it should be easily modifiable, and any damage or alterations should not be a cause for concern. Instead, such modifications should encourage students' creativity. This setup should allow students to interact with the materials, make changes to test their hypotheses, and enhance various aspects, such as aesthetics, scientific relevance, or practicality. Additionally, it stimulates teamwork.

The teacher preassembles the experiment in advance and introduces it to the students at the beginning of the class. After, explains the assembly process, how it works, and what physics principles apply. Additionally, provides enough materials for students, organized into groups, to replicate the experiment. But students are challenged to go beyond the teacher's model in certain aspects. Most importantly, they are required to document their decision-making process during the construction, including identifying the system's components, operating conditions, variables, parameters, and constants. Towards the end of the session, each group must present their creations, leading to comparisons and debates among the students.

4.3.1.2 Contribution to a process of mathematization of physics

This way of experimentation can be particularly valuable for the phase of systematic observation of a physical system. It involves refining language and identifying the interdependence of variables. It promotes collective decision-making and helps students recognize both achievements and challenges as they work towards finding answers.

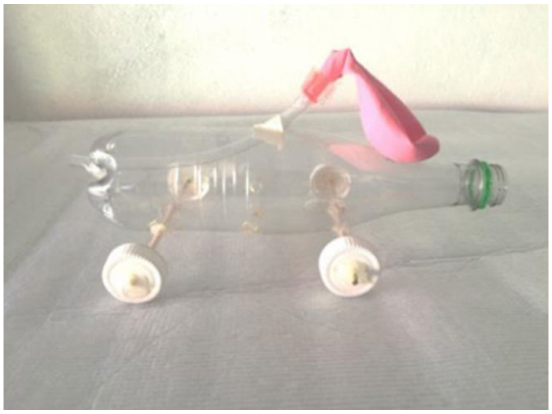

FIGURE 1. Air-powered car made by the teacher and presented to the students [6].

4.3.1.3 Example of developed experiment: Air powered car

The operation involves inflating the pump using the attached hose, sealing it, placing the car on the ground, and then unsealing the hose to release air, resulting in the car's movement. This phenomenon is explained by the principle of action and reaction, a concept from classical mechanics. According to this theory, every action (a force in one direction) is accompanied by an equal-magnitude reaction (force) in the opposite direction. In this scenario, the release of air from the pump initiates the action, leading to a reaction that propels the car in the opposite direction.

The challenge was to create a car that could outperform the teacher's model in terms of the distance it could travel. Various materials were made available, including bottles identical to those used in the teacher's model, as well as bottles of different sizes, plastic boxes, hoses of varying diameters, playdough, lids of different sizes, scales, paper, rubber pumps of various sizes, and any other materials requested by the students. Specific time slots were allocated for analyzing each component of the system.

Various interpretations and strategies surfaced within the groups. Some believed that reducing friction was the key, while others aimed to enhance speed by experimenting with larger wheels or smaller bottles. Some sought to increase power by using additional pumps, and some combined multiple approaches. In all instances, lively debates revolved around the applied physical principles and the organization of the physical system since the precise factors affecting speed were not entirely clear. Notably, one group encountered difficulties in making their car move forward, leading to a sense of concern. Below are reflections from Group $G1$ of the second cycle and Group $G2$ of the third cycle.

> G_{12}: *(...) In our quest to make it move faster than the model, we contemplated the idea of using wheels of different sizes for the front and rear axles. Additionally, we thought that using two hoses for propulsion instead of one might boost its speed (...) Initially, these two hoses were directed downward, under the assumption that air pushing against the ground would provide greater propulsion. However, we soon realized that the source of propulsion was the air itself, rather than the ground. Consequently, we reoriented the hoses horizontally. Another issue arose when the two pumps toppled over on the ground, impeding movement due to friction. To address this, we added extra support. We also opted for the smallest bottle, believing that reduced weight would translate to increased speed. The guiding physics principle is the action-reaction law, although it does give rise to some doubts. Specifically, we contemplated whether it might be connected to the Bernoulli principle operating inside the hoses due to the air flow. Furthermore, we pondered the mystery of how lunar modules manage to move in a vacuum, devoid of any air, whereas there is an abundance of air here...*

> G_{23}: *Our car has a two-story design, as we aimed to incorporate two chambers. Our initial challenge involved deciding whether to join or separate the two hoses. Ultimately, we opted for a T-shaped connection to link the two systems. However, this choice proved ineffective, as the T-piece caused some obstruction in the hose, reducing the air's outflow pressure. Consequently, the air emerged with less force. We subsequently separated the hoses and installed a pump for each one. Key parameters we considered included the bottle's shape and the identical wheel radius. In this context, the independent variable was the quantity of air supplied, while the dependent variable was the distance the car traveled.*

4.3.2. Illustrative experiment

4.3.2.1 General characteristics

This approach involves the teacher presenting a natural phenomenon, and then, demonstrating it through an experiment. During the presentation, the teacher engages in a dialogue with the students, ensuring that everyone gains a thorough understanding of the experiment's operation. Following this, students are challenged to explore alternative methods for illustrating the same phenomenon, using the same setup but introducing variations or additional elements not initially used by the teacher. Assembles that are best suited for this approach are those providing immediate and visible demonstrations of the phenomenon without requiring lengthy setup processes. This process allows them to test their hypotheses based on comprehension of the phenomenon. Following the teacher explanation, students can share their new proposals for illustrating the phenomenon, fostering opportunities for reflection and debate regarding different explanations of the same occurrence.

4.3.2.2 Contribution to a process of mathematization of physics

This approach is well-suited for the development of the phenomenological approach phase because it allows the quick engagement of students with the phenomenon, drawing from their prior experiences. It encourages a conducive environment for dialogue, the generation of questions for deeper understanding, and the collective construction of knowledge about what truly occurs, often extending beyond common sense explanations.

