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Fostering lower secondary school teachers' professional development: a teaching experiment in classical mechanics

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Abstract

Teacher professional development in science education often struggles to translate theoretical knowledge into meaningful classroom practice, particularly at the lower secondary level. This study presents an original teaching experiment in classical mechanics, designed to foster both pedagogical content knowledge and conceptual change through a situated, inquiry-based approach. Grounded on situated learning theory, our methodology integrates the PEC model (prediction, experimentation, comparison) within modular teaching episodes enabling authentic engagement with physics concepts through low-cost, hands-on activities. Unlike many top-down professional development programs, this initiative builds from teachers' intuitive knowledge, actively confronting and reconstructing misconceptions through guided inquiry and collaborative

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reflection. Relying on qualitative data—collected through classroom observation, discussion transcripts, and informal interviews—we document how teachers revised deeply held misunderstandings about motion, force, mass, and weight. Findings reveal a substantial shift in participants' conceptual frameworks and teaching practices, including increased use of student-centred experimentation, more accurate use of scientific language, and improved ability to model inquiry-based instruction. This research contributes original evidence that sustained, situated learning environments can effectively promote long-term professional growth and epistemological transformation in science teachers, even in structurally constrained educational systems.

Keywords: teacher professional development, teaching/learning sequence, pedagogical content knowledge, classical mechanics

1. Introduction

Despite being academically qualified in science, many teachers—especially at the lower secondary level—struggle to teach physics effectively. Educational research consistently emphasizes that success in science education is closely tied to how well teachers are prepared for the realities of the classroom [1–3]. Effective physics instruction requires more than content expertise; it calls for the ability to create inquiry-rich learning environments and foster student reasoning, experimentation, and reflection [4, 5]. Scientific education must go beyond mere knowledge transmission—it should cultivate reflective, metacognitive engagement with scientific ideas and practices [6–8].

Despite ongoing efforts, a significant gap persists between the theoretical preparation of science teachers and the practical implementation of effective classroom strategies. In Italy, lower secondary school science teachers frequently hold degrees in biology, geology, chemistry, or mathematics, rather than in physics. As a result, physics is often misrepresented—either conflated with technology or taught in a rigid, overly formal manner that feels disconnected from students' everyday experiences and interests [9, 10]. This issue is compounded by structural weaknesses within the Italian lower secondary school system, a sector long recognized as fragile.

Earlier TIMSS findings [11] highlighted that many Italian science teachers rely heavily on textbooks and dedicate limited time to hands-on, experimental, or inquiry-based activities. Although a more recent survey [12] suggests slight improvements, classroom practices still fall short of fostering meaningful engagement with scientific concepts. Italy's performance in eighth-grade science has remained stable over the past two decades, closely aligning with international averages. However, physics-specific content scores are 15 points below the international mean. While Italian students perform relatively well in the 'knowing' domain (10 points above average), they score lower in 'applying' and 'reasoning'—1 point and 10 points below the international averages, respectively. Additionally, the growing gender gap in science achievement warrants attention. In 2023, Italian boys outperformed girls in science by 17 points (509 vs. 492), a significant increase from the 5-point gap reported in 2003. Both genders have made modest gains over time, with boys improving by 9 points and girls by 10.

To address these challenges, there is a pressing need to redesign professional development programs for science teachers—particularly in physics. These programs should emphasize active, inquiry-based methodologies that directly address common student misconceptions and help make physics more relevant, accessible, and engaging [13–15]. pedagogical content knowledge (PCK) offers a theoretical framework to evaluate and improve teachers' professional skills, elevate their professional identity, and guide their educational development. Following Shulman's foundational work [16, 17], PCK has emerged as a cornerstone of teacher education. It refers to the amalgam of content and pedagogy that enables teachers to transform disciplinary knowledge into forms that are pedagogically meaningful, engaging, and adaptable to students' diverse backgrounds and learning needs [18–20]. PCK includes not only knowledge of the subject matter but also an understanding of how students learn, the misconceptions they may hold, and the most effective instructional strategies to support conceptual development [21–23]. As Kind [24] points out, PCK often operates tacitly—teachers rarely articulate its use, though it underpins their classroom practices. Two key components of PCK are instructional processes and understanding of student learning. The former involves deploying strategies such as analogies, examples, and demonstrations, while the latter encompasses recognizing students' preconceptions, mental models, and potential learning barriers [25–27]. High-quality science teaching, therefore, is not solely defined by disciplinary knowledge but by the ability to integrate that knowledge with a deep understanding of how students learn science [28].

