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School-University Collaboration and Teachers' Professional Development

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Abstract. Teachers' professional development is a central theme in Physics Education Research. Building on a long tradition of collaborative research between schools and universities within the community of the Italian "Scientific Degrees Plan", and in cooperation with the broader physics education community, we identified research questions relevant to envisioning future perspectives about teachers' needs, the strategies and methods to adopt, and the challenges teachers face. Starting from these questions, participants in the 4th World Conference on Physics Education have been engaged in an open workshop, prepared through a participatory process, to share and reflect on common concerns. The workshop highlighted several significant dimensions to guide future reflection: use of laboratories and technologies, the development of mentoring and community of practices, teacher education on interdisciplinary content, and conceptual paths in both classical and modern physics. In this paper, we report on this community reflection and offer perspectives for future work in this topical area of physics education research.

1. Introduction

Teachers' professional development is a central theme in Physics Education Research (PER) [1-3]. The GIREP community has been working for many years on this topic, through dedicated conferences and seminars [4,5]. The literature offers several models, including Metacultural, Experiential and Situated [6]. Recently, PER studies have emphasised the value of community-based approaches, supported by experts and focused on specific aspects such as the role of technology, interdisciplinarity frameworks, and the teaching and learning quantum physics [7-19].

In the context of the Italian "Scientific Degrees Plan" (*Piano Lauree Scientifiche*, PLS) [13], a network was set up as an action for teachers' professional development[1], leveraging university-school collaborations and informed by PER findings. The network compared the tools and methods used by different institutions through a survey of 136 activities from 33 universities, some of which also cooperate within an institutional *post-lauream* initiative (IDIFO Master) [9]. Other actions included a survey on teachers' professional development [20] and a study on physics education training for primary school teachers [21]. Initial perspectives from these actions were summarised in a prior publication [22], based on which the Italian PER community decided to engage the broader PER community at the 4th World Conference on Physics Education (WCPE). As a result, a workshop was prepared and conducted at the 4th WCPE, drawing both on contributions presented at the 4th WCPE and others[2].

2. Methodology and research questions

The workshop was prepared for over six months prior to the 4th WCPE. As a first step, the workshop proponents identified the research questions (RQ) and methodology for the workshop. The RQs were:
RQ1. What needs do teachers express and perceive?
RQ2. What strategies, methods, and activities should we focus on, in which contexts (individual, local/regional, national)?
RQ3. What challenges do teachers face? What role and commitment do we envision, with what continuity over time, and with what impact on professional development?

All GIREP members were invited to submit their WCPE extended abstracts to serve as the basis for the discussion. From the 20 contributions collected, four main dimensions emerged, based on which the following working groups (WGs) were established:
WG1. Labs and new technologies
WG2. Mentoring, communities of practice, and conceptual paths
WG3. Teacher education on interdisciplinary contents
WG4. Conceptual paths in classical and in modern physics

Each WG was taken in charge by coordinator, a discussant and a rapporteur, who organized and conducted the discussion at the conference. After an introduction summarising the main contributions, each WG engaged in a one-hour discussion in relation to the research questions. Participants included PER researchers, teacher trainers, faculty involved in the PLS, and representatives of physics teachers' associations. Finally, the outcomes from each WG were reported in a 30-minute plenary session.

3. Findings

3.1. WG1: Labs and new technologies

A laboratory is a physical or virtual space equipped for scientific experiments, research, and teaching. It provides opportunities for students to become familiar with scientific equipment and terminology, to

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[2] The extended abstracts of the contributions referenced in this paper are available at *Book of Ext. Abs. 4th WCPE* eds M Kaczmarek and D Sokołowska (Kraków: Fac. Phys. Astr., Appl. Comp. Sci. Jagiellonian U) https//indico.cern.ch/event/1162407/attachments/2724388/5191435/BookAbstractsWCPE2024_FINAL.pdf

train in experimental methods, and to practise the analysis and presentation of data. In the lab, students can develop manipulative, critical, and problem-solving skills through learning by doing. This promotes deeper understanding and greater motivation to study physics. The laboratory also enables teachers to respond more effectively to students' needs, supporting them in overcoming difficulties.