4.3.2.3 Example of developed experiment: the alcohol thermometer

It is a sealed glass droplet with two bubbles connected by an internal glass filament. Inside it contains a small amount of alcohol with dye, which is quite sensitive to heat, so when you touch the bottom of the glass bubble with your hands,

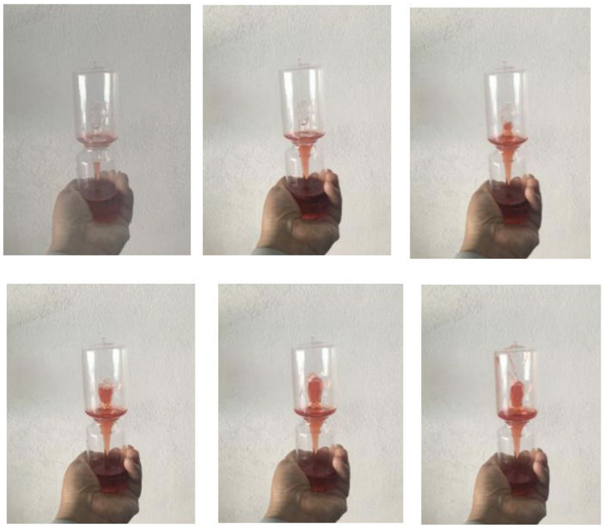

FIGURE 2. Sequence of operation of the alcohol thermometer [6].

the substance rises through the filament to the bubble located at the top.

The challenge was to manipulate the same assembly in other ways to show the physics principle more evident, which in this experiment, is the principle of thermal expansion. The students must describe what they observed when touching the bubble with their hands. Afterward, to explain why these differences occurred, students engaged in building argumentations that would facilitate the development of a consensus explanation. As a result, two distinct forms of argumentation emerged, leading to lively debates among the students,

> G_{11}: *What happens in the tube is that the liquid (alcohol) dilates and tends to increase its volume and cannot rise because there is higher pressure in the part where the liquid is, while through the tube with a small area the pressure it is smaller, and it is easier for him to ascend.*
>
> G_{21}: *Alcohol rises only if thermal energy is transferred in the area where it is housed, locating itself in the upper glass bubble (...) this is explained by the following equations,*

$$\frac{\Delta L}{L_0} = \alpha \Delta T; \quad \frac{\Delta A}{A_0} = 2\alpha \Delta T; \quad \frac{\Delta V}{V_0} = 3\alpha \Delta T;$$

The first group believes that the volume of the liquid increases as its temperature increases due to contact with the hand, causing it to expand. And since its only exit is through the filament inside the bubble, then it moves through there. To this argument they add the fact that the diameter of the filament is smaller than that of the bubble, which produces less air pressure on the liquid and therefore allows it to rise there.

According to the second group, it has nothing to do with differences in air pressure but is directly due to the transmission of thermal energy, and to corroborate their statement, they expose the equation of both linear and volumetric thermal expansion. However, when asked whether this equation should apply to the air above the liquid, just the liquid, or both substances, we find they are not sure.

The students engage in a discussion about whether it's the air or the liquid that expands within the thermometer. This debate arises because some believe that it's the air that expands and pushes the liquid up, while others argue that the liquid itself expands and compresses the air above it, causing it to rise. Despite having an equation that describes the behavior of the thermometer, they find it insufficient to resolve this dilemma. To address this, the students decide to experiment further. They cool the upper part of the thermometer by submerging it in water and simultaneously heat the lower part using a stove. Through this process, they hope to gather more evidence and clarify their hypotheses. It becomes clear that they need to conduct additional tests to verify their theories.

4.3.3. Mental Experiment

4.3.3.1 General characteristics

The teacher initiates this activity by providing printed material containing a thought experiment. The teacher reads this experiment aloud to the entire class, elucidating each sentence and addressing any questions or concerns through an extensive dialogue. Throughout this discussion, the teacher incorporates various resources, including analogies, representations, and examples, to facilitate comprehension. Subsequently, students are tasked with expanding upon this experiment. To do so, they must consult additional sources to develop their own interpretation of the experiment. This process begins at the individual level and then evolves into collaborative efforts, first in pairs and then in groups. The aim is to construct a more comprehensive and coherent version of the experiment. Throughout this process, students are encouraged to enrich their versions by utilizing various forms of scientific language, such as graphs, drawings, diagrams, tables, equations, definitions, analogies, and comparisons with real experiments. The activity culminates in a socialization and debate to determine the most complete and coherent version of the experiment.

4.3.3.2 Contribution to a process of mathematization of physics

This form of experimentation serves as a valuable resource for encouraging the modeling of a phenomenon. It challenges students to synthesize a significant amount of information to explain a specific situation. Additionally, it necessitates the development of a coherent language for effective communication with others in the collaborative construction of ideas. This approach also empowers students to create their own scientific discourse. The teacher plays a crucial role in this process by consistently guiding discussions, mediating disputes, and offering suggestions to help students discern which ideas are more coherent. In essence, the teacher acts as an academic peer, facilitating meaningful interactions and fostering a deeper understanding of the subject matter.

4.3.3.3 Example of developed experiment: the Galileo's boat

The proposed experiment involves two ships: one anchored in the sea, and the other moving at a constant speed. A bag of sand is dropped from the mast of each ship. According to Aristotle's perspective, on the anchored ship, the object falls to the side of the mast, while on the moving ship, it is believed to fall behind the mast. Aristotle's explanation was that when the bag was dropped, the ship continued to move horizontally, and the object fell vertically, causing it to land behind the mast.

However, Galileo contested this explanation, arguing that the bag moves at the same speed as the ship because it is part of the same system. Therefore, it doesn't fall behind the mast but to the side, just like in the anchored ship. Students provided their own interpretations of this experiment based on the teacher's initial description.

Students E_{71} and E_{81} presented their classmates with a representation of the experiment depicted in Fig. 3 and 4, accompanied by an explanation. In the first representation, the ship and the bag move at the same speed, while in the second, the ship is stationary, and the bag is released. In both cases, the bag falls on the same part of the ship. The image illustrates the trajectory of the falling object as observed by an external observer, as well as by an internal observer.

Student E_{81} further demonstrated the concept by running and simultaneously throwing a pencil vertically upwards, asking everyone to observe the trajectory of the pencil. He ensured that he ran at a relatively constant speed and threw the marker as vertically as possible. The observation indicated that the marker did not land at the point from which it was thrown, leading to questions and discussions among the students. Let's see some of their questions.

> E_{31}: *Why does it fall further forward if it would be expected to fall further back?*
>
> E_{11}: *"If the system were accelerated, would it fall the same?"*

The questions that arose during the experiment led to contemplation about the concept of a reference system when discussing the movement of objects in relation to others or relative movement. Particularly, when pondering why the object falls forward when it might have been expected to fall backward, it came as a significant surprise to the presenters. They initially assumed that everyone had explained the experiment in the same way. Upon further examination of the representations on the blackboard, it became apparent that some students had drawn parabolic trajectories as seen from the perspective of an external observer, resulting in forward and backward representations. This discovery highlighted the importance of clarifying the reference frame when discussing motion and relative movement.