To address this challenge, the physics education research (PER) group at the University of Cagliari, in collaboration with the Cagliari Division of the National Institute for Nuclear Physics (INFN), developed and implemented a professional development program in classical mechanics for in-service lower secondary school teachers. Conducted between 2019 and 2024, the initiative was part of the *AggiornaMenti* project—an INFN national program aimed at promoting hands-on, cooperative STEM education in lower secondary schools [29]. The project emphasizes collaborative problem-solving and the construction of low-cost experimental setups, encouraging teachers to engage with physics in a practical and meaningful way. The broader *AggiornaMenti* program covers topics such as mechanics, fluids, optics, and electromagnetism.

Specifically, our program had three main objectives: (i) to strengthen teachers' physics literacy and awareness, (ii) to introduce a methodology for teaching classical mechanics through real-life, low-cost experiments, and (iii) to support the development of teachers' PCK through situated and reflective practice. In this study, we aim to address the following research questions:

- RQ1: how can a professional development program in classical mechanics be designed according to PER outcomes related to PCK?
- RQ2: what conceptions, difficulties, and benefits emerge from this professional development experience?
- RQ3: how does teachers' PCK evolve through participation in the proposed program?

In the following sections, we outline our theoretical framework, grounded in teaching experiments and situated learning theory [30]. We then describe the methodology for designing our professional development tool, discuss its implementation, and evaluate its impact on participants' teaching of classical mechanics.

2. Theoretical framework and educational tools

2.1. Pedagogical framework

Research in science education has consistently shown that teachers' professional knowledge plays a central role in shaping classroom practices and student learning [31, 32]. To understand how such knowledge develops and can be effectively supported, several complementary models have been proposed. Although different in emphasis, these models converge on the idea that teacher learning emerges through participation in authentic disciplinary activities, reflection, and continuous engagement with pedagogical challenges.

The metacultural model guides teachers in critically analysing disciplinary content and teaching practices, helping them uncover the epistemological assumptions underlying physics instruction and fostering coherence between conceptual understanding and pedagogical choices [31]. The experiential model emphasizes learning through direct involvement in the same conceptual and experimental paths that students follow; by engaging hands-on with phenomena, teachers can better evaluate materials, anticipate students' difficulties, and refine coherent instructional sequences [32].

Situated learning theory frames learning as a contextualized and socially mediated process, in which knowledge is constructed through participation in authentic practices rather than abstract transmission. It emphasizes authentic contexts, social interaction, and active knowledge construction, where learners engage in tasks mirroring real professional situations, enabling the transfer of knowledge to classroom settings [30].

Building on this perspective, the situated model, grounded in the seminal work of Brown, Collins, and Duguid (1989) and Greeno (1989) [30, 33, 34], conceptualizes teacher development as participation in a community of practice in which knowledge is constructed through shared inquiry and contextualized problem-solving. As highlighted by Green, Eady, and Andersen (2018), professional preparation must bridge the gap between tertiary experiences and classroom realities to foster adaptive and context-responsive educators [35].

The situated model, grounded in the seminal work of Brown, Collins, and Duguid (1989) and Greeno (1989) [30, 33, 34], conceptualizes teacher development as participation in a community of practice in which knowledge is constructed through shared inquiry and contextualized problem-solving. As highlighted by Green, Eady, and Andersen (2018), professional preparation must bridge the gap between tertiary experiences and classroom realities to foster adaptive and context-responsive educators [35].

A more unified and contemporary perspective is offered by the refined consensus model (RCM) [36–39]. The RCM explains how disciplinary understanding, classroom experience, and beliefs about learning interact across different levels of teacher knowledge—from general disciplinary ideas to topic-specific PCK and situation-specific instructional decisions. These levels are dynamically related: as teachers participate in authentic activities and reflect on their experiences, they transform theoretical knowledge into actionable, classroom-relevant PCK.

Within this framework, active learning and inquiry-based approaches play a crucial role. inquiry-based learning (IBL) supports the construction of knowledge through prediction, investigation, and reasoning [40]. The PEC cycle—prediction, experimentation, comparison—is particularly effective in guiding teachers through the epistemic practices of science, fostering both conceptual understanding and reflective engagement with scientific reasoning [41–46]. Integrating cooperative learning within inquiry activities further enhances communication, reasoning, and teamwork, which are recognized as essential components of modern science education [47–49].