Contributions in this group presented research supporting the use of labs and digital technologies in physics education. They highlighted the importance of active learning, with students engaging both hands-on and minds-on, moving from the known and visible to what is not directly observable [16]. Laboratories can also be conceived as exploratory activity to be conducted anywhere, involving the design, construction, and testing of low-cost apparatus for physics experiments [19]. Digital technologies can be used as versatile scientific tools, aiming to transform the laboratory from a physical location to any setting where experimental skills can be developed. The strategies proposed to support teachers' ownership of PER-based interventions included the use of teaching-learning sequences, inquiry-based learning and experimental design, alongside evaluation tools to assess the effectiveness of the activities. As the Greek experience particularly highlighted [23], a gap persists between research findings and educational policies and practices.

3.1.1. Answers to the Research Questions

RQ1. Teachers emphasized the importance of creativity in laboratory activities. A recurring concern is that institutional constraints often represent an obstacle to efforts to improve laboratory w.

RQ2. The approach is usually to theorize the interventions with a lack of connection between theory and practice; therefore, strategies should be aimed at connecting thinking with doing. In this respect, peer instruction could be highly significant, although it is recognised as a rarely adopted approach.

RQ3. The challenges posed by lab and technology training call for a closer collaboration between schools and universities, which should play a stronger role in in-service teacher training.

3.2. WG2: Mentoring and community of practice

The analysis of participants' contributions highlighted the centrality of professional learning communities [24,25] in teacher training across different national contexts, while adapting to local regulations and constraints.

In Italy, the CoLLabora model [26] builds on action research, teacher-researcher collaboration, and teacher learning communities. Over the course of a year, teachers co-design teaching-learning sequences and discuss research-based proposals. These processes have led to diversified professional growth pathways. In Trieste, Bologna et al. [18] developed "creative ateliers" based on cognitive apprenticeship, designed to help teachers cultivate productive habits such as administering innovative problems for the development of scientific abilities and improving formative assessment practices.

In Israel, a multi-level teacher network includes a national professional community of "teacher leaders" who guide local communities [1,27]. This model inspired the approach adopted in the Italian ADELANTE project [8], where 15 "teacher leaders" from three Italian partner universities co-designed teaching sequences and seeded larger local teacher communities experimenting with the proposals.

The role of teacher leaders resonates with the concept of mentoring [28]. Jutkowitz et al. [28] analyzed mentor-mentee relationships as collaborative inquiry processes, showing that mentors also grow professionally while engaging in this relationship.

Addressing the challenge of large-scale, research-based training underscores the importance of national networks. The IDIFO network [9,11] supports PER-based professional development in Italy, promoting teacher ownership and personalized learning. The need for such national networks to bridge gaps, particularly in regions without local PER groups, was also emphasised in a national survey conducted by Montalbano et al. [15] withing the national physics teachers association.

Table 1 summarizes the themes that guided the discussion and the corresponding open questions.

Table 1. WG2: Emerging common themes, understandings, and open questions

Theme	Open questions
PER grounding, teachers' ownership, personalization of professional development, classroom implementation	What are the characteristics of an "authentic collaboration" between teachers and researchers? How can teachers be sustained towards independence?
Need for extended time and quality interactions versus scalability	How can we leverage expert/trained teachers as "teacher leaders"? How do we coordinate inter-university collaborations and networks?
Teachers experience professional growth when mentoring or teaching peers	Professional learning communities with novice and expert teachers as partners in the process? What is the role of mentors in initial teacher training across the different educational contexts? What training do mentors need?

3.2.1. Answers to the Research Questions

RQ1. Teachers express a range of professional needs that extend beyond traditional classroom support. These include comprehensive professional guidance, particularly for novice educators; resources that build confidence in delivering complex scientific content or practices; and practical, immediately applicable classroom activities that can be integrated into their curriculum. However, teachers also desire recognition for their professional development efforts, sustained support, and platforms that enable sharing of experiences and challenges.

RQ2. Recommended strategies operate across multiple, interconnected levels. At the individual level, they include peer observation, mentoring, design of actionable classroom activities, and ongoing professional learning. At the local and regional level, teachers benefit from regular community meetings, which provide supportive networks. At the national level, systemic approaches are crucial, including official recognition and funding of teacher collaboration, structured school-university partnerships, national or supra-regional network, and an official system for professional development recognition. Through these instruments, teachers have access to research-based materials, reduce preparation time, and benefit from a support ecosystem empowering them professionally.

