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Innovating physics teaching through teachers' learning communities and action research

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Summary. — The paper provides information, foundation and supporting evidence about a possible structure of a research-based in-service program for physics teachers aimed at improving their use of the laboratory. We present our model and we describe the CoLLabora project where the model was first implemented. The results suggest that the program actually produced positive changes in the participants' ideas about the laboratory, its actual use in their teaching practice, and in students' outcomes. We also present two case studies and we outline some research lines and the 'teacher training cascade' that have developed from the project.

1. – Introduction

Innovating physics education is an effort that has been going on for many years all over the world and in Italy as well. The proposed initiatives are numerous and valuable, and many of them are recounted in this special issue. However, this endeavor cannot succeed unless it personally involves those who work in the field every day to bring a more authentic and meaningful understanding of physics to new generations: teachers.

In international literature, the problem of teacher education has been treated from different viewpoints and is also identified as one of the strategic factors of the United Nations 2030 Agenda for Sustainable Development [1]. A lot of work has been done in the past twenty years through projects, conferences and research programs [2, 3]. In physics education research (PER), one of the key nodes is the encounter between teacher education and discipline-based research, specifically concerning the innovation of the contents, instruments and methods of physics teaching [4-6]. In fact, numerous studies have revealed that the application of PER results in the classroom is still limited and there is often a lack of understanding, appropriation and internalization of innovations. One major example concerns the laboratory and the use of inquiry-based practices [7].

This background suggests that a deep work of reflection, re-elaboration and integration of research results from different fields, and further research —both theoretical and empirical— is still needed. This is particularly true in the Italian context, where a decades-long regulatory gap has made initial and in-service training structurally fragmented, provisional and tied to economic and political contingencies [8, 9].

The Research GRoup in Astronomy and Physics Education of the University of Padua (GRAPE) aims at contributing to this international debate and to the enhancement of physics education in Italy by focusing on the development of teacher training programs based on current disciplinary and educational research and characterized by a laboratory- and inquiry-based approach. Our perspective is rooted in a view in which the relationship between teachers and physics education researchers is conceptualized through the learning community construct [10,11]. This means that teachers and researchers not only collaborate to design and implement specific teaching-learning sequences, but also learn together continuously, engage in reciprocal training, experiment and reflect on common research questions. This implies sharing an 'inquiry stance' on teaching [12] that is more strongly understood as action-research, an intentional action geared toward improving the teaching of physics based on data and observations [13]. In all of this, an effort is made to always maintain a focus on the context and needs of the schools, designing innovative but sustainable and shareable teaching-learning paths, with the goal of 'training the trainers', the teachers who will then take the tested innovations to their territory, producing a cascading effect and thus a greater impact than the one that can be directly sustained by the research group.

Concretely, in recent years our group has been experimenting an in-service teacher training model that builds on the characteristics recognized by international literature (content focus, active learning, coherence, long duration, collective participation) [14] and poses the learning community approach and action research as the key underlying elements. Participants meet on a regular basis for at least one year, in which, in addition to experiencing research-based proposals and discussing specific issues in physics education, they are involved in designing and experimenting teaching-learning sequences (TLSs) for their own classroom as a form of action research. In this paper, after better clarifying the theoretical frameworks and perspectives on which our approach is based, we will present CoLLabora, the first project in which we have experimented it, and which has become paradigmatic for the design of our in-service training courses. We will discuss the results of the project and the new research questions it has opened up.

2. – Theoretical frameworks and perspectives

2˙1. *Perspective on teachers' education and training.* – Our approach to teacher training is grounded in a theoretical framework that builds on two key ideas:

1) Teacher training should be situated in practice and subject to reflective inquiry.

2) The innovation of physics teaching requires 'authentic collaboration' [15] among teachers and between teachers and researchers.

These ideas can be traced to a theory of learning in which learning is considered both social and situated [16].

Ball and Cohen [12] suggested that teachers' training should be a matter of *learning* rather than *updating*, and argued that this lens implies the interplay of three elements: knowledge, practice, and reflection on practice. The latter involves adopting an 'inquiry stance' about one's teaching. When it is specifically oriented to solving a particular problem, this approach is often called action-research. In action research, a teacher identifies an area of improvement for his or her classroom, plans actions to tackle the problem, collects and examines data, and uses the results to improve practice [13]. Action research often involves an interaction between teachers and researchers, who can have different roles. In particular, 'participatory' action research is characterized by a close collaboration between researchers and teachers, through activities aimed at identifying problems, coaching during the research process, and shared analysis of results [17].

Couso [15] proposed the paradigm of 'authentic' collaboration to characterize the relationship between teachers and physics education researchers. Authentic collaboration is a bottom-up strategy alternative to top-down approaches where materials produced by researchers are experimented with limited teacher participation. The idea stems from the belief that a true sense of ownership of innovation can only be achieved if teachers share and co-construct innovation, adapting it to their own context. A key element of the paradigm is that authentic collaboration is not limited to the relationship between teachers and researchers, but also to the interaction with other teachers. This vision calls for a new way of conceptualizing teacher education, that can be done using the construct of the learning community [10, 11].