Taken together, the metacultural, experiential, situated, and RCM perspectives—combined with inquiry-based and cooperative approaches—constitute the backbone of our professional development model. Teacher knowledge is viewed as socially mediated, context-embedded, and dynamically reconstructed through participation in authentic tasks that mirror real classroom challenges. By engaging in hands-on inquiry, collaborative reflection, and structured modelling activities, teachers progressively integrate disciplinary content, pedagogical strategies, and epistemological awareness, in alignment with contemporary understandings of PCK development. These perspectives provide the foundation for examining how teachers construct and revise their conceptual understanding, as discussed in the following subsection on modelling, semiotics, and teaching experiments.

2.2. Models, semiotics, and teaching experiments

As Duval (2006) and Tiberghien (2000) argue [13, 50], conceptual understanding in science emerges from coordinating multiple semiotic registers—natural language, diagrams, algebraic expressions, and symbolic notation. Teachers must therefore learn to navigate between the world of events and the world of theories, linking representations to phenomena. However, they often rely on intuitive mental models rooted in prior experience rather than in scientific reasoning [51, 52], and these pre-instructional conceptions shape how they interpret and teach physical ideas. For this reason, a central aim of our methodology is to make such assumptions explicit and reorganize them within a coherent scientific framework. To support this process, we draw on Ohlsson's taxonomy of epistemic tasks—describing, explaining, predicting, arguing, defining—which scaffold comparison, abstraction, and model construction [53]. Through these tasks, teachers gradually refine their reasoning, supported by collaborative dialogue and feedback.

To investigate and promote these changes, we adopt the teaching experiment methodology, widely recognized in PER as a flexible, interventionist approach for studying learning and fostering conceptual change [54–57]. Teaching experiments consist of structured episodes in which participants engage in cycles of exploration, model building, and application through hands-on and minds-on activities designed to challenge misconceptions and support scientific reasoning. The researcher alternates roles—eliciting teachers' ideas, providing scientific input, and mediating between intuitive and disciplinary reasoning—adapting the learning environment to participants' evolving understanding. This dynamic mediation reflects situated learning principles, where knowledge is negotiated within a community of inquiry [58].

Close attention to teachers' semiotic and linguistic productions during these episodes provides insight into how they process and communicate physical concepts. Analysing verbal, graphical, and symbolic representations helps identify gaps between everyday and scientific language [59], making semiotic inconsistencies visible and supporting the reconstruction of more coherent conceptual frameworks—an essential dimension of PCK development. Research shows that addressing such discrepancies through reflective practice improves both teachers' conceptual understanding and their ability to facilitate conceptual change in students [24, 60, 61].

3. Methodology

The general design of our teaching experiment has been presented in a previous paper [62]. Here we summarize it for sake of completeness. The teaching experiment is structured around a macro- and micro-level design to support the professional development of lower secondary teachers. The macrostructure defines the course's overall goals, content, teaching strategies, safety protocols, and assessment tools, ensuring that each teaching episode can stand alone and be easily implemented in classroom settings. The microstructure focuses on individual episodes built around every day phenomena and follows a cycle of inquiry, experimentation, modelling, and reflection, inspired by the PEC methodology.

Each episode begins with teachers drawing on their prior knowledge to predict outcomes, followed by hands-on and minds-on experiments designed to challenge their conceptions and stimulate discussion. Teachers compare their expectations with observed outcomes, reflect on the discrepancies, and develop explanatory models. Through guided questions, they are encouraged to articulate their reasoning and connect new ideas to broader physics concepts. During this collegial explanation phase, participants are prompted to articulate and analyse their observations:

- *What did you observe?*
- *Can you explain the physical phenomenon?*
- *Which features of the setup influenced the outcome?*
- *What physical quantities were at play?*
- *What changed when the experiment was repeated?*

The next phase involves modelling, where teachers develop conceptual frameworks to explain the observed phenomena. The facilitator asks:

- *How can you describe the physical phenomenon in general terms?*
- *What local and global patterns do you notice?*
- *Can you relate this behavior to other physical entities or experiments?*

Finally, in the discussion phase, teachers reflect on the broader implications of the activity. They are invited to consider:

- *What new concepts have emerged?*
- *What do your results mean for understanding key physics ideas?*
- *Do any concepts need to be redefined or expanded?*
- *Has your view of physics changed as a result of this activity?*

- *What are your thoughts on the pedagogy used, and how might it apply to your own classroom?*

These activities are framed by Ohlsson's epistemic tasks [53] to promote deep conceptual understanding and make teachers' mental models explicit. Our design emphasizes collaborative problem-solving and the construction of low-cost experimental setups, encouraging teachers to engage with physics in a meaningful, practice-oriented way. Special attention is given to the role of semiotic representation—how language, diagrams, and formulas interact in the learning of physics. Teachers reflect on their use of these representations and consider how they impact students' learning.