RQ3. A significant challenge is the lack of an institutional support system. The variety of professional backgrounds and individual needs also need to be considered. Addressing these issues requires that universities commit to adopting a long-term, "patient", and continuous approach rather than relying only on short workshops. Authentic and sustainable professional growth requires temporal continuity, which can be achieved through regular community meetings, ongoing peer support, and a gradual skill- and confidence-building process. The ultimate goal is to create professional development models that not only meet teachers' immediate needs but also foster long-term career satisfaction, classroom innovation, and improved student outcomes. One possible structural measure is to include regular professional development within teachers' role definition.

3.3. WG3: Teacher education on interdisciplinary contents

To frame the group discussion on teacher education on interdisciplinary contents, the meaning of "interdisciplinarity" was initially shared. Following [29], inter-disciplinarity was defined in contrast with multi- and trans-disciplinarity. Multi-disciplinarity places disciplines side by side without merging their approaches, while trans-disciplinarity seeks to transcend individual disciplines by forging an overarching synthesis. Interdisciplinarity occupies the middle ground, integrating concepts, methods, and epistemologies from different fields.

In the workshop, we mainly focused on inter-disciplinarity, also opening towards transdisciplinarity, since almost all the contributions we discussed assumed that disciplines and their integration matter. Three papers that contributed to the workshop refer to experiences of teacher education on intrinsically interdisciplinary topics: climate change, time, sustainability, colours, radioactivity, space science, and quantum technologies. One paper refers to physics education for primary school and focuses on how to value an imaginative approach to dealing with forces of Nature. In this case, interdisciplinarity comes before disciplinary action: it is used to make sense of the process of conceptualization that is progressively framed within disciplines. Finally, one paper refers to teacher experiences aimed at promoting gender equality in STEM disciplinary teaching and self-assessment skills in students. The paper refers to the need to equip teachers with transversal competences and methodologies that transgress and go beyond teachers' disciplinary backgrounds.

All the papers show that interdisciplinarity is problematic in education since it involves a dual process of boundary unmaking and making [30,31]. It requires teachers to navigate between disciplines while fostering new ways of crossing disciplinary boundaries and redefining them. This complex process reflects not only individual challenges but also institutional and relational dynamics.

3.3.1. Answers to the Research Questions

RQ1. When dealing with interdisciplinarity, teachers usually express and perceive some needs and have to grapple with challenges of different natures. They are often enthusiastic about interdisciplinarity, motivated by themes (e.g. climate change, artificial intelligence) that connect disciplines and the broader need to regenerate schools. However, they also express concerns. On an individual level, they worry about feeling isolated, unsupported or getting lost, particularly when navigating unfamiliar interdisciplinary territories and environments. A further concern regards the possible lack of external motivation and resources. They recognize the need to develop skills that are not traditionally part of their disciplinary backgrounds, such as self-assessment and the ability to identify biases. These needs extend beyond the individual and touch on institutional gaps, such as the lack of spaces for teachers to prepare and collaborate collectively.

RQ2. Possible strategies, methods and activities to support interdisciplinary teaching therefore operate at different levels—individual, local/regional, and national—and recognize the diverse contexts in which teachers work. At the individual level, teacher training programs should value the resources and expertise teachers already have, rather than treating them as *tabula rasa*. Teachers often come from specific disciplinary backgrounds like chemistry, mathematics, or physics, and training can build on the already existing knowledge, fostering connections between different knowledge domains. A strategy can be to start from topics that are, by nature, multi- or interdisciplinary such as climate change, the changing of the seasons, the growth and development of vegetation, as well as the study of historical problems like the study of projectile motion within the ballistic field. These kinds of problems can immediately shed light on the possibility to unpack the interdisciplinarity of the theme.

Project-based learning offers opportunities for interdisciplinarity at the local and regional levels. Engaging teachers in local or regional challenges can highlight the interdisciplinarity between STEM and STEAM disciplines, blending the boundaries between science and societal issues. These approaches encourage teachers to engage with complex topics while fostering cross-disciplinary connections.

At the national level, systemic barriers often hinder interdisciplinary efforts. In France and Italy, for example, disciplinary-based syllabi make it difficult for teachers to cross boundaries. Addressing this requires political solutions, such as more flexible curricula, as well as the creation of a safe environment in which transgressing boundaries is endorsed by the institutional level.