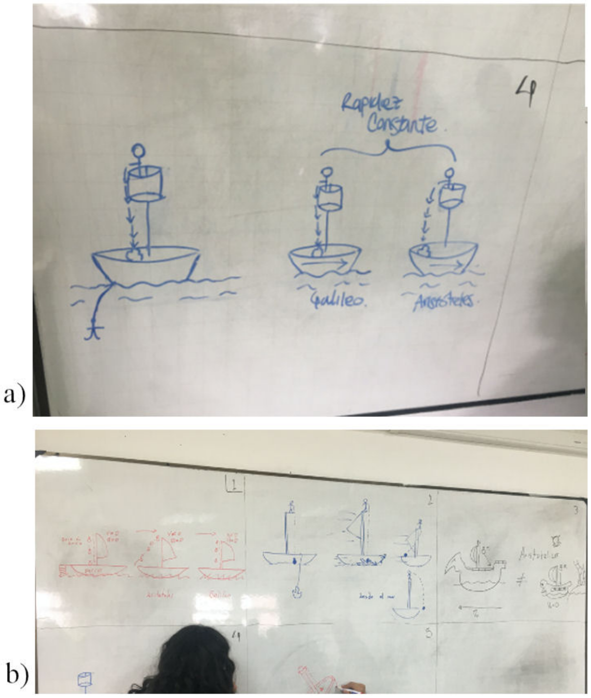

FIGURE 3. a) Representations of Galileo's Boat thought experiment. b) Different representations by students of Galileo's Boat thought experiment.

The second question raised the necessity to clarify their understanding of movement with constant speed, movement with a constant speed increase, and movement with random speed variation, each of which would have different consequences on the behavior of the experiment. This prompted them to seek clarification regarding the notion of instantaneous speed, as they realized that the moment when the object is released and the ship's speed at that moment are crucial factors in determining the outcome of the experiment.

The notion of relative movement sparked extensive debate, particularly the understanding that it is not merely an apparent movement but rather a real movement contingent upon the chosen point of reference. The students expressed concern that these concepts, which they have encountered in various physics courses over their academic journey, will significantly influence their teaching practices. They also found it noteworthy that, even after consulting the same source material, they could not easily reach a consensus on their individual expressions or the types of representations they should employ. This situation emphasized their inclination to seek information from multiple sources to ensure confidence in their explanations.

4.3.4. Discrepant experiment

4.3.4.1 General characteristics

The teacher prepares an experiment designed to challenge common sense. Instead of immediately performing the experiment, the teacher starts by asking the students for their hypotheses about the outcome. The students share their predictions, and the teacher groups them based on the tendencies of these hypotheses. The students then work together to construct possible explanations for what they believe will occur. Subsequently conducts the experiment to compare the actual outcome with the students' predictions. This often results in multiple thought tendencies emerging among the students. In response, the students can form new groups to refine their explanations and propose alternative ways to interact with the setup to test their hypotheses, promoting consensus building. If time and resources permit, the teacher can encourage students to propose their variations as long as they explain what they intend to observe. This method fosters critical thinking, collaboration, and a deeper understanding of complex concepts. but especially it helps them overcome common sense ideas.

4.3.4.2 Contribution to a process of mathematization of physics

This experiment typology offers versatility and can be applied effectively in any of the three phases of mathematization of physics process in classroom. It is particularly well-suited for the phenomenological approach, as it encourages students to explore their prior knowledge and formulate hypotheses. Additionally, it can support the observation phase, as working in groups prompts students to characterize the system and its variables while seeking explanations. Furthermore, it is relevant for the modeling phase, especially if students have already engaged in the study of the phenomenon and wish to assess their understanding. In this context, the formulation of hypotheses and the quest for consensus in their explanations enable students to put their acquired knowledge to the test and further enhance their comprehension.

4.3.4.3 Example of developed experiment: rubber pumps inflated with air and water

This experiment involves inflating two balloons, one with air and the other with a mixture of air and water. Both balloons are then held by hand, and a flame is placed underneath them. The initial questions were: What happens when you apply heat to the balloon filled with air? And what will happen when the balloon is filled with a combination of air and water? The results show that the balloon filled with only air bursts shortly after the flame is applied beneath it. Conversely, the balloon containing air and water remains intact for a significantly longer period. In this case, we observed it for up to 5 minutes without any signs of bursting.

FIGURE 4. Air and air-water ballon inflated [19].

In general, the answers, although describing the same phenomenon, involve various explanations rooted in different models. Some attribute it to the different heat capacities of air and water. Others suggest it's due to the varying temperatures of the rubber when in contact with water, which is much lower compared to the rubber in contact with air. Therefore, more heat is needed to warm the rubber in the water-filled balloon. Some explanations are based on the concept of fluid density inside the balloon, stating that the water-air mixture is denser and, as a result, more resistant to heating. Here are some of the statements:

> E_{12}: *The balloon filled with only air bursts because the air inside heated up, causing it to expand in conjunction with the heat from the plastic of the balloon encountering the flame, resulting in the balloon's explosion. In the case of the water-filled balloon, the water serves as an insulator, preventing the air from heating up in the same way.*
>
> E_{42}: *(...) In the first case (air), the conditions included lower density, while in the second case (water-air), higher density was present. Additionally, in the second situation, the water acts as a medium between the air and the rubber. The different heat capacities of the materials also play a role.*
>
> E_{72}: *For the water-filled balloon to burst, the surface of the balloon needs to become hot enough. However, some of the energy is transferred to the water. If the heating process occurs faster than the energy transfer, the balloon will burst as its surface reaches the necessary temperature.*

Some students believe that what heats up and causes the explosion is the air inside the balloon. They argue that when the air heats up, it expands, and this expansion, in combination with the heat from the plastic of the balloon encountering the flame, leads to the balloon's explosion. Others hold the view that it is the rubber of the balloon itself that heats up and causes the explosion. They argue that when the rubber gets hot, it weakens or melts, and this weakening of the material leads to the balloon bursting. There are also students who propose that it's the heated air that plays a role in melting the rubber. According to this perspective, the air inside the balloon heats up, and this hot air encounters the rubber, causing it to melt and eventually leading to the balloon's explosion.