Each episode concludes with a discussion of the experience and its classroom applicability. The final phase includes a broader reflection on the methods used and their potential for integration into everyday teaching, supported by take-home materials such as slides and kits. Overall, the experiment promotes situated and experiential learning, helping teachers refine their PCK through authentic engagement, reflection, and participation in a professional learning community.

4. Implementation of the teaching experiment in classical mechanics

To ground teacher professional development in authentic, school-based practice, we designed a sequence of teaching episodes (TE)s centred on key topics from the Italian lower secondary school curriculum: motion, forces, Newton's laws, and weight.

Our design was implemented using a longitudinal, descriptive development research method [63]. This approach allowed us to track the evolution of teachers' PCK over time, and to assess how conceptual and methodological development occurred through participation in our teaching experiment. The program ran from 2019 to 2024 as part of the INFN *AggiornaMenti* project [29], with approximately 15 in-service teachers participating each year (about 90 teachers in total). Only one participant held degrees in physics; the others were in biology, chemistry, mathematics, geology, or natural sciences. The

Figure 1. An example of the objects used during the activities to explore free fall under gravity: on the left, plastic spherical containers employed for experiments on gravitational phenomena; on the right, rigid plastic videotape boxes used to compare the fall of two identically shaped objects with different masses.

intervention was structured into a series of three-hour modules delivered at the Physics Department of the University of Cagliari. In each annual cycle, participants engaged in content-rich modules on classical mechanics, electricity and magnetism, fluids, and optics. Teachers were then asked to reimplement one or more TEs in their classrooms and report on their experiences—providing feedback on content adaptation, student engagement, material constraints, and any challenges they encountered in applying the situated methodology.

4.1. Teaching episodes in classical mechanics

The TEs were intentionally designed to mirror authentic classroom scenarios and encourage reflective practice. Each episode lasted approximately one hour and was based on phenomena observable in daily life, used as anchors for inquiry and conceptual exploration.

Reversing the traditional textbook approach that introduces motion first, we began with forces emphasizing their causal nature in initiating and altering motion. For example, in the first episode, teachers investigated why an object resting in their hand remains still. This led to a discussion on equilibrium—not as mere stillness, but as a condition involving balanced forces.

Next, we introduced gravitational acceleration through a series of fall experiments, see figures 1 and 2. Teachers predicted and then

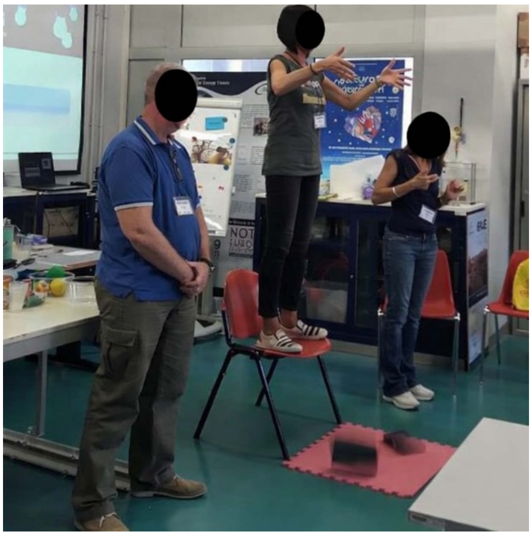

Figure 2. A teacher guided by researchers showing the falling of bodies with different masses and equal shape approaching the ground at the same time.

observed the falling of various objects (e.g. sheets of paper, crumpled balls, and different-sized spheres). They explored how air resistance, shape, and mass affected motion, challenging the general, and intuitive—but incorrect—belief that heavier objects fall faster. This created a moment of cognitive conflict, essential for conceptual change. Participants compared expectations and outcomes, modelled results using natural language and scientific reasoning, and collaboratively built explanations grounded in Newtonian mechanics.