A learning community is not just a group of participants in a course or belonging to a class. In fact, it contains the important idea of *community*, the distinctive features of which have been identified by Brown and Campione [10]: individual responsibility coupled with communal sharing; ritual, familiar participation structures; a community of discourse; multiple zones of proximal development; seeding, migration, appropriation of ideas. Teachers' learning communities (TLCs) are based on mutual trust and respect, and are characterized by a common commitment to a goal. TLCs can foster the quality of discourse on the teaching of a subject and enable encounters with different practices and perspectives on practice. The results of such communities are not only improvements in an individual teacher's practice: they also contribute to collective professional inquiry and have the potential to sustain themselves even after the initial phase [11, 15].

Alongside these elements, it is important to consider some structural features of teacher education programs that have been recognized as effective by research. In a review of the literature, Desimone [14] identified five core features: content focus; active learning opportunities; coherence; sufficient duration; collective participation of teachers from the same school or grade. One can see how some of these characteristics are intrinsically embedded in an approach based on learning communities and action research.

Finally, research has discussed the elements to be considered in assessing the impact of teacher training, *i.e.*, the changes produced by the training program. Three dimensions of change are common throughout the literature: the personal domain (knowledge, skills, attitudes, and beliefs), teaching practice, and the outcomes (effect on students). Different models have been proposed to explain how these effects occur, and specifically about the order in which they appear and the processes that link them [14, 18, 19]. In this paper, we refer to Clarke and Hollingsworth's model [19], according to which the three dimensions are interconnected in a non-sequential way between themselves and with the external domain (the teaching training program), through the processes of enactment and reflection. Individual teachers' paths of change may have various entry points and develop differently. This model highlights the importance of analyzing teacher development along with the conditions that promote it and acknowledges the possibility of multiple developmental pathways [20].

2˙2. *What about physics teachers?*. – Research on physics teacher education has embraced general perspectives on teacher education but has integrated it with the characteristic elements of physics and the results of PER. In fact, it is now widely agreed (though not always realized in practice) that physics teacher education and training should be rooted in research and capitalize on the wealth of results, tools and strategies developed by PER [4, 5]. For example, Etkina [21] emphasises elements such as:

- a deep conceptual understanding of physics and of the physics curriculum;
- an orientation towards physics teaching that acknowledge the role of students' ideas, the roles of experiments in the classroom, etc.;
- knowledge of typical students difficulties and learning processes in physics, including productive ideas and resources;
- knowledge of instructional practices that are effective in scaffolding students' learning of physics concepts and practices;
- knowledge of assessment methods (*e.g.*, how to assess students' work in the lab).

As for the method, Etkina acknowledges the importance of cognitive apprenticeship (teachers observe experts modeling the desired practices, then apply them with the expert providing scaffolding, advice and feedback), and the importance of creating a professional learning community, which provides support and facilitates the retention of innovations. Etkina and colleagues [22, 23] go further by proposing that cognitive apprenticeship and participation in a diverse community of practice are the elements of a model for teacher training, that is able to 'explain' the empirical core features of effective programs. According to the authors, these two factors are important in developing not only knowledge and orientations, but also habits of practice. The two factors resonate with the two elements that we propose here (learning community and action research), and their interplay and synergy find further support by additional recent literature in physics and science education [24-26].

2˙3. *Approach to the physics laboratory*. – In the discussion on the improvement of physics education, laboratory activities always play a central role [27]. In particular, inquiry-based approaches have been advocated as particularly promising in order to foster the development of science content, scientific abilities, and the understanding of the nature of science [28, 29]. All models of inquiry-based science education emphasise the active role of learners, the importance of connecting experiences and theories, and the value of collaboration [30].

Despite the unanimous recognition of the potential efficacy of these approaches, teachers encounter many difficulties in applying them in the classroom [31, 32]. The concept of inquiry itself is not easy to grasp [7]. In the light of these observations, 'scientific practices' were introduced as a way to re-conceptualize and operationalize inquiry-based teaching approaches in a way that is more meaningful for teachers [33, 34]. A possible list of practices has been proposed: asking questions; developing and using models; planning and carrying out investigations; analyzing and interpreting data; using mathematics and computational thinking; constructing explanations; engaging in argument from evidence; obtaining, evaluating, and communicating information.

Different approaches have been proposed to implement the principles of inquiry-based science teaching. One that particularly values the role of practices is ISLE (*Investigative Science Learning Environment*) [35]. ISLE puts an emphasis on the development of different 'scientific abilities' and on the role of different types of experiments for a meaningful and deeper understanding of physics [36]. Different abilities can be developed through different types of experiments: in *observational* experiments, students observe a new phenomenon and try to identify patterns; in *testing* experiments, students put hypotheses and explanations to the test; finally, in *application* experiments, students use their knowledge to solve new problems or explain new phenomena [37]. The three types of experiments represent different moments of an investigative cycle where they are complemented by interpretation, conceptualization, and meta-cognitive activities [38].