> E_{12}: *highlights the role of heat capacity. In the case of the balloon filled with air, the rapid heating of air particles causes quick expansion and an explosion. In contrast, the presence of water in the second balloon increases its heat capacity, slowing down the heating process and preventing an explosion.*
>
> E_{22}: *emphasizes the stabilizing effect of water. The presence of water inside the balloon with air prevents the rubber from reaching a temperature high enough to damage and break it.*
>
> E_{32}: *focuses on the differential heating of air and water. Air particles heat up more easily, leading to faster heating of the rubber in the air-filled balloon, while the presence of water requires more heat to raise the temperature and melt the rubber.*

In any case, many students were notably surprised when they observed that, in the second scenario, the balloon did not explode in the following minutes. As they began to seek explanations, they expressed uncertainty and engaged in collective idea-building during the process of argumentation. This involved a search for complementary elements among various ideas to construct a more comprehensive explanation.

4.3.5. Virtual experiment

4.3.5.1 General characteristics

This typology involves the teacher presenting a virtual experiment or simulator to the class, explaining its mechanics, including the interacting variables, units of measurement, initial conditions, and modifiable parameters. Students are allowed to interact with the system, and they are later introduced to the concept of epistemological obstacles. They learn to identify situations or expressions that may seem explanatory but, in fact, create confusion. Various types of epistemological obstacles are studied, such as the animist, language-related, general knowledge, daily experience, and technological application. Students return to the simulator to identify potential epistemological obstacles and how to overcome them. The results are then shared within a context of reflective criticism and a quest for a deeper understanding of the experiment's actual purpose.

4.3.5.2 Contribution to a process of mathematization of physics

This type of experimentation is highly suitable for the modeling phase. If students have already been exposed to the phenomenon, it allows for a deeper and more conscious reflective criticism. Identifying epistemological obstacles encourages students to transform their scientific discourse and engage in discussions with their peers about the challenges they encounter. This process often necessitates extensive research to clarify doubts, enabling a more comprehensive understanding.

FIGURE 5. Sum of forces simulator [21].

4.3.5.3 Example of developed experiment: the balance of forces

This experiment is well-suited for teaching the concept of adding forces and determining the resultant force. It allows students to observe that movement occurs in the direction where the force is applied and involves fundamental concepts like force, the summation of forces, friction, balance, and motion, as depicted in Fig. 5. However, while working with this experiment, students may encounter certain aspects that appear less suitable. For example, the idea of increasing force by increasing the size of a person can lead to contradictions and raise questions. It may imply that a very large force would require a giant-sized person, which could be viewed as questionable.

Another issue is the assumption that the force applied by these "people" is entirely horizontal. Students may find it challenging or even impossible to replicate such a situation in real life. The teacher may need to emphasize the concept of idealizing physics systems for the purpose of understanding them. In this case, idealization could involve alternative ways of producing force that don't necessarily rely on these "dolls". Here's one of the conclusions from the group's discussion during the socialization process:

> G_{12}: *The virtual experiment depicts a competition between the blue team and the red team, with each team pulling a rope connected to a car with blocks. The size of the figurative characters pulling the rope can be adjusted, which symbolizes the concept that greater force leads to more significant movement of the car in the direction of the applied force. However, this representation is not easily replicated in reality. Firstly, it is challenging for a human to exert an entirely horizontal force in that position. Secondly, an increase in force does not necessarily correlate directly with a person's size. These disparities between the virtual experiment and real-world physics can potentially confuse students. Therefore, the teacher's guidance is essential in helping students bridge the gap between the simulation and real-world scenarios.*

It's worth noting the significant role that teachers play in using virtual experiments. There's a common misconception that the simulator provides all the necessary tools for understanding, but it remains abstract without a prior explanation. Furthermore, the simulator itself can introduce conceptual errors or, at the very least, confuse certain elements. This is where the teacher's intervention becomes crucial. They must guide students in using the simulator and help them analyze the underlying theory of the illustrated phenomenon.

4.3.6. Recreational experiment

4.3.6.1 General characteristics

In this teaching approach, the teacher starts the class with a series of simple and engaging experiments to captivate the students' interest. They create an atmosphere where students spontaneously come up with many questions, and the teacher responds to these questions patiently but swiftly. It's like a game with rapid-fire questions and answers. The teacher then organizes the students into pairs, and each pair chooses one of these experiments or creates their own. They prepare to present their setups at a science fair held within the class. During the fair, half of the class acts as exhibitors, presenting their setups, while the other half rotates through each setup, spending no more than five minutes at each one. This format ensures that student exhibitors are well-prepared to quickly answer questions from their visitors, with guidance from the teacher. Visitors are also prepared to ask questions. Later, the roles switch. This typology primarily stimulates the development of scientific language and the ability to ask and respond from a scientific discourse, promoting effective and assertive communication among peers.

4.3.6.2 Contribution to a process of mathematization of physics

This experience typically requires a minimum of four class sessions to prepare for the science fair. It can serve as a suitable conclusion to a physics modelling process, where students delve into a single phenomenology demonstrated through various experiments. Additionally, it can be an effective resource as an introductory activity for the phenomenological approach, if students are adequately prepared to grasp the essential language needed to discuss the setups they will present. The complexity of the arguments put forth by students can vary depending on the context and the level of understanding. It can also be applied in the observation phase of the system, particularly to help students distinguish between the characteristics of the observer, the observed, and the observable. In this scenario, the teacher should emphasize these aspects when preparing students for formulating questions and answers.

4.3.6.3 Example of developed experiment: the recreational fair

In this instance, the teacher formed teams of two individuals, deliberately seeking pairs with complementary dynamics in the classroom. The objective was to avoid situations where one person dominated decision-making or where both members displayed equal passivity or authoritativeness. Achieving this balance was facilitated through role-play dynamics. Following the formation of these balanced teams, the teacher introduced several examples of recreational experiments. In this specific context, which pertains to a didactics of physics course rather than a regular physics class, the students were given the freedom to select physics topics of their choice and create their own experiments. This approach was designed to promote collaborative learning and encourage students to take an active role in their learning process.

The selected experiment should be visually captivating and feature a straightforward setup. The goal is not to collect extensive data through prolonged systematic observation but rather to enable the rapid observation of a phenomenon within a short timeframe. Simultaneously, the presenter must possess the ability to provide a concise and lucid description of the taking place, offering explanations that pique curiosity and stimulate inquiries from the audience.

The orientation process entails a series of steps, including drawing a diagram, listing the required materials, identifying potential technical challenges, addressing uncertainties or unknowns, organizing the scientific language, and outlining a plausible explanation. The teacher works individually with each team to assess feasibility, enhance ideas, recommend relevant readings, and address any concerns raised by the students. This collaborative effort continues until the students have gained the necessary independence to proceed with the assembly.

