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# PRIMARY SCHOOL TEACHERS' TRAINING NEEDS TO MEET THE CHALLENGES OF 21ST CENTURY SCIENCE EDUCATION

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## Abstract

In the age of the Anthropocene, ordinary citizens have to make choices and decisions on complex and controversial socio-scientific issues that can have dramatic consequences on both their individual lives and the community's public life. That is why today, more than in the past, science education matters, and in OECD countries, it is compulsory for all students from kindergarten to age 15 or higher. According to the Pisa 2025 Science Framework, a 15-year-old school leaver aspiring to think and act as a responsible citizen should have developed specific scientific competencies that require the mastery of content, procedural and epistemic knowledge in order to be performed. Such an ideal of science education – which implies a certain image of science (epistemological variable), a specific educational task of the school (pedagogical variable), and a peculiar conception of scientific learning (didactic variable) – raises two distinct but related problems, which will be addressed concerning the Italian situation. The first problem concerns how to conceive of teachers' didactic competence in relation to the type of variables mentioned above. The position defended in this contribution is that the epistemological and pedagogical variables are mutually independent but not the didactic variable. Insofar as the choice of what is worth teaching and having students learn is concerned, the latter is constrained by the first two. Embracing this stance entails recognizing that teachers' didactic competence depends as much on their disciplinary expertise as on specific epistemological and pedagogical awareness. The second problem concerns the types of learning at stake. Since the competencies identified by Pisa 2025 are complex long-term learnings hindered by deep-rooted misconceptions about what science is and how it works, it is necessary to define the goals of science teaching from the perspective of a vertical curriculum and to identify the specific training needs of teachers of different school orders accordingly. Taking physical education as a case study to explore these issues, a theoretical reflection and operational suggestions are provided for updating in-service and pre-service teacher training, focusing on primary school teachers.

***Keywords:*** *Science education, teacher training, epistemology, physics teaching, vertical curriculum.*

## 1. Science education in the 21st century

In the age of the Anthropocene, ordinary citizens have to make choices and decisions on complex and controversial socio-scientific issues that can have dramatic consequences on both their individual lives and the community's public life. That is why science education matters today more than in the past. In many countries, it is a goal of the school curriculum from kindergarten until the completion of compulsory education, which usually ends at the age of 15-16. According to the Pisa (Programme for international student assessment) 2025 Science Framework, a 15-year-old school leaver "prepared for life" in modern society should be able to a) explain phenomena scientifically, b) construct and evaluate designs for scientific enquiry and interpret scientific data and evidence critically, c) research, evaluate, and use scientific information for decision making and action. For such domain-specific competencies to be performed, students must master and integrate three kinds of scientific knowledge – content, procedural, and epistemic knowledge – and feel engaged and confident in science as a collective human endeavor.

Concerning Italy, this entails that during ten years of compulsory education, students should learn not only selected content from the main fields of science but also how such knowledge is produced and why we consider it reliable (Duschl & Osborne, 2002; Sandoval, 2005). However, in 2015, the last year in which science was a major domain, the mean score of Italian 15-year-olds on the overall science scale was 481 points against the OECD average of 493 (OECD, 2015), with a mean performance on the procedural and epistemic knowledge subscale lower than that on the content knowledge subscale (479 vs.

483). In subsequent assessments, Italian students' scores remain below the OECD average: 468 vs 489 in 2018 and 477 vs 485 in 2022. While the causes of these negative results may be multiple, in this paper, an attempt is made to highlight those somewhat related to the ideal of science education fostered by Pisa in order to identify teachers' training needs, which differ according to their academic background (generalist vs. specialist) and/or the school level they teach in. Therefore, the research questions to be addressed are as follows:

**RQ1.** What kinds of competencies and awareness do teachers need to develop to promote the ideal of science education outlined by Pisa 2025?
**RQ2.** How can in-service and pre-service teacher training be updated to meet these formative needs?