ISLE also involves a focus on the assessment of scientific abilities, which are evaluated using specially constructed rubrics [36]. These rubrics are adapted to each specific experiment and are also shared with students with the goal of favoring self-assessment.

3. – Our model and our research

Moving from the background outlined above, our group is experimenting a model for organizing in-service teacher training programs that is represented in fig. 1:

- The learning community approach and action research are the pillars around which the programs develops.
- The core features identified by the literature (clear disciplinary focus; coherence with teachers' backgrounds and needs; active learning opportunities; sufficient duration) provide structure to the program.
- The program is grounded in physics education research, from which it draws the results, tools, strategies and methods.
- The approach to physics education is inquiry-based, and in particular the proposed activities aim at the integration of science content and practices.

The model is called "the CoLLabora model" as the first program in which it was developed and experimented was *CoLLabora - A Community of Learners on LABORAtory work*, developed between 2018 and 2020.

Fig. 1. – The CoLLabora model.

Our research hypothesis is that this approach can produce positive changes in both the personal environment, teaching practice, and students' outcomes. Specifically, the research question that moved the project was:

[RQ1] How do we organize in-service physics teacher training in a way that generates authentic changes in teachers and activates further positive effects in the territory?

4. – The CoLLabora project

The CoLLabora project started in 2018 and involved 15 upper secondary school physics teachers from 11 schools in the Veneto region. Their teaching experience ranged from 5 to 20 years. Most of them were teaching in Italian Licei (university-oriented high schools), either with science- or non-science majors; three of them were teaching in technical schools. Eight participants had a degree in mathematics, while the others had a degree in physics (3), engineering (3), or astronomy (1). Most of the teachers had very low (5) or medium-low (6) personal laboratory experience; only 4 teachers used to propose laboratory activities regularly in the classroom, while the others offered them occasionally (7) or almost never (4).

The program was originally scheduled for one year, during which teachers met 13 times, totaling 45 hours of face-to-face training. The program was then continued for a second year with additional 9 meetings (25 hours of training).

We focused the program on a specific physics topic: waves. For the development of the laboratory activities, we mainly relied on the ISLE model by proposing the three types of experiments (observational, testing, and application experiments) and reflecting on the assessment of scientific abilities. Alongside laboratory activities, we proposed reflections on problem and issues related to the teaching and learning of waves, complementary approaches (*e.g.*, visits to museums of scientific instruments), and reflections on specific aspects (*e.g.*, use of digital technologies in the laboratory).

4·1. *The disciplinary topic: waves.* – The topic of waves is a key idea in physics, as it represents a way of modeling and describing a variety of phenomena in classical and modern physics [34]. The choice of this topic not only allowed hooking into different grades and types of schools, but also promoted a more fundamental understanding of the physics curriculum.

In outlining the training path, we started by considering the educational reconstruction of the subject of waves, summarized for example in Balzano *et al.* [39]. The schedule and topics of the first year of the program are reported in fig. 2(a).

The two introductory meetings were aimed at introducing the topic of waves and the theme of the laboratory. To this end, we proposed ISLE labs on ray optics and compared them with traditional labs on the same topic. These experiments were then resumed later in the course when we treated wave optics.

The third, fourth and fifth meetings were dedicated to mechanical waves, starting with the study of impulses on strings and springs. The study of single pulses allows challenging a common difficulty in the interpretation of waves, *i.e.*, distinguishing between the motion of the pulse and the local oscillation of particles in the medium [40,41]. Moreover, it allows strengthening the description of wave phenomena in terms of the source-medium-receiver scheme, identifying the involved variables, their relationship, and their dependence on the different elements of the system. The use of different graphical representations was emphasized, highlighting the distinction between the spatial view ('snapshot graphs') and

(a)

Date	Activity
May 2018a	Introduction, initial ideas on the use of the laboratory, learning community kick-off.
May 2018b	Laboratory (testing experiment + application experiments) on ray optics + discussion.
September 2018a	Laboratory (observational experiment) on mechanical waves with ropes and springs. Formulation of action-research questions.
September 2018b	Educational reconstruction of the topic of waves. Design of action-research plans.
October 2018	Discussion of the Mechanical Waves Concept Survey (MCWS) and reflection on the teaching and learning of mechanical waves. Introduction to scientific practices. Laboratory on standing waves.
November 2018	Discussion of PER results on sound waves. Laboratory on sound waves using the PhyPhox app.
December 2018	Visit to the Museum of the History of Physics + reflection on the role of instruments in physics education. Group work on the role of different types of experiments and their role in a teaching/learning sequence.
January 2019	Co-design of a laboratory on wave optics. Introduction to ISLE assessment rubrics and discussion on the assessment of laboratory activities.
February 2019	Laboratory on wave optics with the three types of experiment (observational, testing, application).
March 2019	Individual and group concept map on the topic of light. Laboratory on light sources and spectra.
April 2019	Laboratory on atomic spectra. Discussion on the value of spectroscopy to introduce modern physics.
May 2019	Final workshop: presentation of individual action research project results.
June 2019	Final focus group.