Below, you'll find a group's description of their assembly and its intended explanation, achieved after the preparation

FIGURE 6. The aim is to attract the ball wrapped in aluminum foil with the electrified pump. Source Authors.

process. In anticipation of potential inquiries from their peers, they have formulated a set of guiding questions to facilitate the comprehension and presentation of the phenomenon.

> G_{32}: *Our experiment utilizes static electricity, where a balloon is negatively charged through friction with woolly surfaces or hair. This generates attraction on another body, a ball covered with electrically charged materials, causing it to move. The movement is harnessed to score a goal in a specific arc on a field. To achieve this goal, we need a general understanding of static electricity. This prompts several questions:*
>
> > *Why does this phenomenon occur?*
> >
> > *What distinguishes static electricity from regular electricity?*
> >
> > *What components make up an atom?*
> >
> > *Why do unlike charges attract each other while like charges repel?*
> >
> > *Why do electrons get lost, and not protons?*
> >
> > *Which materials should be used to achieve electrical repulsion?*
> >
> > *When a person rubs a balloon on hair or wool, can we say that the hair or wool becomes positively charged?*

Two dedicated classes were assigned to each team to independently test their assembly along with the corresponding explanation. During this phase, the teams were not exposed to their peers, and the teacher provided guidance and assistance as needed. They had the freedom to make any necessary modifications to ensure the proper functioning of the experiment. The teacher's primary objective was to empower the teams, encouraging them to present the phenomenon with autonomy and clarity, using coherent language, and inviting visitors to ask questions when interacting with the experiment.

Certain rules were established to improve the presentations. For instance, it was agreed that exhibitors should not begin their presentation by posing questions to visitors. This decision came after observing that in initial attempts, exhibitors who led with questions overwhelmed the visitors, hindering the overall understanding of the experiment. To further refine their presentations, each team was tasked with creating a document that detailed the characteristics and construction process of their assembly, explained the scientific principles involved, described the presentation methods, and provided guidance on language, attitude, and emphasis when interacting with the public.

The process of preparing and testing the experiments revealed important insights. It became evident that the students became acutely aware of the intricate details necessary for the smooth operation of their experiments only when they attempted to replicate them in class. This first-hand experience raised numerous questions and concerns regarding the physics phenomenon, the appropriate language for explanation, its applications, and its connections to various topics. The need to equip students with precise and clear language was highlighted, as they often exhibited imprecision or confusion in their explanations. They were guided to anticipate potential questions that might arise from the audience and prepare well-thought-out responses. Moreover, they were encouraged to structure their presentations to spark curiosity and stimulate questions from the viewers.

To illustrate this process, a group that presented an experiment titled "Surface Tension" shared the questions they aimed to generate among their peers, see Figs. 7a), b) and c). These questions were instrumental in prompting thoughtful discussions and enhancing the overall learning experience.

> G_{23}: *Our experiment aimed to understand why liquids inside bottles with just a fabric lid do not spill. We conducted the experiment using three different types of-*

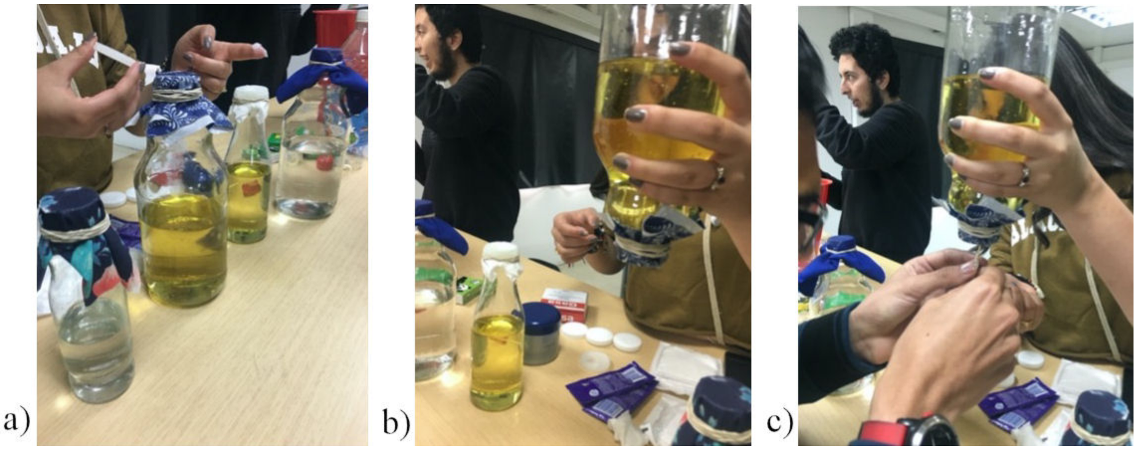

FIGURE 7. a) Containers with different substances and covered with different types of materials are observed. b) Turning the bottle does not spill the substances. c) Inserting a stick to try to "break" the surface tension. Source: Authors.

> *fluids (oil, water, and alcohol) and three distinct fabric lids, such as gauze. Our intention was for our peers to interact with the experiment by turning the bottles with the liquids inside to observe how the lids and various insulators on the caps prevent spillage. To achieve this, we utilized deodorant and Vaseline due to their differing densities. During the presentation, we anticipated several questions about the concept of surface tension, including inquiries about whether it depends on fluid density, how it behaves in various materials, why the liquid doesn't spill with a fabric lid, the rationale behind different lid types on jars, why gauze allows liquid to escape while cotton does not (specifically for bottles with oil), the purpose of adding Vaseline or deodorant to the caps, why alcohol filters through the fabric but not water, and why inserting a toothpick or pin through the cap doesn't break the surface tension and cause liquid to spill.*
>
> *But unexpected questions also arose during our presentation, provoking deep reflection. We provided responses based on our acquired knowledge, particularly concerning the connection between viscosity and surface tension, as well as potential technological applications of these principles. While we addressed these inquiries to some extent, they left us pondering new concerns. The questions that caught us off guard included: Does the liquid still have surface tension at the moment it starts to flow? Can a viscous fluid overflow the cap? Does deodorant function the same way on my skin? Does it block sweat? These unexpected questions encouraged us to delve further into the intricacies of surface tension and viscosity, leading to a richer understanding of these concepts and their potential applications.*

It's noteworthy that all these questions arose from the visiting students' own curiosity, not from the teacher, and the exhibiting students were able to provide answers due to the prior guidance they received from the teacher in understanding the phenomenon. However, they still had several questions to address, which demonstrates how engaged they are in the process of understanding the phenomenon.

