IL NUOVO CIMENTO **46 C** (2023) 203
DOI 10.1393/ncc/i2023-23203-x

Colloquia: IPER 2022

An epistemological approach to align physics teaching with the society of acceleration and uncertainty

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received 13 July 2023

Summary. — In this paper, we present an epistemological approach to physics education research that was progressively developed to build teaching modules aimed at aligning physics teaching with the society of acceleration and uncertainty. This approach is characterised by the choice to exploit the epistemological richness of physics in order to regenerate disciplinary knowledge, and make the discipline a locus wherein to develop the personal identities and competences needed to navigate our current complex society. The approach combines different frameworks, from science education to learning sciences, including the model of educational reconstruction, coordination class theory for conceptual change, the meta-theory of boundary for interdisciplinarity, and the family resemblance approach (reconceptualised for the nature of science). We first describe the process that led us to outline the approach, before referring to some modules (in particular concerning special relativity, thermodynamics and climate change) to discuss our design principles. Specifically, we will argue how these principles represent a compass to make the epistemology of physics resonate with students' personal processes of sense-making, as well as grounding in the disciplines the development of sustainability competences such as embracing complexity, envisioning futures and enacting creative thinking.

1. – Introduction

In this paper, we present an approach to physics education research which has been progressively developed in Bologna to deal with issues that affect school teaching.

The approach is characterised by a strict interplay between socio-cultural commitments, theoretical orientation, design principles, implementations, and empirical analysis of real classroom episodes. The development of the approach has been supported by systematic collaboration with school teachers, foreign colleagues, experts in the learning sciences, and the institutional scaffolding provided by European projects.

The work began about 20 years ago, when schools and society started to note a significant decrease of interest in science as a subject matter [1, 2].

Science, and physics, have proved to be perceived at school as personally, societally or vocationally irrelevant disciplines [3]. Physics consolidated its image as an inherently difficult subject, hierarchically organised, objective, rigorous, and elite [4]. As a result, it seemed (and still can seem) to students to be a "closed and exclusive club" where the few (but satisfied) participants correspond to a specific stereotypical physics identity [5]. This "silos" image of physics is progressively losing its appeal in the society of acceleration [6, 7], where the complexity of societal problems requires crossing the boundaries between disciplines, exploiting new perspectives and searching for new interdisciplinary approaches. In the pandemic and post-pandemic era, the sense of misalignment between school science and society has been exacerbated, and young people struggle to find, in formal education, the resources needed to navigate this complex, fragile and fast-changing society [8].

For the past two decades, our physics education research group has been working to address these issues by designing curricula for upper secondary students based on the idea that there is an unexplored potential in the epistemological core of physics (and science); this potential is assumed to be the key to regenerate physics to reach students with different cultural interests and provide them with the tools necessary to navigate our current society [9, 10].

A set of theoretical frameworks has been used to test the assumption and explore the epistemological potential by designing and implementing innovative teaching materials. The set includes the Model of Educational Reconstruction [11, 12], the boundary metatheory for interdisciplinarity [13], the Family Resemblance Approach reconceptualized for the Nature of Science [14], and the Coordination Class Theory for conceptual change elaborated within the Knowledge in Pieces perspective [15].

In this paper, we show how we combined the different frameworks into a design-based iterative process, and pointed out design principles to align physics teaching with the society of acceleration and uncertainty.

Initially, the group worked on advanced physics topics (thermodynamics, relativity and quantum physics) that are included, however, in the secondary school physics curriculum. Since 2016, the approach has been applied to STEM topics like climate change, artificial intelligence, quantum computers, and simulations of complex systems.

We will briefly mention the different cases in describing the progressive exploitation of the epistemological core of physics and its summary into a set of design principles. In particular, the main goal of the paper is to argue for the role of design principles as a compass to hold together a plurality of dimensions of our educational reconstruction, without losing sight of the final goal of making the epistemology of physics resonate with students' personal processes of sense-making while grounding, in the disciplines, the development of societal competences.

After the presentation of the theoretical frameworks used, we will present the methods we followed to define the approach and, finally, the results. These results will take the form of a set of design principles, produced progressively.