(b)

Date	Activity
October 2019	Introduction to TLS design and *backward design*. Division in sub-groups according to the topic of choice and start of co-planning.
November 2019	Discussion of the relationship between inquiry-based learning, scientific practices, ISLE approach. Continuation of co-planning.
December 2019	Presentation of a TLS designed using the backward design approach, previously experimented by one of the participants. Experimentation of some of the activities included in the TLS.
January 2020	Micro-teaching/1 + feedback.
February 2020	Micro-teaching/2 + feedback.
March 2020	(online) Presentation and discussion of TLSs; reporting about experimentation in the classroom.
April 2020	(online) Presentation of TLSs and discussion of some disciplinary nodes; reporting about experimentation in the classroom.
May 2020	(online) Presentation of TLSs; reporting about experimentation in the classroom.
June 2020	(online) Final focus group.

Fig. 2. – The schedule and topics of (a) the first year and (b) the second year of CoLLabora.

the temporal view (‘history graphs’). The Mechanical Waves Concept Survey [42-44] was used to raise typical interpretive difficulties and discuss strategies to deal with them [45].

Sound waves were treated next; an experiment on standing waves was proposed as the bridging element. Sound was characterized in relation to mechanical oscillations in different musical instruments; the Phyphox app [46] was used to measure sound characteristics and introduce frequency analysis.

We finally studied light waves, observing similarities with the phenomenology of mechanical waves. In this case, the step was supported by the observation of two-dimensional waves in water using a ‘wave scope’ [39]. Wave optics phenomena were compared with ray optics phenomena studied in the preliminary meetings, proposing a reflection on the role of models in physics. As the last step, we approached modern physics through experiments on spectroscopy. In particular, we built a cardboard spectroscope [47] for spectral analysis of different light sources, including spectral lamps, and discussed the related teaching issues [48, 49].

4·2. *The second year: CoLLabora - Into the classroom.* – A focus group held at the end of the first year revealed the participants’ wish to maintain the learning community, with further support in the design of TLSs and in-depth collaboration. We therefore decided to continue the program for a second year; 11 of the original 15 teachers, from 9 schools, participated. The new course was called *CoLLabora - Into the classroom*, since the focus was on classroom experimentation of the innovation proposed in the first year.

The community approach was reinforced by introducing activities such as co-planning, micro-teaching, and peer review. To provide structure to the design of TLSs, we proposed the *backward design* model [50], which emphasizes the reversal of the traditional activity-oriented logic: the design of a teaching unit starts from the identification of essential and enduring 'understandings' for a topic, followed by the identification of what constitutes evidence of learning; identifying the sequence of activities is the last and third step.

The schedule of the second year is reported in fig. 2(b). As for the disciplinary content, we released the focus on waves, as with the new school year not all teachers were teaching wave-related topics, whereas the opportunity for all participants to concretely experiment in the classroom was an indispensable element. We therefore let the teachers choose the topic of their experimentation, while requiring that they clustered in a limited number of groups in order to allow co-planning.

The first three meetings were devoted to co-design: working in sub-groups, teachers engaged in a conceptual analysis of their topic and identified the 'enduring understandings'. Questions such as: *What do we want students to learn and be able to do? What is essential, and what is complementary? What do we know about students' ideas in this topic? What are productive representations, resources, and learning approaches for this topic?* guided the teachers in this phase. In defining the learning goals, we paid attention to the alignment with the Italian National Directions, in order to comply with one of the elements of effectiveness of teacher training programs, *i.e.*, coherence with the teachers backgrounds and contexts, including institutional contexts.

In the second part of the course, after completing their design matrix individually, each teacher engaged in a micro-teaching session, in which he/she proposed some of the planned activities to the colleagues and received feedback. In March 2020, due to the COVID-19 pandemic, we moved the meetings online. At the time, two micro-teaching sessions (6 teachers) had already been done. Although the others could not propose a real micro-teaching at a distance, they nevertheless presented their plan and activities and discussed them with the colleagues.

4·3. *The learning community and action research.* – Here we provide a brief description of how we practically implemented the two methodological pillars of our program, *i.e.*, the learning community approach and action research.

The starting point for the creation of the learning community was a common intention for improvement and change with respect to the use of the laboratory. With specific activities in the first part of the course, we started from recognizing this common endeavor in order to write down the expectations we had from ourselves and from one another. The community was then sustained with group work, peer-review activities, co-planning, and opportunities for discussion. A specific attention was posed in creating a climate of trust and respect, and to the sharing of ideas and materials.