The final phase involves staging a fair of recreational experiments where everyone interacts with one another. As exhibitors, they face recurring questions and improve their explanations to make them more concise and compelling. As visitors, they stimulate their own thinking and generate a variety of questions they are eager to have answered.

The staging of the recreational experiment should be accompanied by the exhibitor's explanation. It should not begin with questions to the visitor since the goal is not to question the visitor but to encourage them to ask questions. This is achieved by using language that is clear and engaging and by presenting the experiment in a way that highlights certain aspects and draws attention to what is happening or not happening. The exhibitor should be prepared to answer any type of question from the visitor and should not dismiss any question or respond in a condescending manner. The following student's testimony illustrates their commitment to their classmates.

> E_3: *...As exhibitors, we learned firsthand the importance of remaining calm during the presentation. We also understood the necessity of mastering the experiment, as any issues or malfunctions had to be addressed promptly to avoid losing the audience's interest or wasting time.*

4.3.7. Crucial experiment

4.3.7.1 General characteristics

The primary objective of historical contextual analysis of paradigm-shifting experiments in science is to debunk myths surrounding the realm of science and scientists. This approach aims to empower students to engage with physics and appreciate that the process of constructing scientific knowledge is not linear but rather unpredictable. It's not solely the work of exceptionally gifted individuals but instead, it's the result of human beings who face challenges, hold aspirations, and possess potential similar to their own. In this method, the teacher recreates a historically significant experiment and provides context by discussing the political, economic, religious, technological, linguistic, cultural, and other elements of the time in which the experiment was developed. This approach stimulates discussions that encompass a wide range of topics that pique the students' interest.

4.3.7.2 Contribution to a process of mathematization of physics

Its power can be used in any of the three phases of mathematical action of physics. This can serve as an intriguing introduction to the phenomenological approach, but also prove invaluable in characterizing systems and comparing them with other experiments during the observation phase. Moreover, these tools can facilitate the modeling of complex phenomena based on essential data. When recreating experiments, a wide range of resources, such as audio, video, models, writings, simulators, etc can be employed, fostering curiosity, sparking controversy, and prompting questions within the scientific community.

4.3.7.3 Example of developed experiment: how Eratosthenes measured the perimeter of the earth.

In this setup, a globe is used with two gnomes placed on different cities. To accurately simulate the conditions, the following steps are essential: First, position each gnome so that it is perpendicular to the surface, simulating a tower's placement in each respective city. Once both gnomes are in place, ensure that one city is at the highest point on the globe. Next, illuminate the setup with a light source, symbolizing the sun's

FIGURE 8. Recreation of the Eratosthenes experiment in class, by measuring the shadow of one gnome located on the globe approximately over the city of Quito and another one in the city of Belen do Pará. Source: authors.

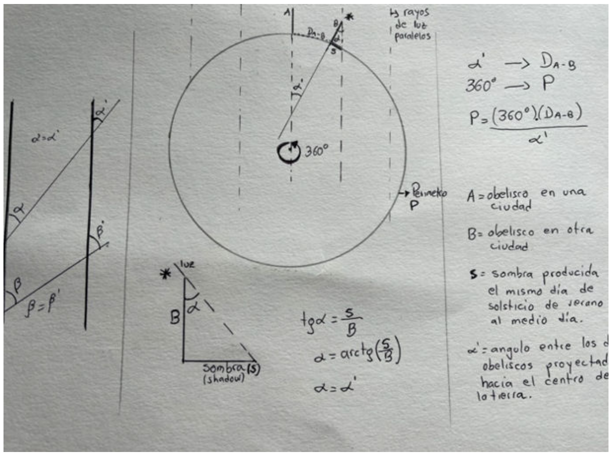

FIGURE 9. Calculation of the perimeter of a circle using the Eratosthenes method. Source: authors.

light reaching the Earth. The goal is to create an image where the rays of sunlight, upon reaching the Earth, are parallel to each other. This means that the ray of light illuminating the gnome at the top of the globe is parallel to the ray of light illuminating the gnome in the second city, though slightly inclined compared to the first.

It is then observed that no shadow is produced on the gnome at the top of the globe, while a shadow is produced on the other one. We can then measure the height of the tower and the shadow it produces, and extract this representation into a rectangle triangle, which will allow us to calculate the angle between the tower and the beam of light that produces its shadow.

Eratosthenes made a profound contribution by pondering the peculiar phenomenon of sunlight casting a shadow on an obelisk in Syene during the summer solstice, while no such shadow appeared on an obelisk in Alexandria, situated to the north. He deduced that the tower in Syene must be inclined in relation to the tower in Alexandria, indicating the Earth's curvature. He envisioned this curvature as spherical and utilized the geometric knowledge of his time to calculate the Earth's circumference, [22].

His method involved projecting the two obelisks' shadows toward the "supposed round Earth" to their intersection point. Additionally, he projected the parallel rays of sunlight that struck the two obelisks. When two parallel lines are intersected by a third line, they form equal and opposite interior angles. By determining the angle between the second tower and the ray of light producing the shadow, he could find the angle formed by the projection of the two obelisks toward the Earth's center. With this information, he applied a simple proportionality rule, relating this angle to the distance between the two cities, using the full circle angle (360°) and its measurement (the Earth's circumference). Figure 9 illustrates the calculation performed by students to replicate Eratosthenes' method for the presented scenario under the teacher guidance, demonstrating the practical application of this historic approach.

Below are some reflections from the students at the end of the activity.