RQ3. These challenges can and need to be addressed in the teachers' professional development, which can play a key role. Unfortunately, current teacher training often lacks the continuity and depth needed to support interdisciplinary practices. Short-term or isolated workshops can fail to provide the sustained engagement teachers need to feel confident and supported. Instead, long-term interdisciplinary professional learning communities can play a crucial role. These spaces allow teachers to experiment, reflect, and grow within a supportive network.

Institutional commitment is equally important. In Italy, for example, in the national guidelines, there is space for interdisciplinarity, but teachers are unaware or tend to show "disciplinary capture" attitudes, which are the instinct to revert to their disciplinary comfort zones, often seeing interdisciplinarity as "not mine" or beyond their competencies and scope. Overcoming this requires teachers to embrace differences, accept the lack of closure and adopt collaborative strategies.

3.4. WG4: Conceptual paths in classical and in modern physics

The discussion was centered on the need to build solid conceptual paths guiding teachers in classical and then towards modern physics, with special focus on quantum physics and technologies [32-35].

Many teachers, especially those who hold a degree in a subject other than physics (e.g., mathematics), feel unconfident with teaching modern physics, and this leads to the use of very standard teaching strategies and a limited range of activities and approaches [35].

In the workshop, both content and methodology were discussed. When topics are more familiar to the teachers, a methodological focus can be put on co-designing conceptual pathways with them. On the other hand, when teachers themselves do not feel fully confident, a preliminary focus on content is required to enable further discussion on implementation and methodology [36-38].

The workshop also highlighted the importance of creating a solid framework of concepts that can be not only transmitted, but also manipulated [39-41]. For example, the new approaches to teaching quantum mechanics based on two-state systems, have not only precise premises but also a steady endpoint with the students' manipulation capability with the physics and math concepts they can master.

3.4.1. Answers to the Research Questions

RQ1. To effectively teach quantum physics, educators must first possess the required confidence and expertise to master the subject matter and associated technologies personally. Furthermore, the educators have indicated that they encounter difficulties in identifying suitable applications of these concepts in the classroom. Both an expressed desire for more content and a need for more effective teaching strategies, particularly with regard to quantum physics, were evident [42-43]. However, teachers themselves asked for self-assessment of their formative needs, sometimes were not able to discriminate between content and strategy needs.

Although there is a recognized need for a shift from summative to formative assessment, this is not a priority for Italian educators. The issue is that the Italian educational system is structured around summative assessment, which is required by schools and the administration. There is a desire to transition towards formative assessment and collaborate with teachers to develop such a framework.

RQ2. When the subject is new for the teachers or the approach is unconventional, such as for modern approaches to quantum mechanics via quantum technologies, one suitable strategy is to first propose to the teachers the same activities that are meant for the students [44]. It is also important that the teachers try to set up the activity by themselves, to explore and overcome all the possible setbacks that could be encountered by students. On the other hand, when the subject is more familiar to the teachers, then co-design of classroom activities can be performed. This injects confidence and responsibility in teachers, enabling them to recognize their capabilities and the concepts they can now master.

The integration of conceptual pathways can start from classical physics topics, as educators are more experienced in this area and can be more focused on methodology rather than on concepts. Also, in our opinion, prioritizing formative assessment and metacognitive approaches in teaching can help.

RQ3. The implementation of unconventional pathways within the curriculum, which could be anticipated by extracurricular activities, is the final goal. The introduction of formative assessment in these unconventional learning paths is desirable, even if at this stage it may result in educators losing sight of the learning process itself. Formative assessment and metacognitive strategies can be utilized to equip educators with the ability to recognize the cognitive processes that are being engaged and to facilitate students in becoming similarly conscious of these processes.

4. **Discussion and perspectives**

Just as personal involvement is essential for learners to develop cultural identity and abilities, it is equally necessary in teacher education and professional development. The discussion highlighted several research-based approaches that aim to concretize this involvement [6,9,45,46], together with strategies that involve the co-design of teaching–learning sequences [47]. Although these experiences were developed in diverse contexts and targeted different competences, they share a common recommendation: the need for reciprocal enrichment between research and practice. Interdisciplinary contaminations are also important to enable teachers and students – as today and tomorrow citizens - to engage meaningfully with societal challenges. The epistemic foundations of physics require multi-perspective competences also in the methods of physics. Teachers should therefore be prepared to design learning environments where students encounter multiple ways of engaging with physics.