The hypothesis is that teachers' didactic competence depends on their disciplinary expertise and specific epistemological and pedagogical awareness. Indeed, designing a science curriculum implies choosing what is worth teaching and how to do it (didactic variable) regarding a set of learning objectives that must be selected according to both a certain idea of the nature of scientific knowledge and knowing (epistemological variable) and the educational purpose that the school should strive for (pedagogical variable). Embracing this stance means recognizing that teachers' didactic decisions are neutral, neither concerning a certain image of science nor a certain idea of school (Martini, 2011; Tombolato, 2020). If this hypothesis is accepted, then it is possible to put the problem in these terms: net of other factors, teachers' didactic choices will be all the more effective in promoting the three competencies identified by Pisa, the more their personal view of science (epistemological variable) and the purpose they assign to their teaching (pedagogical variable) will be consistent with the image of science and the purpose of science education underlying the PISA framework.

The rest of the work is organized as follows. In section 2, the main features characterizing the image of science to which Pisa refers (PIoS) are identified by analyzing the types of scientific knowledge required to perform the three competencies. The objectives of science education will also be clarified based on the select competencies and the document's rationale for such a choice. Next, an attempt will be made to highlight the different training needs of primary and secondary school teachers. Finally, some suggestions are offered to update teacher training, focusing on primary school teachers.

## 2. The ideal of science education in Pisa 2025

According to the Pisa 2025 framework, which refines and extends previous competencies (PISA 2015), learning procedural and epistemic knowledge and disciplinary content is necessary for developing and implementing scientifically responsible behaviors in a STEM-oriented society. Procedural knowledge is defined as knowing the standard procedures and practices implemented by scientists to obtain reliable statements about the natural and human-made world and to evaluate evidence that can be used to support claims in a disciplinary domain. It includes, for example, knowledge about measurement and experimental procedures, modeling techniques, and processes of peer vetting within the scientific community. In general terms, epistemic knowledge concerns understanding the relationship between the aims (describe, explain, predict) and the means (e.g., models, data, evidence) of science as a collective and collaborative enterprise. It involves an awareness of why scientists' procedures, practices, and forms of reasoning must be considered reliable and within what limits.

At the core of this perspective, which differs from that of many school curricula dominated by content knowledge (Pisa, 2025, p. 10), is the shift from products to practices characterizing recent trends in science education (e.g., Duschl & Osborne, 2002; Kelly, 2008; Chinn & Rinehart, 2016) that take on board the views of scholars (e.g., Giere, 1988; Kitchener, 1993) interested in what scientists do to make reality intelligible and how they justify their findings. Within curriculum studies, a spokesman and, to some extent, the forerunner of this position is Joseph J. Schwab (1964), who maintains that what characterizes a discipline is not only the set of its concepts and theories but also its "syntax", i.e., the peculiar disciplinary modes of investigation, discovery, and verification that determine the different ways in which disciplinary knowledge claims are "true". Thus, the ideal of scientific education promoted by Pisa is based on an image of science conceived not only as an organized system of knowledge (ready-made science) but also as the collective effort of a community to solve problems by applying shared rules and criteria and by using disagreement (on methods, facts, interpretations, objectives) and rational discussion as tools to promote the advancement of knowledge (science in the making). This epistemologically sophisticated view of science can inform different didactic decisions according to the educational purposes assigned to its teaching. Pisa's choice to privilege education for citizenship is realized in the selection of competencies that do not concern the production but rather the informed and critical consumption of knowledge. Indeed, becoming acquainted with procedural and epistemic knowledge helps students develop a trustworthy attitude toward scientific research by understanding the norms and values to which community members express their commitment.