2. – Theoretical frameworks

Since 1997, the Model of Educational Reconstruction (MER) has been strongly influencing science education in Europe. It is a methodological framework designed to provide research-based orientations to instruction design (*e.g.*, [4, 12, 16]). The main message it aims to convey is that the content knowledge structure of a certain domain and the content structure for instruction are structurally different, since their scope and goals are different. The first type of content knowledge emerged from scientific processes of checking, testing, and evaluating, and its structure is shaped in order to foster inner control procedures of coherence and consistency, within communities of experts. Content structure for instruction, meanwhile, is intended to foster deep understanding by novice learners and, hence, it should be shaped to effectively activate fruitful cognitive resources. According to this idea, content knowledge has to be transformed, and "re-constructed" for teaching purposes. This process of transformation implies that the scientific contents have, firstly, to be elementarised to become accessible for learners but also enriched with epistemological and cognitive elements that foster processes that make sense to the learners. In this process, issues of science content and learners' perspectives (their conceptions and views about the content as well as affective variables like their interests and science learning self-concepts) have to be taken into account and highlighted. Clarification and analysis of science content is the first component foreseen in the model. It must also be combined with two other elements: taking into account the research on teaching and learning, with emphasis on students' perspectives; designing and evaluating the teaching and learning environments. The interplay of these three components is essential in the constructive orientation of the MER, according to which the content structure for basic instruction cannot be taken directly from the science content structure as though it were a monolithic body of knowledge. It has to be (re)constructed while paying attention to the educational goals, students' cognitive, aesthetic and affective perspectives, and the teaching contextual conditions [11, 12].

At the basis of MER there is an epistemological commitment that makes educational reconstruction a creative and intellectually stimulating process: physics is not as monolithic as it appears to students, who see no space for personal positioning; it is, instead, a discipline that, like every human construction, has its own "plasticity", being rich and complex enough to allow its contents to be analysed, elaborated and re-structured in many ways according to many different cultural, intellectual or educational goals. MER has been employed in developing teaching-learning sequences on several physical topics, including chaos theory [12] and non-linear systems [17]. MER has been applied in the development of a further model for science teacher education [17] and for the development of science exhibitions [18].

While MER can be used to analyse the content knowledge from an educational perspective, the coordination class theory is a framework that can be used to unpack the cognitive processes of students' learning.

Coordination class theory is situated with the knowledge-in-pieces perspective, according to which knowledge is seen as a broad complex system of many kinds of knowledge elements and structures (*e.g.*, [19, 20]). The learning of a concept is modelled as a process of reading out, coordinating and relating diverse elements —arriving from the prior conceptual path of the learner— in multiple ways. In this view of multiplicity of elements and relations, "coordination class" means —partially— conveying precise relations among knowledge pieces (coordinations) within a complex system perspective. References [15, 21, 22] define coordination class as a model of a particular type of concept, where —consistently with the perspective that knowledge is a complex system— "concepts are large and intricately organised systems, which effectively coordinate activation and use of many specific elements according to context" and the "learning of a concept is seen as a process of recruiting and coordinating a large number of elements in many ways."

Coordination class theory responds to the need for a framework able to interpret the complexity and disorganisation of human learning and action, and provide new lenses for making sense of what is happening in the complex, more-or-less real world instructional setting in which a design study can be conducted [23]. The crucial point of a coordination class is understanding the many particular strategies and processes by which individuals determine the implicated class of information across the variety of situations the world presents. Coordination class focuses indeed on the internal structure of concepts and their gradual construction.

According to this theory, having a concept means being able to see and read the information that defines the concept in an appropriate range of relevant situations. Indeed, the architecture of coordination class entails two elements [15, 21, 22]:

- readout strategies: "the ways in which people focus their attention and read out any related information from the real world";
- the causal (or inferential) net: "the total set of inferences one can use to turn related information readouts into the particular information at issue."

The coordination class architecture highlights the fact that diversity of contexts can lead concepts to include many context-specific elements. So, the application of knowledge concerning a concept in specific different contexts implies making an operation of concept projection. This element allows for some intrinsic natural difficulties that can occur during the processes of concept learning [24]:

- the span problem: "having adequate conceptual resources to operate the concept across a wide range of contexts in which it is applicable."
- the alignment problem: "being able to determine the same concept-characteristic information across diverse circumstances."

The choice of using both the MER and the coordination class theory within the instruction design allowed us to move consciously across two epistemological domains: one referring to physics as a discipline (a type of knowledge that has its own mature and historically developed epistemic structure), and the other that refers to students' knowledge and their cognitive processes. This two-pronged epistemological layer is needed to keep under control what Sherin calls "ontological slippage" [24]. Ontological slippage can occur when a researcher fluctuates between the construct "concept" as characterised within a cognitive model of knowledge and the term "concept" as used to refer to an idea appearing in a textbook or curricular learning objective.