From the discussions in the WGs, a number of shared answers to the research questions emerged.
(RQ1) Teachers expressed the need for professional development that is both PER-grounded and sensitive to context, provided within collaborative spaces and supported by institutions. They often face institutional constraints that hinder sustainability and report feelings of isolation. Importantly, initial teacher education should be revised to include both content knowledge and strategies relevant to contemporary themes in science education, such as interdisciplinarity and modern physics.
(RQ2) Effective innovation requires coordination across multiple levels. A long-standing challenge is to connect theory with practice, which can be addressed through communities of practice and co-designed teaching activities. Emerging priorities include national coordination to reach teachers in remote areas, fostering interdisciplinarity to engage teachers from different backgrounds, and recognising the leadership role of teachers with PER expertise.
(RQ3) Research should address the "second order" challenge of adapting innovative proposals to specific local contexts. This requires creativity and a deep understanding of both intra- and interdisciplinary connections. Long-term professional development, supported by networks and particularly valuable during the early stages of a teacher's career, is essential. While demanding, this process is often experienced as rewarding. Finally, alongside intrinsic motivation, external recognition of teachers' professional development efforts is crucial.
In conclusion, the discussion across the different WGs pointed to several lines of research that require further exploration. These include: the management of complex communities of practice, the role and challenges of mentor teachers in initial and early-career training; the integration of laboratory and technology competences in both initial teachers' education and in-service professional development; the connections between school science and societal challenges such as energy needs, resource conservation, and climate change, adopting an interdisciplinary stance; and the challenge of bringing modern physics meaningfully into the high school curriculum.

References

[1] Levy S, Bagno E, Berger H, Eylon B S 2022 Professional Growth of Physics Teacher-Leaders in a Professional Learning Communities Program: the Context of Inquiry-Based Laboratories *Int. J. Sci. Math. Educ.* vol 20 p 1813 https://doi.org/10.1007/s10763-021-10217-7
[2] Etkina E, Gregorcic B, Vokos S 2017 Organizing physics teacher professional education around productive habit development: A way to meet reform challenges *Phys. Rev. Phys. Educ. Res.* Vol 13 p 010107 https://doi.org/10.1103/PhysRevPhysEducRes.13.010107
[3] McDermott L C, Shaffer P S, Constantinou C P 2000 Preparing teachers to teach physics and physical science by inquiry *Phys. Educ.* Vol 35 p 411 https://doi.org/10.1088/0031-9120/35/6/306
[4] Pinto R and Surinach S eds. Physics Teacher Education Beyond 2000 *GIREP book - Selected contributions of the Phyteb2000 Intl. Conf.* (Elsevier); Kaminski W and Michelini M eds. Teaching and Learning Physics Today: Challenges? Benefits? 2014 *GIREP book of the GIREP-ICPE-MPTL Intl. Conf., Reims 2010* (Udine: University of Udine) Retrieved from: https://www.fisica.uniud.it/urdf/libri/pdf/08Teaching.pdf
[5] Michelimi M ed. Quality Development in the Teacher Education and Training 2004 *GIREP book Forum selected papers* (Udine: Forum, Ed. Universitaria Udinese); Borg Marks J et al 2022 *Physics Teacher Education: What Matters* (Switzerland: Springer Nature AG); Borg Marks J