Although the participants were moved by this common intention, each of them had their own starting point and focus that needed to be made explicit and dropped into the reality of their classroom; that is, they needed to identify their own action research question. Teachers guided through the process of formulating a research question and designing a research plan with specific activities, many of which were inspired from materials produced by the LINPILCARE project [24].

Figure 3 shows an example of an action-research plan submitted by a teacher, and some of the results she obtained. Based on these results, she revised her laboratory activity and started a new research cycle the next year. Since then, she continued refining her activity and expanded it to more topics. Another example of an action research plan developed during the first year of CoLLabora was described in [51], while a TLS developed in the second year using the backward design model is discussed in [52].

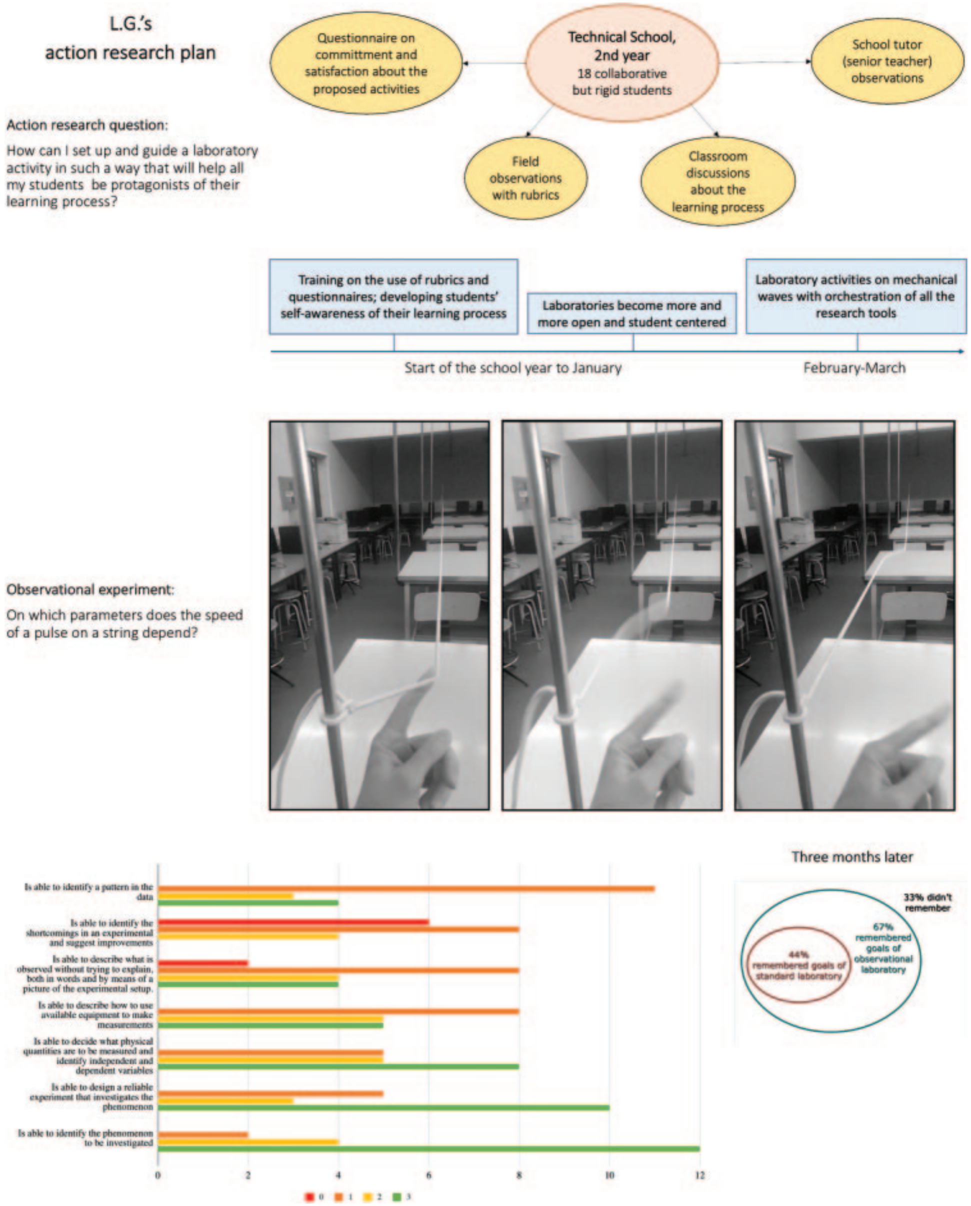

Fig. 3. – The action research plan and results of one of the teachers (1st year).

5. – Methods

To gain insights into our research question we used different instruments:

- Moodle questionnaires at the end of each year were used to survey aspects such as the degree of satisfaction and the most useful activities. They also contained open-ended questions about changes in the use of the lab and the program in general.