To better characterise the disciplinary content knowledge (as opposed to the cognitive one) from an epistemological perspective, a specific framework has been more recently included in the set of reference frameworks: the Family Resemblance Approach for the Nature of Science. This framework was elaborated for education by Irzik and Nola [25] and later reconceptualised for science education by Erduran and Dagher [14, 26]. Its potential lies in avoiding an attempt to define science, offering instead an overall view of the many aspects that characterise sciences. The view is summed up in the FRA wheel ([14], p. 28), where 11 categories are reported to characterize the Nature of Science ([26], p. 1003). The wheel has an epistemic core, articulated in 4 categories: aims and values, methods and methodological rules, practices, and scientific knowledge. The core is enriched with two external circles that emphasise the nature of science as a social-institutional system (encompassing professional activities, scientific ethos, social certification and dissemination of scientific knowledge, and social values), immersed in a socio-political organisation of power and of funding. The FRA has been used in science education for many purposes: developing teaching strategies in teacher education [27,28] as an analytical tool for textbooks [29], for science and physics curricula [30-33].

This specific function of the FRA has been used and intertwined with the framework of boundary objects and boundary crossing mechanisms [13] in the design and implementation of interdisciplinary modules.

Interdisciplinarity is a complex and timely challenge. Pressure to renew curricula in a STEM perspective has been strongly exerted from outside the schools (policymakers, entrepreneurial world, labour market) [34,35] and is mainly motivated by the belief that students have to be prepared to cope with contemporary societal challenges that involve intrinsically interdisciplinary topics (*e.g.*, climate change, artificial intelligence, nanotechnologies) (*e.g.*, [36,37]). Consistently with the definition of Alvargonzález, interdisciplinarity differs from multidisciplinarity, where disciplines are juxtaposed and remain separate. It differs yet again from transdisciplinarity, where the goal is to overcome disciplinary worldviews through an overarching synthesis [38]. Interdisciplinarity (as in a boundary zone) implies forms of interaction, the acceptance of playing the role of boundary people, the activation of boundary crossing mechanisms, also through the use of boundary objects [13].

In the following section, we show how the use and combination of these frameworks allowed us to exploit the potential of physics to deal with societal needs.

3. – Methods

The development of the approach has been carried out as design-based research [23]. Two main features of the design-based approach [23,39] have been particularly emphasized throughout the whole process: the iterative dynamics and its theoretical orientation. Materials and activities have indeed been developed through an iterative process of designing, testing, revising, according to a back-and-forth dynamic between theoretical hypotheses and empirical results. This process has informed the method of materials production in as much as it did not follow a linear process (preparation, implementation and evaluation) but a back-and-forth, multiple round, dynamic process of revision and refinement. The results of the process did not only lead to the improvement of the materials, but also —and mainly— to a "theoretically-oriented" evaluation of the impact of the implementations on students' processes of knowledge and skills development. Data have been systematically collected from different sources (*e.g.*, classroom video and audio-recording, focus groups, individual interviews) and analysed by qualitative and microgenetic methods of data analysis. Through these methods we were able to highlight what happened in a specific teaching/learning experience, and to provide an interpretation of why, when and how that happened [40]. This was particularly evident in the thermodynamics implementation, which allowed us to build the theoretical construct of appropriation [40], and to unveil the orchestration strategies that the teacher activated [41].

The study on appropriation allowed us to develop a method to build theoretical constructs characterized by "operational markers". The markers are different from not only pointed out to code data but also to capture the main joints of a phenomenon that can emerge in real teaching/learning contexts and provide an interpretation of what happened. The markers are operative tools to recognize them both in students' discourses (by analysing oral or written discourses) and in actions (by analysing students' artefacts).

The iterative dynamics and theoretical orientation methodologically guided the whole process that, throughout the different domains, led us to identify our design principles.

This whole process can be reconstructed, a posteriori, along three macro-phases. They correspond to the identification of societal issues that have been challenging teachers, schools, and research in science education:

- The lack of personal relevance of physics and the perception that, unlike humanities, science could not be a locus wherein to develop one's own personal identity [1, 2];
- The difficulty of navigating the current society of acceleration and uncertainty, envisioning futures and embracing complexity [6];
- The "silos effect" and the crisis of the current vertical organization of knowledge in disciplines to prepare the young to deal with societal problems that require a multi-trans-interdisciplinary perspective to deal with [7].

Each macro-phase included at least three iterations of design-implementation-analysis. Each iteration was articulated in five micro-phases:

- investigation of the societal issue and its reformulation as a problem addressable through science education;
- identification of the epistemological potential of physics to deal with the societal issue;
- content clarification and its reconstruction to transform epistemological potential into the design of teaching modules and, consistently, into the explicit formulation of design principles that also ensure results in science education on students' learning;
- implementation of the modules, collection and analysis of classroom data aimed to test whether, and how, the epistemological potential was activated and, in this event, the relevant impact;
- de-briefing on the whole iteration and reformulation of the design principles.