and Galea P 2023 *Physics Teacher Education: More About What Matters* (Switzerland: Springer Nature AG); Borg Marks J et al 2022 *GIREP Malta Webinar 2020 IOP Conf. Series* vol 2297; Borg Marks J *et al* 2023 *GIREP Malta Webinar 2021 IOP Conf. Series* vol 2490 Retrieved from: https://www.fisica.uniud.it/urdf/articoli/ftp/2004/2004-13.pdf
[6] Michelini M 2020 Dialogue on Primary, Secondary and University Pre-service Teacher Education in *Physics Research and Innovation in Physics Education: Two Sides of the Same Coin, Challenges in Physics Education* eds J Guisasola and K Zuza (Cham: Springer) https://doi.org/10.1007/978-3-030-51182-1_3
[7] Borg Marks J 2021 An overview of the outcomes of the GIREP Webinar 2020; *Book of Ext. Abs. 4th WCPE Embracing changes together* eds M Kaczmarek and D Sokołowska (Kraków: Jagiellonian U)
[8] Organtini G, Carli M, Pantano O, Sapia P 2024 The ADELANTE project *Book of Ext. Abs. 4th WCPE Embracing changes together* eds M Kaczmarek and D Sokołowska (Kraków: Jagiellonian U)
[9] Chiofalo M, Michelini M, Santi L 2024 The IDIFO Master *Book of Ext. Abs. 4th WCPE Embracing changes together* eds M Kaczmarek and D Sokołowska (Kraków:Jagiellonian U)
[10] Sutrini C, Malgieri M, Zuccarini G, Macchiavello C, Teacher professional development on quantum science and technology: the Pavia approach *Book of Ext. Abs. 4th WCPE Embracing changes together* eds M Kaczmarek and D Sokołowska (Kraków: Jagiellonian U)
[11] Michelini M 2024 Italian universities network for teacher professional development *Book of Ext. Abs. 4th WCPE Embracing changes together* eds M Kaczmarek and D Sokołowska (Kraków: Jagiellonian U)
[12] Levrini O and Tasquier G 2024 Challenges of Climate Change Education for Teacher Education *Book of Ext. Abs. 4th WCPE Embracing changes together* eds M Kaczmarek and D Sokołowska (Kraków: Jagiellonian U)
[13] Fazio C 2024 The PLS-Physics project *Book of Ext. Abs. 4th WCPE Embracing changes together* eds M Kaczmarek and D Sokołowska (Kraków: Jagiellonian U)
[14] Tuveri M, Steri A, Fanti V 2024 Designing a teaching experiment for training lower secondary school teachers in classical mechanics *Book of Ext. Abs. 4th WCPE Embracing changes together* eds M Kaczmarek and D Sokołowska (Kraków: Jagiellonian U)
[15] Montalbano V and Mariotti E 2024 Professional Development Programs in Physics in Tuscany; Montalbano V 2024 The training needs of physics teachers: a challenge from the APT; Montalbano V and Marchini D 2024 Active in-service training on transversal skills: two pilot cases in STEM disciplinary teaching *Book of Ext. Abs. 4th WCPE Embracing changes together* eds M Kaczmarek and D Sokołowska (Kraków: Jagiellonian U)
[16] Carpineti M, Giliberti M, Guess the Color at the Edge of the Rainbow *Book of Ext. Abs. 4th WCPE Embracing changes together* eds M Kaczmarek and D Sokołowska (Kraków:Jagiellonian U)
[17] Giliberti M, Michelini M, Pagliara S, Pavesi M 2024 The Beauty of Teaching Physics: a PLS joint Teaching Training Course *Book of Ext. Abs. 4th WCPE Embracing changes together* eds M Kaczmarek and D Sokołowska (Kraków: Jagiellonian U)
[18] Bologna V, Longo F, Modugno G, Peressi M 2024 Developing new habits for Physics teachers through Creative Ateliers *Book of Ext. Abs. 4th WCPE Embracing changes together* eds M Kaczmarek and D Sokołowska (Kraków: Jagiellonian U)
[19] Organtini G, Del Santo M, Bombaci G 2024 Design for Physics *Book of Ext. Abs. 4th WCPE Embracing changes together* eds M Kaczmarek and D Sokołowska (Kraków: Jagiellonian U)
[20] Corradini O *et al* 2022 Inquiry on Italian PLS University Initiatives for teacher professional development on quantum physics (preprint, private communication)
[21] Chiofalo M *et al* 2023 Physics for Primary School Teachers in Italy: Comparative Analysis in a Dedicated Survey *Physics Teacher Education, Challenges in Physics Education* eds J Borg Marks and P Galea (Switzerland: Springer) p 163 https://doi.org/10.1007/978-3-031-44312-1_12

[22] Immè J, Michelini M 2022 Fondare sulla ricerca la formazione in didattica della fisica degli insegnanti di scuola primaria *Giornale di Fisica* 63 https://doi.org/10.1393/gdf/i2022-10468-2