- Focus groups, also at the end of each year, allowed gaining insights into the groups' views on the program and its effects. Specifically, the first-year focus group investigated the role and relevance of the program features, of the learning community, and of action research. The second year's focus group, besides investigating the effectiveness of specific choices (*e.g.*, micro-teaching activities; backward design approach), delved deeper into the role of the learning community and action research after two years of experiencing them.

- Finally, individual interviews at the end of the program allowed for in-depth investigation of the changes that occurred in each teacher.

The interviews, focus group transcriptions, and the other qualitative data were coded against the changes reported by the teachers, using emergent categories (*e.g.*, "Knowledge of different types of experiments"; "Use of the laboratory for more topics"). The changes were then macro-categorized into Clarke and Hollingsworth's (2002) three domains (personal domain, domain of practices, domain of consequence). To gain further insights into the process that led to the reported changes, we coded the data according to the following categories, also emergent from the teachers' comments, describing different elements of the program: ideas and information; practical activities; colleagues' experiences; direct experimentation and action research; feedback and discussions.

6. – Results

6˙1. *Relevance of the elements of the model*. – We start by summarizing the results about the relevance of the different elements of the CoLLabora model. For further in-depth analysis in this regard, see [53, 54].

Participants acknowledged the importance of situating the course in a specific physics topic. The choice of waves was appreciated for its transversal value throughout the curriculum: "At the beginning, I didn't think the topic would be of interest for my students. Instead, I understood that it is a cross-curricular topic; it made me see physics in a different way." (M.R.F.). Enlarging the focus in the second year allowed everybody to experiment, but some teachers reported more difficulties in participating actively.

An increased awareness of PER results encouraged teachers to experiment the new strategies despite an unfavorable context: "I was really thirsting for it. It gave me a sigh of relief, seeing that I'm not alone, there is someone who is working on this" (L.G.).

Active learning opportunities were recognised as very relevant. Experimenting research-based laboratories with colleagues was judged as one of the most useful activities. Participants also mentioned the value of group discussions, coaching and support, and, after the second year, of micro-teaching activities.

The long duration of the course was appreciated as it allowed gradual implementation and appropriation of the proposed innovations: "It was so good that we could experiment during the course, reflect, and try to apply something in the classroom. And if something went wrong, the next month you could catch up" (F.C.).

Participants appreciated the opportunity of engaging with action research: "I was tired of doing things for pretend [...]. This time I had a classroom and I had to experiment in it" (L.G.); "If someone proposes a methodology, I would also like to try it out, so I can better understand what its strengths are, how to use it, in which contexts" (S.D.). A crucial element was accompanying teachers' experimentation and providing tools for inquiry: "I appreciated so much how you guided in the formulation of our action-research question, starting from where we were, from our strengths and weaknesses" (L.G.).

Finally, participants reported that the learning community approach supported learning, favored collaboration with colleagues, sustained classroom experimentation, and fostered the relationship between schools and the university. With reference to the features of learning communities identified by Brown and Campione [10], participants talked about the CoLLabora group as a "community of discourse" where you can share interests and visions: "For me, this group was like an anchor; it gave me company, pleasure, inspiration, and quite a bit of confidence for the future" (M.P.); they acknowledged the presence of individual responsibility coupled with communal sharing: "I think a course is truly "developmental" when I prepare myself to train others, and, in doing so, I also train myself." (L.G.); "What I have done in the classroom really comes from the contribution that all the people here have given me" (M.R.F.); finally, the seeding, migration, and appropriation of ideas was also very important: "I have my folders with all the different teaching units, and I am putting in the colleagues' ideas... I will take them out at the beginning of the next school year, and see if I can do something of what they did" (E.P.).

6·2. *Changes*. – Figure 4 summarizes the changes reported by the teachers over the 2 years. After the first year, teachers mainly reported changes in the personal domain (*e.g.*, deeper understanding of the physics curriculum; knowledge of different types of experiments; more positive self-efficacy beliefs) and in teaching practice (increased use of