The third episode explored mass and inertia. Using toy trucks of equal shape but differing mass, teachers examined how objects resist motion when subjected to the same external force (e.g. a hair dryer), see figure 3. The more massive truck accelerated less, reinforcing the concept of inertial mass. This experiment led to a qualitative discussion of the equivalence principle, the conceptual bridge between inertial and gravitational mass, and an introduction to general relativity through thought experiments like Einstein's elevator scenario.

In the fourth episode, we addressed the concept of weight using spring-based dynamometers and weight scales. Teachers explored how weight results from the gravitational force acting on mass, analysed the balance between elastic and gravitational forces, and reflected on the common linguistic confusion between weight and mass. This episode emphasized the role of semiotic registers, including everyday language, in shaping conceptual understanding—a key concern in both PCK and situated learning theory.

The final episode focused on inclined planes as a historical and didactic tool, inspired by Galileo's classical experiments [64], see figure 4. Teachers worked in groups to design experimental devices using simple materials (cardboard, marbles, plastic cups), see figure 5. They were asked: *'In which condition does the marble travel further before falling off the table?'* This open-ended, inquiry-driven task required teachers to identify relevant variables (plane height, length, inclination, and initial velocity), measure distances, and share results with peers. The activity supported critical thinking, planning, and reflection on measurement uncertainty and error analysis.

Each episode concluded with a guided reflection, where teachers discussed the feasibility of the activities, the conceptual difficulties encountered, and how the episodes aligned with their classroom needs. They reported how the experiments helped make abstract physics more tangible and accessible for their students. At the final meeting of each training cycle, teachers presented classroom implementation reports. They described how they adapted the methodology, selected materials, navigated logistical constraints, and interpreted student responses. Feedback revealed a generally high level of engagement and appreciation for the situated nature of the activities. Teachers highlighted the value of collaborative learning, hands-on experimentation, and the opportunity to link theory with practice.

5. Discussion and conclusions

The teaching experiment presented in this study was developed to promote the professional growth of lower secondary school teachers in classical mechanics, following the principles of RCM and situated learning theories. Rather than offering decontextualized content, the approach immersed teachers in authentic, inquiry-based activities that reflected the cognitive and pedagogical demands

Figure 3. On the left, an example of objects used to study the motion of bodies on the inclined plane. On the right, tutors show and analyse with the class the motion of two bodies with equal shape and different masses on the inclined plane.

Figure 4. Researchers using a home-made reproduction of Galilei's inclined planes with acoustic bells to describe the motion of bodies according to the studies of the Italian scientist [64].

of real classrooms. The quotations reported in this section are drawn from the 2023 implementation of the program, which is used here as a representative case study for discussing the results. Qualitative data collected across the other years of the intervention are fully consistent with the patterns observed in this cohort.

A central element was the use of the PEC model, which guided teachers through structured cycles of reasoning, investigation, and

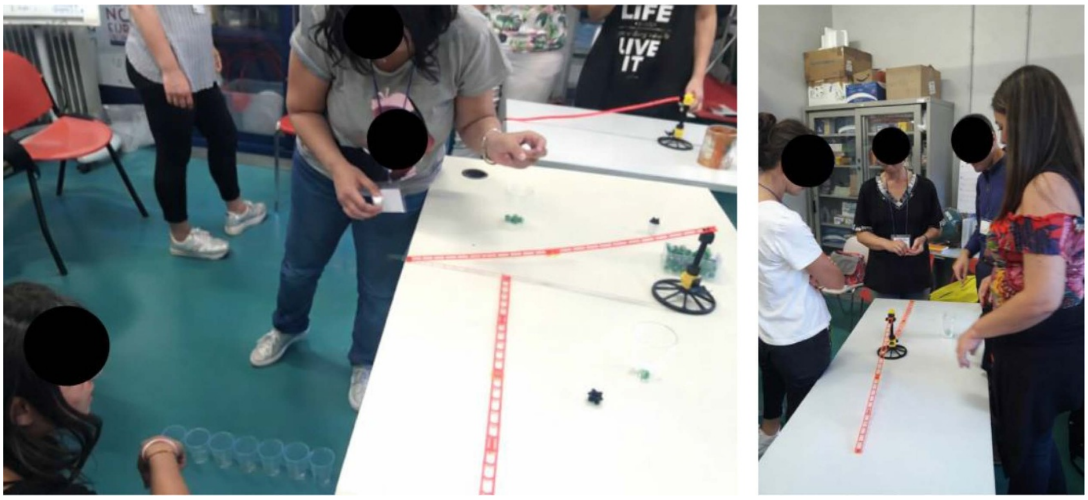

Figure 5. Teachers designing and studying the motion of bodies with their own-made inclined plane.

reflection. This methodology fostered conceptual understanding, supported the development of PCK, and helped bridge the gap between theoretical physics and classroom practice [42–46].