[23] Gidari-Gounaridou C, Lefkos I 2024 Greek Science Teachers' Views about the Use of Educational Simulations in their Practice *Book of Ext. Abs. 4th WCPE Embracing changes together* eds M Kaczmarek and D Sokołowska (Kraków: Jagiellonian U)

[24] Vangrieken K, Meredith C, Packer T, Kindt E 2017 Teacher communities as a context for professional development: a systematic review *Teach. Teach. Educ.* Vol 61 p 47 https://doi.org/10.1016/j.tate.2016.10.001

[25] Vescio V, Ross D and Adams A 2008 A review of research on the impact of professional learning communities on teaching practice and student learning *Teach. Teach. Educ.* **24** 1 https://doi.org/10.1016/j.tate.2007.01.004

[26] Carli M and Pantano O 2023 Collaborative physics teachers: Enhancing the use of the lab through action research in a community of learners *Phys. Rev. Phys. Educ. Res.* **19** 020162 https://doi.org/10.1103/PhysRevPhysEducRes.19.020162

[27] Ofir K, Levy S and Yerushalmi E 2024 Teachers TPACK: promoting self-monitoring in physics problem solving through digital activities *Book of Ext. Abs. 4th WCPE Embracing changes together* eds M Kaczmarek and D Sokołowska (Kraków:Jagiellonian U)

[28] Lehavi Y, Merzel A, Segal R, Baram A, Eylon, B-S 2019 Using Self-video-based Discourse in Training Physics Teachers *Concepts, Strategies and Models to Enhance Physics Teaching and Learning* eds E. McLoughlin and P. van Kampen (Cham: Springer) https://doi.org/10.1007/978-3-030-18137-6_14; Lehavi Y, Merzel A, Segal R, Jutkowitz R 2021 Introducing pedagogical content awareness to model growth in the context of teacher peer mentoring *Proc. 2021 AERA Annual Meeting* https://doi.org/10.3102/1690625*;* Segal R, Merzel A, Lehavi Y 2024 Improving the Professional Awareness of Mathematics Teachers/Instructors Using Evidence-based Curiosity-driven Discourse - A Case Study *Intl. J. Sci. Math. Educ.* vol 22 https://doi.org/10.1007/s10763-023-10418-2*;* Jutkowitz R, Merzel A, Lehavi Y 2024 Mentor Learns the Most: The Effects of Curiosity-Driven Discourse on Physics Mentors B*ook of Ext. Abs. 4th WCPE Embracing changes together* eds M Kaczmarek and D Sokołowska (Kraków: Jagiellonian U)

[29] Alvargonzález S 2011 Multidisciplinarity, Interdisciplinarity, Transdisciplinarity, and the Sciences *Intl. Studies Phil. Sci.* vol 25 p 387 https://doi.org/10.1080/02698595.2011.623366

[30] Akkerman S F, Bakker A 2011 Boundary crossing and boundary objects *Rev. Educ. Res.* vol 81 p 132 https://doi.org/10.3102/0034654311404435

[31] Satanassi S, Branchetti L, Fantini P, Casarotto R, Caramaschi M, Barelli E, Levrini O 2023 Exploring the boundaries in an interdisciplinary context through the Family Resemblance Approach: the dialogue between physics and mathematics *Sci. & Educ*. Vol 32 p 1287 https://doi.org/10.1007/s11191-023-00439-2

[32] Michelini M *et al.* 2022 An overview of physics teacher professional development activities organized within the Italian PLS-Physics plan over the past five years *J. Phys. Conf. Ser.* vol 2297 p 012030 https://10.1088/1742-6596/2297/1/012030

[33] Riedel M, Kovacs M, Zoller P, Mlynek J, Calarco T 2019 Europe's quantum flagship initiative *Quantum Sci. and Tech.* vol 4 p 020501 https://10.1088/2058-9565/ab042d

[34] Sutrini C, Malgieri M, Macchiavello C 2022 Quantum technologies: a course for teacher professional development *J. Phys. Conf. Ser.* Vol 2297 p 012018 https://10.1088/1742-6596/2297/1/012018

[35] Sutrini C, Malgieri M, Zuccarini G and Macchiavello C 2023 A teacher professional development course on quantum technologies: discussion of results *J. Phys. Conf. Series* vol 2490 p 012006 https://10.1088/1742-6596/2490/1/012006