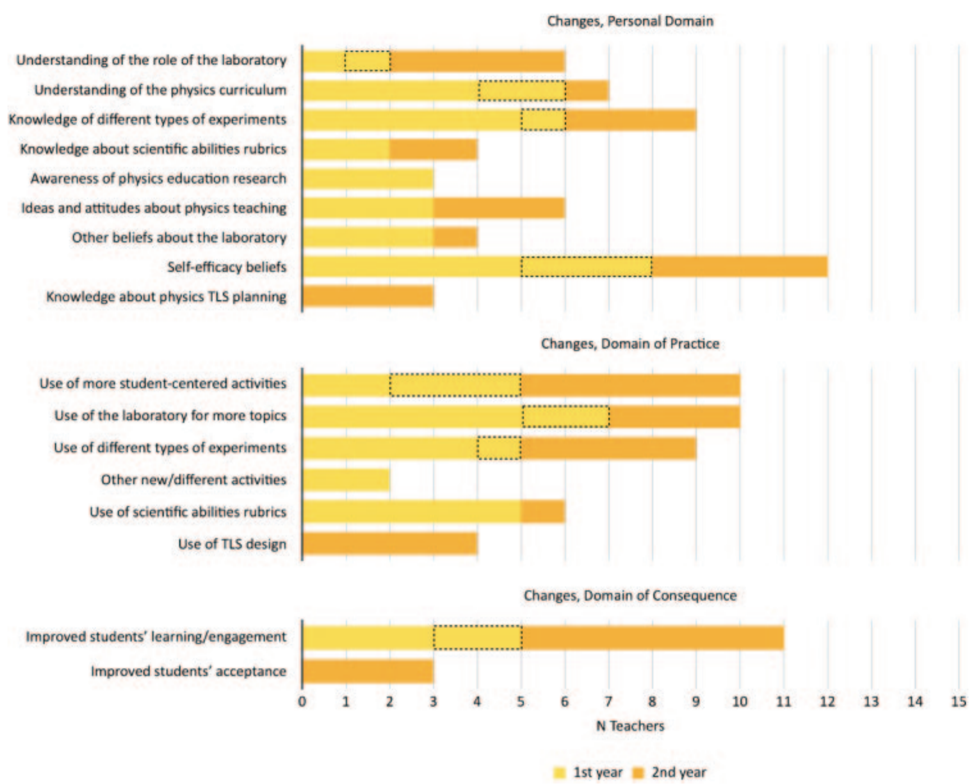

Fig. 4. – Changes reported by the teachers after the first year (lighter color) and after the second year (darker color). The part of the bar marked with a dotted line refers to teachers who attended the first year only.

the laboratory; use of different types of experiments; use of rubrics for evaluating scientific abilities). After the second year, almost all the participants reported improvements in students' achievement as well: "The shift from cooking recipe to having students design the experiment, I have introduced it in almost all experiments. It works well, and the students also find the lab more engaging. And even when an experiment looks like a cooking recipe, I see that their approach has changed, because they know what's behind it" (E.P.); "I started going to the lab regularly once a week. In the lab, the students are more active, they work, they ask questions, they are more independent" (G.L.).

We can summarize the reported changes in the use of the laboratory as follows:

- Quality of the experiences: "I used to give students recipes to follow step by step; now I often give them the opportunity to plan the experiment." (E.P.).
- An improved planning phase: "I pay attention to the intermediate goals of the experiment, and not only to the final result" (G.L.).
- An increased attention to assessment: "One thing I have introduced permanently is the use of assessment rubrics designed for the physics laboratory, which I always share with the students" (L.G.).
- Increased self-efficacy: "I take old instruments out of the cabinets, which I would never have done before. I no longer want the technician to lead the lab" (M.R.F.).
- Improved classroom management: "I used to find it difficult to collect data and manage students' questions. Now I am in control of the situation" (F.C.).

To better understand the processes that led to these changes, we counted co-occurrences between references to changes and references to course elements/activities. As for the latter, the following categories emerged: ideas and information; practical activities; colleagues' experiences; direct experimentation and action research; feedback and discussions. In fig. 5 we report the results of this counting. We can see how ideas and information were especially important in producing changes in the personal domain,

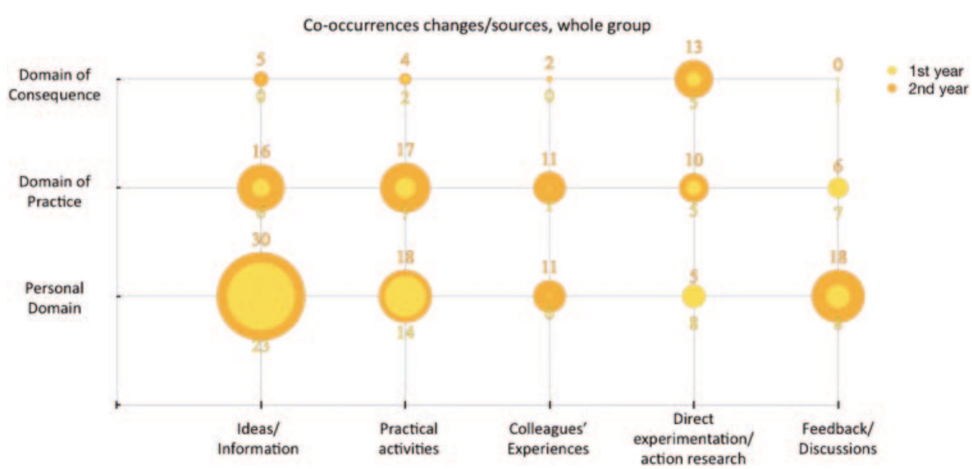

Fig. 5. – Co-occurrences of reference to elements of the program and reported changes after the first year (lighter color) and after the second year (darker color).

whereas ideas, activities, colleagues' experiences, and direct experimentation in the classroom were equally important to produce changes in the domain of practice. For changes in the domain of consequence (students' outcomes), direct experimentation was the pivotal element. The results also highlight how elements in the personal domain continued to evolve in the second year, while changes in the domain of practice were reinforced; feedback and discussions about the TLSs emerge as one of the most important sources of change in the second year. This analysis highlights the multiple links between the "External Domain" identified by Clarke and Hollingsworth's model, and the three domains of change.