> E_{52}: *This experiment truly makes you appreciate that groundbreaking ideas don't necessarily depend on advanced technology. It's more about how you think and the ingenuity behind the concept. I've known for a while that the Earth's diameter was calculated in ancient times, but this experiment helped me understand how they did it.*
>
> $E_{13\ 2}$: *To perform this experiment, we had to grasp the fundamental idea of proving the Earth's roundness. We often take this idea for granted because it's well-established today, but explaining something as simple as the shadows it creates can be challenging. It made me realize how important it is to truly understand the basic principles behind scientific concepts.*
>
> E_{22}: *I was fascinated by how ancient the idea of Earth's roundness is. I wasn't sure how people in the distant past discussed the Earth's shape and measured it without the benefit of space exploration. Exploring the historical context and the lives of these early thinkers is eye-opening. It's clear that scientific curiosity and the desire to observe and understand nature have always been integral to human thought.*

4.3.8. *Experiment by research*

4.3.8.1 General characteristics

Formulating research questions is indeed a complex process, often surrounded by misconceptions. The common belief is that one needs extensive knowledge of a subject to ask meaningful questions, and while this is true for the scientific community pushing the boundaries of knowledge, a school environment fostering scientific thinking can approach it differently. This type of experimentation initiates with a teacher presentation about the significant challenges that the scientific community is currently tackling within various branches of physics. This initial phase necessitates the teacher's thorough preparation and contextual understanding. The primary objective is to stimulate students' curiosity, encouraging them to recognize and explore the topics that genuinely intrigue them. Following the teacher's presentation, students are prompted to engage individually in the process by documenting the aspects that pique their curiosity. These aspects may relate to the teacher's presentation or stem from questions they had beforehand.

The next step involves the dynamics of the clock, where individual writings are rotated, ensuring that each student has the chance to read and analyze everyone's questions. They are encouraged to provide comments and insights that help complete the questions, making them more specific and focused on study-able facts. Following this, each student generates a new question, which they submit to the teacher. These questions serve as the basis for organizing groups based on common interests or curiosities. Within their respective groups, students work together to synthesize their questions into a single, unified inquiry. Meanwhile, the teacher circulates among the groups, offering guidance on refining the question's language and exploring potential approaches for experimentation, considering the available resources and time constraints.

Finally, students are tasked with planning an experimental process to address their unified question. They must execute this plan, coordinating their efforts to gather data systematically, enabling them to observe the phenomenon. Following data collection, students collaborate to draw conclusions based on their findings. These conclusions are then presented to the entire class for validation and discussion.

4.3.8.2 Contribution to a process of mathematization of physics

This methodology presents an opportunity to promote the modelling phenomena. It's well-suited for students who have prior experiences with a particular phenomenology that has sparked their curiosity and led to questions. It's also beneficial for students who have practiced systematic observation of systems, as this background knowledge provides a foundation for their inquiries. Implementing this type of experiment typically spans multiple class sessions, as students can become deeply engaged in questions that genuinely captivate them. This level of autonomy in their pursuit of understanding goes beyond typical classroom tasks. As students become more independent in satisfying their intellectual curiosity, it fosters a sense of ownership over their learning.

Moreover, this methodology is flexible and adaptable, making it suitable for different phases of the scientific process in mathematization of physics, contingent on the context and the teacher's didactics capabilities.

4.3.8.3 Example of developed experiment: how to verify experimentally the entropy?

In this scenario, three student groups shared a common desire to deepen their comprehension of the concept of entropy. These students were concurrently studying thermodynamics, and entropy was a concept they found particularly challenging to grasp. They expressed difficulties, especially when trying to associate entropy with terms like "disorder" or "chaos". Among the groups, certain phrases related to entropy remained salient, such as:

> *"Entropy is the measure of disorder."*
>
> *"Entropy relates to the irreversibility of thermodynamic systems."*
>
> *"Entropy serves as the foundation for the second law of thermodynamics."*

Upon attempting to expand the meaning of these sentences, the student groups collectively recognized their limited understanding, particularly in reconciling the concepts of "order" and "disorder." They realized that they lacked the necessary insights to demonstrate these ideas within an experimental context. Consequently, they decided to consult various sources and requested time to collaboratively construct a more comprehensive and coherent definition of entropy.

> G_{13}: *The first thing we collide with is that one finds that entropy is defined as the measure of disorder, however, when we were looking at simulations of the phenomenon, one sees that it is actually a certain order.*

Their reflections led them to consider the concept of microstates and macrostates, as explained by Boltzmann. In this context, macrostates refer to those properties that can be directly measured, such as temperature or pressure, providing a way to characterize the overall behavior of a system. In contrast, microstates are shaped by the behavior of individual molecules within a fluid. For instance, during a temperature increase, molecules go through numerous states that are not observable, but it's precisely within these microstates that the principle of entropy operates. This deeper understanding allowed them to explore entropy within the context of molecular behavior and its relationship to macroscopic properties.

As they worked on defining an experimental setup, the question of how to measure entropy emerged. They grappled with the fact that entropy results from the behavior of microstates, yet it characterizes the behavior of the macrostate. They collectively contemplated the challenge of measuring it because each physics system's conditions are unique. The

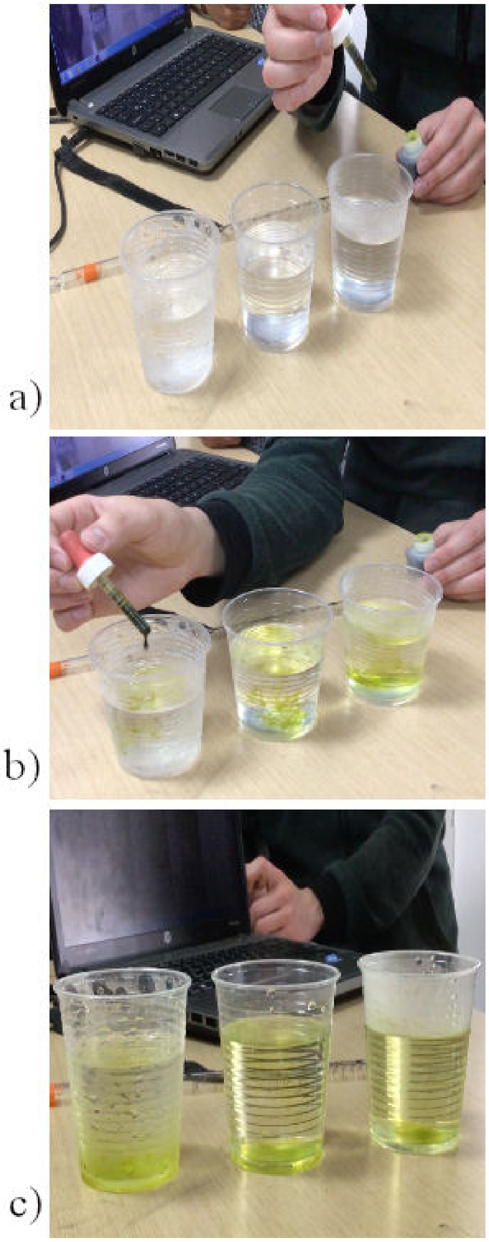

FIGURE 10. a) Entropy experiment: Three glasses, different temperatures and an ink drop in each one. b) Dropping the same amount of ink drops into the three liquids. c) Observe how the ink distribution changes over time. Source: authors

number of possibilities for the behavior of microstates depends on the system's initial conditions and the time it takes for the system to reach an equilibrium state.