In summary, the choice to emphasize the epistemological aspects of science (procedural and epistemic knowledge) and not only the disciplinary aspects (content knowledge) is aimed at improving students' understanding of "science in the making" to enable them to evaluate information better and make responsible decisions, in order to avoid irrational and dangerous behavior stemming from naive beliefs. However, based on the data mentioned above, it is plausible to assume that the ideal of science education promoted by Pisa has been poorly implemented in Italy (but also in other countries), where teachers, while recognizing, to a greater extent than in the past, the importance of promoting the formative and cultural value of science, do not seem to be able to design teaching activities consistent with this goal, which requires shifting the focus from knowledge as a product (content knowledge) to knowledge as a process (procedural and epistemic knowledge). A major cause, though not the only one, is that university curricula do not foster the integration of the "two cultures," i.e., scientific knowledge and epistemology informed by pedagogical aims, the latter sometimes labeled by educational researchers as the "nature of science" (e.g., Abd-El-Khalick & Lederman, 2000). By taking physics education as a case study, I will explore this hypothesis first concerning upper and lower secondary school teachers (a more precise differentiation is not possible for this article) and then to primary school teachers, trying to bring out based on their respective strengths and weaknesses, the different training needs.

## 3. The training needs of primary and secondary school teachers

In Italy, university physics curricula offer repeated exposure to concrete problems deemed paradigmatic by the scientific communities (Kuhn, 1997), thus providing students with an opportunity to learn the syntax of the discipline (Schwab, 1964). As the philosopher of science Ronald Giere (1988) explains, through the study of standard textbooks and laboratory experiences, university students tacitly acquire new techniques and methods of knowledge production legitimized by the relevant scientific community. So, they learn alongside the practice of modeling the conditions of applicability of models to the target phenomena, and they get used to controlling different types of variables (independent, dependent, and control variables) during experiments to avoid confounded findings. In short, through extensive practice, physics novices acquire the way physics represents the world and, with it, the constraints to which it is subject. However, unless explicitly brought to students' attention through epistemological discussions (e.g., Bächtold et al., 2021), such knowledge embedded in practices and conveyed through exemplars (Kuhn, 1997) usually remains tacit, only becoming visible through competent actions. This is what happens to many future secondary teachers since university physics curricula do not offer any course entirely focused on the "nature of science" (Dibattista & Morgese, 2012, pp. 151-153), which at most is mentioned in the "Didactics of Physics" course, but only a "History of physics" course.

While this "epistemological naivety" is not necessarily a problem for scientists (Rosenblueth & Wiener, 1945), it negatively affects teachers' didactic choices as they generally fail to include procedural and epistemic goals in their school curriculum planning. As a result, in carrying out the didactic transposition of scientific knowledge into knowledge to be taught (Chevallard, 1985; Schubauer-Leoni, 2008; Martini, 2011), epistemologically naive teachers are more likely to isolate the content of a discipline from its syntax, thus providing students with mostly inert knowledge, i.e., information that they can memorize but not use to interpret reality. Actually, according to Sandoval (2005), there is not necessarily an agreement between practical epistemologies (i.e., epistemological beliefs manifested through practice) and formal epistemologies (i.e., explicit epistemological beliefs), a hypothesis that seems to be confirmed by Michela Mayer's (1996) investigation of commonplaces about scientific practice in secondary school science teachers. Among the most widespread clichés that Mayer (1996, p. 136) identified by analyzing the responses of some groups of teachers to a semi-structured questionnaire on scientific knowledge (Mayer & Vicentini, 1996, pp. 65-68) are worth highlighting: the superiority of nomothetic sciences, conceived as examples of a single universal explanatory model, over ideographic sciences; the naive empiricist idea that laws and theories are derived inductively from observations and experiments; the myth of a universal and ahistorical method, which provides privileged access to truth and demarcates science from pseudoscience.

This trivialization of the relationship between reality and scientific representation, also prevalent in various school texts, strengthens the naive ideas of students, which eventually turn into deep-rooted misconceptions. Based on many years of experience teaching physics (labs and lessons) to primary school students, most have a dogmatic and naive view of how scientific knowledge is produced and justified. Specifically, practices devised and/or employed by Galileo to make the natural world intelligible, such as the asymptotic approach to "pure case," the causal simplification in experiments (i.e., the strategy of controlling variables), or the design of counterfactual mental experiments (McMullin,1985; Koertge, 1977), seem extremely counterintuitive to prospective primary teachers. Indeed, they often mistake the ideal cases (e.g., movement in the absence of friction, oscillations of a mathematical pendulum) described in textbook problems as real and concrete, fail to identify and control different types of variables (dependent, independent, and control) while doing simple experiments, or struggle to connect observed phenomena with their mathematical or graphical representations. Making such errors, examples of which can also be found in the specialist literature (Matthews, 2001; Schecker, 1992; Oberle et al., 2005; Roth & Tobin, 1997), denotes a lack of knowledge of both disciplinary epistemic practices and the conditions under which such practices can be used to produce reliable knowledge about the natural world.