Each teaching episode was designed to build from teachers' prior knowledge and intuitive ideas. Through prediction, experimentation, and group discussion, participants reconstructed their conceptual frameworks. Emphasis on modelling and collaborative reflection aligned with PER that stresses the importance of experiential learning [41, 42, 62–65]. The activities supported conceptual change, particularly when teachers encountered cognitive conflict between their expectations and experimental outcomes—an essential step in developing scientific reasoning.

This development was especially evident when exploring common misconceptions in mechanics. At the beginning of the activity on falling bodies, teachers relied heavily on phenomenological, intuitive explanations grounded in everyday perception rather than Newtonian reasoning. Typical responses included '*because the feather flutters*,' '*because it is lighter,*' or '*because the heavier one is attracted more*.' Similar arguments appeared even after observing that two identically shaped objects with different masses reached the ground simultaneously. Such ideas reflect a persistent non-Newtonian, force-as-mover or Aristotelian framework, well documented in the literature [66–69], and illustrate teachers' initial uncertainty—several answered simply '*I do not know*.'

As the teaching experiment progressed and teachers encountered controlled variations—same shape/different mass; same mass/different shape—they began reorganizing their conceptual resources. Observations involving sheets of paper falling together but diverging when one was crumpled prompted teachers to reference '*surface area*,' '*impact with air*,' and '*drag*,' indicating the emergence of more structured explanatory models.

When presented with a force concept inventory-style question [70], all predicted that a heavier object would fall faster, typically justifying this by invoking a stronger gravitational pull. The failure to recognize that identically shaped bodies experience similar drag revealed the persistence of an Aristotelian conception in which force sustains motion rather than causes changes in it—a form of 'active force thinking' [71]. As shown elsewhere [72, 73], this misconception indicates that Newton's second law is not fully integrated. One teacher, attempting to reconcile intuition and observation, remarked: '*It would be useful to have a longer distance to appreciate the difference*,' illustrating productive cognitive tension, but difficult in contextualize it within a specific conceptual framework.

As teachers were prompted to reconsider the relationship between force, mass, and motion, they gradually moved away from the idea that heavier objects are '*pulled more strongly*' by gravity. They initially overlooked that gravitational acceleration is mass-independent, but inquiry and guided discussion helped them reconstruct this principle. A qualitative excursus on the equivalence principle and Einstein's elevator thought experiment further supported this shift by reframing gravity as a geometric property of spacetime rather than a conventional force. Through this process, teachers began to recognize that acceleration—rather than force magnitude—is the critical observable.

Teachers openly reflected on the pedagogical implications of this shift. One noted: '*According to the textbook, motion comes before force. Then I realize I cannot explain why things move if I never talked about causes*.' Another added: '*I cannot explain what happens in the phenomenon because motion is introduced without talking about the causes of motion*.' These reflections indicate increased awareness of their own PCK and of the limitations of traditional textbook sequencing.

A significant conceptual development emerged during the discussion on equilibrium. Initially, teachers interpreted equilibrium as the absence of motion. Many believed that a force is required to maintain constant velocity, confusing velocity with acceleration. As the tutor introduced examples involving net-force conditions and constant-velocity motion, teachers began to conceptualize equilibrium as a state of balanced forces rather than a static configuration. They came to understand that changes in velocity imply acceleration, and that acceleration is the observable effect of a net force. This reframing also clarified the role of mass—no longer perceived merely as a parameter in formulas, but as a physical quantity indicating resistance to motion. As noted in [74], acceleration is a sufficient condition to infer the presence of a force, and Newton's second law presupposes acceleration. The toy truck experiment, in which two trucks of equal shape but different mass experienced the same force, further reinforced the concept of inertial mass: many were surprised to see the more massive truck accelerate less.

This episode also illustrated teachers' ability to build cross-disciplinary analogies, revealing deeper conceptual integration. One teacher linked mechanical equilibrium to osmosis, noting: '*In osmosis nothing is still—there is dynamic equilibrium*.' Another compared it to phase transitions, explaining that students often imagine molecules as static. These analogies indicate both conceptual deepening and metacognitive engagement.