In the following section, we present the process and report the main results of our epistemological analysis and its summary in the design principles.

4. – Findings

The first societal challenge, *i.e.*, the perception of a lack of personal relevance of physics teaching, prompted us to apply the Model of Educational Reconstruction to question the history and philosophy of physics in the search for personal stances. The analyses led us to focus our attention on foundational debates in special relativity and quantum physics, which could show that also in physics there is room for a plurality of perspectives and personal points of view. This is possible also in compliance with the constraints imposed by normative knowledge.

In this perspective, instructional materials on relativity [42] and quantum physics [43] were designed by evaluating historical papers from the fathers of such theories, debating on foundations or epistemological issues. In particular, the materials on relativity have been built on the debates on the nature of space and time between Einstein, Minkowski and Poincaré [44], and the materials on quantum physics on the debates about visualisation between Heisenberg and Schrödinger, about the meaning of complementarity and uncertainty between Einstein, Bohr, Heisenberg and Schrödinger [43].

Three design principles have been identified to characterise the content reconstruction: multi-perspectiveness, multi-dimensionality and longitudinality.

By multi-perspectiveness we mean that the same concepts are analysed from different perspectives and through different "voices", such as that of Einstein to introduce the algebraic/operational perspective in special relativity, contrasted with the voice of Minkowski presenting the geometrical perspective. The "voices" become part of classroom discussion through a selection of original papers used to introduce and discuss the basic concepts. Multi-perspectiveness is expected to expand the span of possible learning trajectories by offering at least two examples of them for each topic.

The second principle, multi-dimensionality, means that the content and the different perspectives are analysed and compared at different levels: conceptual, experimental, and applied, as well as in their philosophical-epistemological peculiarities. Operationally multi-dimensionality is introduced through a plurality of activities, including the analysis of different texts and materials (*e.g.*, epistemological essays, videos and applets, scientific reports on climate change for policymakers, tutorials for inquiry-based activities). Multi-dimensionality is expected to play two main roles: a) offering students a plurality of access points to the discipline (formal, experimental, logical-argumentative, historical-epistemological, applicative; b) fostering a sense of belonging through the exploration of the many dimensions of science.

Finally, longitudinality means that students are guided throughout the entire physics curriculum to recognize long-term themes that cross different scientific domains and topics and that characterize science as a whole. One example of a theme is modelling and its specifications in different topics and domains. Longitudinality is implemented by tutorials or in specific lessons where students' attention is focused on the "chapters" of the collective story that the class is developing. Longitudinality, explicitly focused on showing what science is and what distinguishes it from other subject domains, has the main role of rendering visible the epistemological structure of the discipline.

The classroom implementation of the materials activated very rich and lively discussions among the students, during which personal resources and deep cognitive processes of learning emerged. In order to unpack such dynamics, the model of the coordination class theory was used. Its theoretical orientation allowed us to argue why exposing the students to multiple contexts and definitions represented a productive strategy to promote conceptual change [22].

On the basis of these results, we reconstructed the basic contents of thermodynamics by exploiting the comparison between the microscopic and macroscopic approaches, and between the different epistemological positions of Clausius, Kelvin, Maxwell and Boltzmann [45].

The plurality of perspectives and multidimensionality contributed to creating a psychologically safe learning environment where students could find room and support to position themselves with regard to the discipline, the class and also their own personal narrative of who they individually are as a person and as a learner. Such a positioning fostered what we called appropriation, a special form of conceptual learning where the individuals populate their understanding of scientific content with their personal tastes and purposes [40]. By means of an analytic process of defining, operationalizing, and testing the definition against classroom data, the term appropriation —borrowed from research fields in linguistics and education— was turned into a theoretical construction in science education. The term appropriation was chosen to characterise a broader sense of productive learning that lies at the nexus of disciplinary engagement and identity. Indeed, appropriation besides implying a deep conceptual understanding, also involves a reflexive process of transforming scientific discourse in a way that is authentic, idiosyncratic and personal [42]. Five discourse markers for operationalizing the construction were discovered, indeed appropriation implies students' discourses are (A) an expression of a personal "signature" idea; (B) grounded in the discipline; (C) thick, in that it involves a metacognitive and epistemological dimension; (D) non-incidental, in the sense of being consistently used throughout classroom activities; and (E) a carrier of social relationships, in that it positions the student within the classroom [40].