[36] Besson U, Borghi L, De Ambrosis A and Mascheretti P 2010 A Three-Dimensional Approach and Open Source Structure for the Design and Experimentation of Teaching-Learning

Sequences: The case of friction *Intl. J. Sci. Educ.* Vol 32 p 1289 https://doi.org/10.1080/09500690903023350

[37] Malgieri M, Sutrini C, Zuccarini G, Pozzi E, Bondani M and Macchiavello C 2023 Search of the keys of deep understanding: Physics education research in Pavia *Nuovo Cim.* Vol 100 p 201 https://10.1393/ncc/i2023-23201-0

[38] Pancani G and Macchiavello C 2023 Logic circuits and optical circuits: A teaching learning sequence to build quantum computation for high school students *Nuovo Cim.* Vol 100 p 80 https://10.1393/ncc/i2023-23080-3

[39] Checkland P and Holwell S 1998 Action research: its nature and validity *Systemic Practice and Action Research* vol 11 p 9 https://doi.org/10.1023/A:1022908820784

[40] Duit R, Gropengießer H, Kattmann U, Komorek M and Parchmann I 2012 The model of educational reconstruction–A framework for improving teaching and learning science *Cultural Perspectives in Science Education* vol 5 D Jorde and J Dillon eds (Rotterdam:SensePublishers) https://doi.org/10.1007/978-94-6091-900-8_2

[41] Tóth K, Michelini M, Bitzenbauer P 2024 From light polarization to quantum physics: Supporting lower secondary school students' transition from gestalt to functional thinking *Eurasia J. Math., Sci. Tech. Educ.* vol 20 em2449 https://doi.org/10.29333/ejmste/14587

[42] Zuccarini G, Malgieri M, Sutrini C, Macchiavello C 2024 Elementarizing quantum algorithms: clarification of the internal structure and preliminary learning outcomes *J. Phys. Conf. Ser.* vol 2750 p 012025 https://10.1088/1742-6596/2750/1/012025; Sutrini C, Zuccarini G, Malgieri M, Bondani M, Macchiavello C 2023 An educational model of the Deutsch algorithm for secondary school *European Journal of Physics* vol 45 p 025302 https://10.1088/1361-6404/ad1399; Bondani M et al 2022 Introducing Quantum Technologies at Secondary School Level: Challenges and Potential Impact of an Online Extracurricular Course *Physics* 4 vol 4 p 1150 https://doi.org/10.3390/physics4040075

[43] Satanassi S *et al* 2022 Designing and Implementing Materials on Quantum Computing for Secondary School Students: The Case of Teleportation *Phys. Rev. Phys. Educ. Res.* Vol 18 p 010122 https://doi.org/10.1103/PhysRevPhysEducRes.18.010122

[44] Giliberti M, Lovisetti L 2025 Teaching quantum mechanics with a nature-of-science framework *Am. J. Phys.* Vol 93 p 172-9 https://doi.org/10.1119/5.0210636

[45] Borg Marks J, Galea P, Gatt S, Sands D eds 2022 Physics Teachers Education Chall. in Phys. Ed. (Cham: Springer) https://doi.org/10.1007/978-3-031-06193-6

[46] McLoughlin E, Sokolowska D 2023 Physics Teacher Professional Learning *The International Handbook of Physics Education Research: Teaching Physics* M F Taşar and P R L Heron eds (CPE: Springer) https://doi.org/10.1063/9780735425712

[47] Carli M, Fontolan M R, Pantano O 2021 Teaching optics as inquiry under lockdown: how we transformed a teaching-learning sequence from face-to-face to distance teaching *Phys. Educ.* vol 56 p 025010 https://10.1088/1361-6552/abcca7; Gabelli L, Carli M, Lissandron G, Pantano O 2025 Teaching scientific practices through low-cost tools: an experiment with high school students *J. Phys. Conf. Ser.* Vol 2950 p 012019 https://10.1088/1742-6596/2950/1/012019; Carli M, Leonardi AM, Ciroi S, Pantano O 2025 Teaching physics through astronomy in secondary school: the Asiago Teachers' Network on Astrophysics *J. Phys. Conf. Ser.* vol 2950 p 012034 https://10.1088/1742-6596/2950/1/012034