One group decided to conduct an experiment involving three glasses of water at different temperatures, each with a drop of ink added. In the photograph, they observed that the hottest water (on the right) resulted in the ink being more uniformly distributed throughout the glass, while the cooler water retained the ink in a concentrated area. This led to the introduction of the concepts of a "molarly ordered" and a "molarly disordered" system. In this framework, the cold water represented a molarly ordered system because the ink was not evenly distributed throughout the available volume, while the hot water exemplified a molarly disordered system as the ink spread uniformly throughout the glass. See Figs. 10a), 10b) and 10c).

The students' questions and debates raised interesting points challenging the conventional understanding of entropy. They questioned why the hot glass, with more evenly distributed molecules, wouldn't be considered ordered and why entropy was associated with an increase in disorder. The argument supporting the cold glass being more molarly ordered is strengthened by the notion that the ink molecules are concentrated in one area, not distributed throughout. It was also recognized that as time progresses, the glasses would exhibit different behaviors. The cold glass would absorb energy from the environment, resulting in varying molecular arrangements, while the hot glass would release heat to the environment. However, it was acknowledged that the processes of giving up heat and absorbing heat might not be equivalent. To illustrate this discussion, let's consider an example.

> G_{13}: *(...) we can directly observe that the ink is quickly dis tributed in hot water, while in cold water it is concentrated in the same area...it all goes to the bottom. One could say that there is a certain order because in the hot water the particles are moving more, in the cold water they are moving less... but it cannot be said that after a while they will be the same because the hot water does not cool down in the same proportion. in which ice water is heated...*
>
> *Q: Do you mean that it is the conditions of the physics system that indicate the order it is going to take?*
>
> G_{13}: *. . . well. . . yes. . . that would be one way of looking at it. . . but you can't totally predict it.*

The discussion ignited a debate about how the ink distributed in the three cups. Surprisingly, after some time, the cold cup had reached 7 degrees Celsius, while the hot one had risen to 56 degrees, yet the ink appeared relatively evenly dispersed across all three cups. Notably, in the hot water, a lighter stripe was visible in the middle of the glass, which was absent in the other two. This led other groups to express an interest in replicating the experiment with greater attention to initial conditions.

Subsequently, another group of speakers raised similar concerns and began with questions regarding the nature of entropy in astronomy compared to thermodynamics, how entropy aids in understanding the operation of thermal machines, and the relationship between Clausius' proposal and Boltzmann's proposal. They explained that Clausius approached the topic from a thermodynamic perspective, where the variation of heat over time could be measured. In contrast, Boltzmann introduced the concept of the probability of combinations of microstates leading to a macrostate, allowing for the analysis of macrostate behavior. This distinction highlighted the fundamental difference in their approaches to entropy. Students' final thoughts on this treatment of experimentation,

> E_{13}: *Then we learned to have a broader and more general vision in the sense of identifying variables, modifying them, one practically dares to put one's hand as such, because as far as I knew it was only recipes and I think I would have done the same if I hadn't be for this course that taught me to think differently as a basis for students to get involved in the experiment, not so technical or so theoretical but something... that helps us to think and analyze, to formulate hypotheses and all that kind of things.*
>
> E_{113}: *We had to review our language because the phenomenon had to be very well explained, and if the words or concepts were not handled appropriately, we would not make ourselves understood.*
>
> E_{93}: *Teamwork allowed the construction of clearer and more real hypotheses regarding the phenomenon, allowing others to understand better when debating. We learned to reflect on how to explain phenomena.*
>
> E_{13}: *throughout the course the experiment is always like a recipe, you receive a guide such as you have to do this experiment, analyze and extract data, what I learned with the typologies is that this is not necessary... that is, a single experiment is not to work on a single concept as is usually done and one was always waiting to see what data had to be taken and how to make the report so that it would work... but in this case we learned to observe the phenomenon and interpret it from different points of view.*

5. Conclusion

The contribution of experimentation typologies to the development of a mathematization of physics process in the classroom.

This work presents a significant contribution by introducing a novel approach to the mathematization of physics in the classroom. This approach aligns more closely with students' natural modes of thinking and fosters the development of scientific reasoning. While the experimentation involved future physics teachers rather than students in a physics course, it successfully guided these prospective educators in developing fresh insights into the processes of phenomenological exploration, systematic observation of controlled physical systems, and the construction of coherent explanatory models.

Each typology studied yielded positive results, showcasing the potential they hold for creating teaching methodologies that encompass the three phases of mathematizing physics during the learning and teaching processes.

Teacher role modifications

Pre-service teachers learn how to plan physics teaching methodologies focused on experimentation in non-traditional ways, exploring how to develop scientific thinking skills in students. They are conscious of the different means of the mathematization process in class, not just checking equations but constructing explanation models. Furthermore, they learn to play a different role, participating in the class to stimulate debates, inspiring reflections, asking for destabilizing situations without installing absolute truths. They offer ideas and information requested by the student or facilitate the development of the activity. Without previously structured fixed speeches, and evaluate the process, not only the product

Student role modifications

They reflect on the importance of educating students about autonomy in their knowledge processes because the effect of learning is very different when they participate in the class only to obtain a score in evaluation than when they are committed to their learning. They expanded their understanding of the use of equations, stating that although they are a model, in a learning process, it is convenient to guide the conceptual construction of the model before introducing this synthetic version of the explanatory model. They also acquired skills for debate, such as tolerance, the construction of appropriate language to build consensus, the assessment of their peers as valid interlocutors, not only the repetition of the teacher's speech.

Alternative treatments of scientific content

Pre-service teachers recognize that the center of an educational process in the natural sciences should not be the scientific content itself, although it is the central topic of conversation, but the student as a social subject. They learned that the knowledge about how to deal with this content in educational contexts is teachers' specific knowledge since it is necessary to contextualize the sequences of activities, the languages, the intentions in the class, and other formative aspects, according to the type of student and the conditions that exist at the moment. In this way, the knowledge built in the class depends on the student's interests, not on the truth imposed by the teacher.

They also realize that it is not mandatory to teach physics in the conceptual ladder traditionally found in books because many topics are related to others, and it can be treated as mixed as the discussions take place.

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