Semiotic aspects also played a crucial role. Teachers frequently used '*mass*' and '*weight*' interchangeably and cited chemical definitions ('*quantity of matter*,' '*moles*,' '*atomic mass*'). Only a minority initially recognized weight as a force. Everyday Italian language reinforces this ambiguity, as 'peso' denotes both. Through hands-on experimentation with spring scales and dynamometers, teachers reconstructed a more accurate conceptual map. One articulated the modern view: '*Mass is inertia*,' while another recognized that balances 'translate' force into mass via calibration. They also identified the forces involved—elastic force and gravitational force—and understood equilibrium within the instrument. Teachers concluded coherently: '*The weight produces a movement of the spring, and from the equilibrium between forces we deduce the mass*.' This represents a notable shift from black-box use of instruments to physically grounded understanding. Such semiotic and representational development aligns with findings on the role of language and representation in physics instruction [24, 59, 60].

Across the teaching episodes, teachers expressed growing confidence in interpreting phenomena and rethinking their instructional approaches. Initially hesitant—several did not respond when asked whether a force is necessary to keep an object in motion—they later explained relationships among variables, identified dependent and independent quantities, and critiqued textbook sequences. They described experimental setups in their own words, used force and equilibrium arguments, and articulated links between disciplinary knowledge and classroom practice. Several commented explicitly on the value of the approach: '*This unsettles me—I used to tell students that an object at rest has a force on it but did not fully understand the implications*.' Another said: '*Now I see why the dynamometer works; before I used it without thinking of the forces*.' These comments reflect cognitive and affective development, including increased confidence and ownership of reasoning.

During the activity, teachers also reflected on their broader instructional practices. Many acknowledged relying on formula memorization and textbook exercises while overlooking students' misconceptions. Time constraints, safety concerns, and exam pressures were seen as barriers to adopting hands-on approaches. Nevertheless, the structure and collaborative nature of the TEs encouraged teachers to reconsider these limitations. Several reported shifts toward low-cost experimentation and inquiry-based methods, noting increased student engagement and improved reasoning when visual and tangible representations were used. Student motivation appeared to rise when learners constructed their own experimental devices. Although some remained cautious about fully embracing inquiry-based pedagogy, the modelling phase—where teachers generated hypotheses, received guidance, and refined their understanding—proved especially effective in consolidating disciplinary and pedagogical knowledge.

Because the TEs were modular and based on low-cost materials, teachers felt more confident and better equipped to facilitate IBL. In the final episode, many demonstrated enhanced pedagogical reasoning, accurately identifying variables, designing experiments, and interpreting data coherently. Discussions on inclined planes showed more precise terminology and references to conservation principles.

Methodologically, our qualitative approach enabled us to trace teachers' evolving understanding over time. Although no quantitative pre/post assessments were administered, observations, classroom discourse, and informal interviews indicated that the PEC-based teaching experiments effectively supported both conceptual and pedagogical development. Future research using structured PCK instruments and systematic observation protocols could further validate these findings and assess long-term impact.

Overall, the findings suggest that science teacher professional development is most effective when rooted in situated, inquiry-rich, and reflective practice. Engaging teachers in the same modelling, experimentation, and reasoning processes expected of their students fosters durable transformations in teaching identity and instructional capacity. While some participants noted persistent time constraints, they recognized the relevance, adaptability, and collaborative value of the approach. Future work should include follow-up questionnaires and focus groups to examine how teachers implement the methodology, whether conceptual gains persist, and what impacts they observe on their students.

Acknowledgments

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Ethical statement

Informed consent to participate in the study has been obtained from participants. Any identifiable individuals participating in the study have also been aware of the intended publication. Informed consent to publish has been obtained from participants of the study. This work was carried out in accordance with the principles outlined in the journal's ethical policy and with the 'Codice etico e di comportamento' of the University of Cagliari.

Declaration of generative AI in scientific writing

The authors declare that no generative artificial intelligence tools were used in the design, analysis, or interpretation of this study. Language editing assistance was limited to grammar and style correction using AI-assisted tools (ChatGPT-5), with all intellectual content, analysis, and interpretation solely the responsibility of the authors.

Conflict of interest

There are no known conflicts of interest associated with this publication, and there has been no significant financial support for this work that could have influenced its outcome.

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