7. – Some answers and new questions

The research presented here provides supporting evidence to the CoLLabora model and suggests that change in the three domains (personal, practice, outcomes) is possible. In particular, our results highlight the importance of establishing a learning community of teachers and researchers, and of supporting teachers' action research. These two foundational elements are best implemented in a course that includes the structural features suggested by the literature (content focus; long duration; active learning opportunities; coherence with teachers' backgrounds and needs).

The CoLLabora experience was the first step in an effort to rethink the professional development of physics teachers, in a way that not only produces meaningful effects in the participating teachers, but also activates changes beyond the program, with the trained teachers acting as the change agents. The project has, in fact, opened up new questions that we are trying to answer with our current research:

- What is the impact of the program in the medium/long-term?
- How can we reach more teachers while maintaining the effort sustainable?

In the following we report some primer answers to these questions, although the research is ongoing; an article about the 3-year impact of CoLLabora is in preparation.

7˙1. *After CoLLabora: a teacher training cascade*. – Following the CoLLabora experience, some of the teachers have themselves become trainers of colleagues in their schools or territory, applying and adapting the CoLLabora model and methodology. This cascade effect is what we are banking on in order to foster the sustainability of the approach.

For example, two of the CoLLabora teachers became the promoters, co-organizers, and mentors of an annual training course entitled "The use of technologies in the physics laboratory", dedicated to physics teachers in the Padua area and held in the school of one of the two. After framing the theme of the laboratory in the context of inquiry-based learning and of the development of scientific practices, the course delved in particular into the use of Arduino and Phyphox, technologies that enable low-cost experiments and the design of the experimental setting at different levels adapting to the schools' needs. Teachers were involved in group planning, discussions and peer evaluations, and insights were offered from PER findings. In the second part of the course, teachers were asked to develop and test short TLSs with laboratory activities.

Starting with CoLLabora, other courses based on the same model were designed. Currently ongoing is *ATENA-Asiago Teachers' Network on Astrophysics*, the goal of which is the co-construction of TLSs integrating physics and astronomy. In this case, the learning community is based on a common research question (*How can we use Astronomy to develop a longitudinal path in secondary school that leads to a coherent comprehension of the physics of the Universe?*). A similar approach was taken in *FisicaMente al Liceo*, which concerns the relationship between mathematics and physics. The program was developed based on previous research [55, 56]. Twelve teachers from five schools participated in an initial training and proposed a pre-test on the use of derivatives, integrals, and vectors in mathematics and in physics in their classrooms. Based on the results of the pre-test, they designed activities to reinforce the link between mathematics and physics. Finally, the learning community approach is also carried on through collaborations with other research groups, such as in the 'Virtual School' project developed jointly with colleagues from the Philosophy, Sociology, Pedagogy, and Applied Psychology Department (FISPPA) of UniPD and from Monash University in Australia [57, 58].

7·2. *From a pilot experimentation to a research approach.* – We conclude with a map of our region, Veneto, showing the currently active collaborations with schools where teachers are taking part, or are themselves organizing teacher training programs based on (or related to) the CoLLabora model (fig. 6).

From CoLLabora on, the map of collaborations is expanding, creating an increasingly strong network of "CoLLaborative" teachers. The larger orange markers correspond to teachers who are also actively contributing to the GRAPE's research through doctoral pathways or other official research collaborations. Such teachers are considered full members of our research group. The CoLLabora approach has, in fact, become a facet of our group's identity: we experience the learning community ourselves in our approach to research in physics education.

The development of CoLLabora since its conclusion has reinforced our idea that to achieve lasting and diffuse change it is necessary to go deep into physics teacher education, building a strong learning community. The impact of such a course goes beyond the effects on the small group of teachers it is initially aimed at, justifying the commitment required to sustain a course that is long in duration, demanding in its care of the relationships with participants, and deep in content.

Fig. 6. – A map of our region highlighting the schools where there are teachers who have participated or are participating in CoLLabora-like programs, or are bringing the CoLLabora model in their own context. The cross marks the position of UniPD.

It is with a phrase from one of the CoLLabora teachers, which well sums up the path we are tracing, that we wish to conclude this contribution: "Valuing, seeking a place... where there is the possibility to research in a way that is serious, but not far from reality. Research at the university gives a foundation; it gives content. But we can also bring a competence and expertise, with the aim of building a network of reflection based on physics content" (G.L.).

* * *

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