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Teaching Scientific Practices through Low-Cost Tools: an Experiment with High School Students

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Abstract: *The study regards the development of a teaching-learning sequence (TLS) for students in a technical institute, aimed at enhancing scientific practices. The TLS was designed following a design-based research methodology, undergoing two cycles of design and test. The study describes the process and analyses students' achievement of a specific learning outcome (the development of the practice 'developing and using models') during the latest version of the TLS. To obtain a more accurate evaluation, an assessment strategy based on the triangulation of multiples sources (students' work and an observation grid filled in by two independent observers) was adopted. The findings suggest that the TLS had a positive impact on the development of the target scientific practice, particularly in some sub-abilities such as the mathematization of motion, its representation through space-time graphs and motion diagrams, and the translation between different representations. On the other hand, students had difficulties in constructing multiple representations and discussing the limitations of models. The study emphasizes the importance of continued refinement of teaching proposals to address emergent challenges and optimize learning support.*

Keywords: *teaching-learning sequence*

I. INTRODUCTION

Between 2018 and 2020, the Research Group in Astronomy and Physics Education at the University of Padova organized a professional development program for physics teachers called CoLLabora [1]. The program aimed to establish a teacher learning community experimenting with a more authentic use of laboratories in secondary school physics teaching. At the conclusion of the program, several teachers expressed the desire to disseminate the proposed approach within their own school contexts. This contribution outlines an action research project conducted by one of the teachers over 2 years after the conclusion of the program. Her focus was on restructuring laboratory activities to promote the development of scientific practices [2]. The emphasis was on both the final product and the process that students used to design, conduct, and interpret laboratory activities, aligning with national and international guidelines [3, 4]. Specifically, a Teaching-Learning Sequence (TLS) on linear motion was designed and implemented in five classrooms of a computer science technical institute. The design of the TLS was also guided by principles of replicability and exportability, with the aim of disseminating it to other school contexts in the future. Here, we present the development of the TLS, its implementation, and the evaluation of its effectiveness, focusing on the development of one specific practice, 'developing and using models'

Background and research questions

Teaching and learning sequences (TLSs) [5] are useful tools for enhancing the effectiveness of classroom teaching. A TLS is a series of instructional activities characterized by robust grounding in research findings on students' learning of the topics and tailoring of methodologies to the specific teaching context. The outcome of this process is both a research result and a product that can be directly applied in instruction. Practical advice on how to design a TLS has been offered by some authors [6, 7]. In this study, we followed the approach outlined by Guisasola et al. [7], which is grounded in the designbased research (DBR) methodology. It consists of six steps: 1. Focus: identify the students targeted by the TLS and define the topic. 2. Understanding: conduct research to identify students' difficulties or prior

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knowledge related to the topic and potential solutions. 3. Define: identify the learning goals as well as the criteria for evaluating their achievement. 4. Conceive: design the activities to be included in the TLS. 5. Build: implement the TLS. 6. Test: evaluate the results and redefine the TLS based on feedback. The TLS was designed according to a guided inquiry approach. An investigative approach to science education has been advocated by several international documents [3] and has been included in national educational guidelines in the United States, such as the Framework for K-12 Science Education [2], the related Next Generation Science Standards [8], and the more recent Science and Engineering for Grades 6-12: Investigation and Design at the Center [4]. The concept of 'inquiry', however, can be interpreted in multiple ways and therefore Crawford [9] suggested clarifying how it is understood in a school setting. The National Research Council, echoed by Crawford and other authors [10], suggested that inquiry should be operationalized in terms of 'scientific practices' to make it more accessible to teachers and more aligned with 'school inquiry'. Specifically, eight scientific practices were identified: 1. Asking questions and defining problems 2. Developing and using models 3. Planning and carrying out investigations 4. Analyzing and interpreting data 5. Using mathematics and computational thinking 6. Constructing explanations and designing solutions 7. Engaging in argument from evidence 8. Obtaining, evaluating, and communicating information Focusing on 'practices' rather than on 'inquiry' also allows emphasizing the importance of theoretical components and their interplay with experimental skills. The amount of guidance students receive from the teacher during inquiry-based activities is another crucial factor. In guided inquiry, the role of the teacher in structuring the activities and in supporting students during experiments is crucial. The teacher acts as a facilitator, guiding students through questions to help them in their investigations. This approach has been suggested as preferable compared to 'open' inquiry, where students are left to their own investigations without support from the teacher [11]. Recent studies at the undergraduate level have further endorsed a guided inquiry approach, suggesting that it is particularly effective for developing scientific skills and enhancing students' agency [12]. Therefore, a guided inquiry approach was chosen for this TLS. The aim of this study was to develop a TLS on linear motion and test its effectiveness in teaching scientific practices to secondary school students. Specifically, the research question that guided the research was: "To what extent did the TLS enable students to develop scientific practices, specifically the ability to develop and use models?". The next step involved identifying the specific learning goals for the TLS and how to assess their achievement ('Define' phase). Consistent with our research question, the main learning goal was to increase students' ability to develop and use models. In the first iteration of the TLS, the teacher referred to the 'scientific abilities rubrics' published by Etkina et al. [20, https://www.islephysics.net/], selecting the items that applied to each experiment. Observation from this pilot iteration indicated the need for a more comprehensive tool to properly evaluate the target scientific practice. This process entailed starting from the practice and detailing it into a full list of indicators formulated as scientific abilities. The indicators should cover different aspects of the practice, such as identifying the relevant variables, constructing representations, using simulations and relating them to the real world, using the model to solve problems, identifying limitations in a model, etc. Some of the abilities were adapted from Etkina's rubrics [20], while others were created by the teacher: the full list is given in table 4. Indicators B1 and B2 deal with the identification and representation of the relevant characteristics of a phenomenon. Indicators B3 to B5 represent the ability to transition between different representations and evaluating their consistency; representations allow students to highlight the important features of a phenomenon, making it easier to build models. Indicators B6 to B8 regard the process of model building. Indicators B9 to B11 regard the use of simulations, a specific type of digital model that highlights the relevant features of a system or phenomenon based on an underpinning physical model. Indicators B12 to B14 refer to using the model to solve problems and analyze data. Indicators B15 and B16 relate to comprehending the limitations and simplifications of a model, and indicator B17 involves understanding how a model can contribute to gaining a comprehensive view and understanding of physics. From this list, the teacher selected the indicators that applied to each lesson and used them for assessing either students' work (for the laboratory experiences) or students' attitude during the lesson, evaluated with an observation grid as described in the Methodology section. It is important to specify that the evaluation of the laboratory experiences that were included in both the first and the second iteration of the TLS was performed using the