Within this framework, the training needs of secondary and primary school teachers appear very different. The former must be helped to explicate, problematize, and integrate the learning they have implicitly developed through practice to overcome commonplaces about their discipline and its teaching and intentionally design instructional activities consistent with the ideal of science education promoted by Pisa. The latter, on the other hand, need to be helped to evolve the different types of misconceptions developed during their schooling while gaining a more sophisticated view of physics so that they can truly understand how and to what extent this discipline can contribute to shaping active and responsible citizens. Suggestions to this effect will be formulated in the next section.

## 4. Epistemology and history of science in the service of teacher training

Due to the generalist degree course they attend, primary school students suffer from the difficulty of having to acquire knowledge and skills in a wide variety of disciplines through a limited set of experiences. Unlike secondary school teachers, they cannot count on implicitly acquiring disciplinary procedures and rules through extended and extensive practice. This suggests acting on two levels - disciplinary and interdisciplinary - to turn what may at first glance appear to be a weakness into a strength and at least partially compensate for the absence of specific courses in history and philosophy of science. On the one hand, I propose to identify synergies between the different areas of knowledge within the curriculum - i.e., the other scientific disciplines, pedagogy, and general education - in order to converge objectives and maximize student learning. On the other hand, I propose to exploit the epistemology and history of the discipline to rethink the transposition of physics in the light of two types of learning goals: those concerning students as learners and those concerning students as prospective teachers. As primary education is the only degree course that directly qualifies students for teaching, they must simultaneously acquire disciplinary and didactic competencies.

Hence, there is a need to work on two fronts. Firstly, students need to understand why physics should be taught from primary school onwards. Thus, they must realize that since the competencies identified by Pisa as essential for the 21st-century citizen are complex long-term learnings (Bateson, 2000; Baldacci, 2012), the objectives of science education must be defined from the perspective of a vertical curriculum. This requires that all school levels involved contribute to their achievement. This kind of awareness can be fostered in students by working in synergy with Pedagogy and General Didactics courses. Secondly, prospective teachers must realize how they can contribute. This implies that they understand how physics produces and legitimizes its knowledge and how and within what limits this knowledge furthers the progress and welfare of humanity so that they can develop a rational trust in research, which they can pass on to their future students. Such a positive and rational attitude can be strengthened if promoted in synergy with other scientific disciplines.

Within this framework, epistemology and discipline history can be used as teaching resources to pursue procedural and epistemic learning objectives effectively. At an operational level, I thus propose to use the following epistemological questions (e.g., Osborne and Duschl, 2002; Sandoval, 2005) to deconstruct the discipline (in this case, physics) and reconstruct it for teaching purposes: a) What exactly do we know through that discipline (e.g., physics)?; b) How do we know what we know?; c) Why do we trust what we know? By analyzing physics and its history in the light of these questions that are consistent with PIoS, some epistemological nodes linked to specific educational goals can be identified, around which it is possible to design teaching activities of different levels of complexity without being bound to specific content. For example, referring to the second question applied to the history of physics, the asymptotic approach to “pure chance” can be identified as an epistemological node. This technique, for whose counterintuitiveness Galileo was also criticized by his mathematical friend Guidobaldo del Monte (Matthews, 2001), can suggest activities that can be designed around different content (e.g., the principle of inertia or the law of falling bodies) and whose level of complexity can be determined in relation to the school level and other learning variables.

In the perspective of a vertical curriculum, these epistemological nodes, which identify procedural and epistemic knowledge consistent with the Pisa ideal of science education, can represent the converging goals of teaching activities that need to be adapted according to students' different needs and abilities.

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