Appropriation became the way to unpack the nexus between conceptual change and identity, and show how learning of and in a scientific discipline can become a way for students to develop their personal identities [46].

The exploration of the nexus between conceptual change and identity is led to the introduction of the notion of personal concept projection, which is an elaboration on the coordination class theory of conceptual change [15]. Indeed, the lens of appropriation, applied to the processes of disciplinary learning, is an example of how coordination class theory can be extended to reveal ways that disciplinary learning and identity formation can be intertwined, looking at how deeply the development of disciplinary learning is related to the development of a "signature idea" [40, 46].

An important impulse to develop the approach in question further arrived from the second societal challenge: around ten years ago, the teachers of the group started to observe the increasing difficulty of young people to grapple with the future and societal uncertainty/complexity. This prompted us to re-analyse physics theories in order to identify models elaborated to deal with the futures. In physics classes at school, teaching insists —almost exclusively— on linear causal models built according to Newtonian physics which historically provided the mathematical models, language and epistemological scaffolding to view the future deterministically, as linear progress towards an ever-better world. Science, however, throughout its history, has developed other temporal patterns and models of causal explanation, like those typical of quantum physics or of the science of complex systems, which are at the basis of scientific fields like climate change, epidemiology or bio-physics. A further design principle has been elaborated: futurizing science teaching. This implies exploiting the scientific temporal patterns and causal models to enable students to borrow from physics those concepts, words and tools required to embrace complexity, envision futures and act for sustainable desirable futures. Modules designed to "futurise" science education have been developed within the project I SEE and, then, in the project FEDORA. They concern STEM topics like climate change, quantum technologies, artificial intelligence, and simulations of complex systems [10, 47].

Multiple rounds of implementation of the module on climate change led us to coin and operationally define the operational construction of "future-scaffolding skills" that this form of design fostered. Future-scaffolding skills are needed to support possible ways of acting in the present with an eye on the horizon. They consist of two macro-types of skills: i) structural skills, which represent abilities to organize pieces of knowledge and build systemic views and to recognize temporal, logical, and causal relationships; and ii) dynamical skills, which represent the abilities to navigate across the complexity of knowledge, relating local details to global views, past to present and future, and individual to collective actions [9, 10, 48, 49]. For us, future-scaffolding skills represent an operational construction, since we identified and extensively described markers that make them operatively exportable and applicable in many different contexts (*e.g.*, [50-52]). Finally, the third societal challenge prompted us to dive into the foundations of disciplines to search for a way to regenerate these areas' potential to turn information into organised reliable knowledge, without becoming trapped in empty technicalities. In the era of acceleration, knowledge is becoming more and more fragmented into pieces of information, and epistemic skills for structuring and making sense of these are particularly important. Interdisciplinarity has been chosen as the approach to reach the aim to unveil disciplinary identities and their forms of knowledge organization. Interdisciplinarity, like any boundary zone, both connects and separates. Through mechanisms of identification, communication, reflection and transformation [13], physics can dialogue with other STEAM disciplines and reveal its learning potential. Creating boundary zones was the last design principle that we incorporated in our model to guide students "learn at the boundaries" [53] in STEAM contexts, and nurture their creativity whilst they become acquainted with the epistemic identities of the various disciplines involved in dealing with climate change.

5. – Concluding remarks

In this paper, we described the design principles that we progressively identified to make the epistemology of physics resonate with students' personal processes of sense-making as well as grounding in the disciplines of the development of sustainability competences such as embracing complexity, envisioning futures and enacting creative thinking. In the last phase of de-briefing the whole process, we realised that the design principles, all together, contribute to forming a comprehensive frame. They, indeed, represent a compass to develop the thinking competences of Pellerey's framework [54]. Pellerey's framework has been built to cohere with Aristotle "dianoetic virtues": the ability to make knowledge part of a significant process of identity formation (the Aristotelian "sophia", wisdom); the ability to turn information into organised reliable knowledge, unveiling scientific epistemic practices and being able to learn at the boundaries (the Aristotelian "episteme"); the ability to turn knowledge into actions, by embracing complexity, embodying values, acting for sustainability (the Aristotelian "phronesis", agency); the ability to nurture intuition, creative thinking (the Aristotelian "nous", intuition); the ability to turn scientific knowledge into an artifact (technological prototypes, artworks, novels, movies, game, etc.) (the Aristotelian "techne", art). We believe this comprehensive picture provides added value to the next iteration of our design-based research, since it offers an articulated but coherent view of the epistemological richness we are searching for in physics and which we wish to enhance.

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