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same indicators. These indicators were then incorporated into the more comprehensive framework outlined in table 4 in the second year. It is also important to note that although only a subset of the items on the list were used for this TLS, the scope of the list is broader. It represents an attempt to relate Etkina's 'scientific abilities' to the evaluation of scientific practices, thus establishing a connection between the 'abilities' approach and the NRC Framework. The list is a useful tool for the teacher if a longitudinal approach to the development of scientific practices is adopted, as different items on the list could apply to experiments in a previous or subsequent TLS. The activities ('Conceive' phase) were structured to allow students to practice different representations and the transition between them. As suggested by Guisasola [7], we identified some 'core' activities that we suggest maintaining even if the TLS is replicated in a different context. These activities were identified in five laboratory experiences, ensuring they were structured to address the identified learning difficulties. For this reason, in table 3 the correspondence between learning difficulties, learning indicators, and activities is highlighted only for these experiences. Nevertheless, learning difficulties were addressed also during the other lessons in the TLS. The TLS was replicated over two consecutive academic years (2021-22 and 2022-23) ('Build' and 'Test' phases). After the first ('pilot') iteration, modifications were made in response to observations and students' feedback, giving priority to reinforcing the development of the target scientific practice. The final structure of the TLS is presented in the next section, while the details of how the TLS was evaluated are given in the 'Methods' section.

Methodology

The TLS was piloted in 2020, refined after the first implementation, and then retested in 2021. Overall, 116 students from five classes (3 in the 1st year, 2 in the 2nd year) were involved. To document and evaluate the TLS, the teacher-researcher considered different sources, listed in table 6. Students' artifacts (written reports and homework) were collected and evaluated after each experience, and students' summative assessment (grade in the final test) was monitored as a measure of their general understanding. The teacher kept a personal reflective journal, compiled at the end of each lesson, documenting observations, reflections, and impressions about the progress of the activities. In the 2nd edition of the TLS, an additional element was introduced, i.e., an observation grid compiled by both the teacher and an external observer independently at the end of each lesson. The observer was another teacher from the school, who also took part in the CoLLabora program and was therefore trained on the assessment of scientific abilities

II. DISCUSSION AND CONCLUSIONS

We presented the development of a teaching-learning sequence on linear motion, designed according to a design-based research methodology with two cycles of iteration. The main learning goal was reinforcing the scientific practice 'developing and using models.' In the 2 nd iteration, a more robust tool for the evaluation of the target scientific practice was introduced, consisting of a list of sub-abilities representing different aspects of the practice. For each lesson, selected items were specifically targeted and assessed using multiple complementary sources, in particular students' written reports and an observation grid compiled by two independent observers.further development. For example, identifying key features (B1) and constructing representations (B2) received positive ratings from both sources of evaluation, while constructing multiple representations (B5) and discussing model limitations (B6) received lower scores. Interestingly, these abilities received higher ratings from observations compared to students' reports. In fact, several students did not report hypotheses or present more than one representation in their reports, although they did so during the experiences and were able to provide them when explicitly asked. This suggests that the evaluation of final reports alone may not be an accurate measure of students' development of scientific practices, advocating for assessment strategies that entail triangulation of multiple sources. On average, several items received medium to high scores, suggesting that the TLS has facilitated students' ability to develop and use models. Students developed competence in understanding graphs and transitioning from this representation of motion to another, whereas they still face challenges in identifying the assumptions underlying the model and utilizing different representations to solve problems. Therefore, these abilities require further refinement. In this regard, it is worth specifying that the proposed

TLS does not represent a stand-alone teaching experiment but is part of a broader learning progression that unfolds along two years, specifically aimed at developing scientific practices (article in preparation). Such a perspective allows the teacher to act at multiple points during the students' journey to target the specific sub-abilities that are not satisfactorily achieved during one specific TLS.

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