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Entangled research methods for the building of coherent conceptual thematic learning paths and connecting research with praxis

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Summary. — In this work we present our content-research studies aimed at identifying conceptual learning pathways in physics for students of different ages and for teacher education in the 30 years of research of the Udine Physics Education Research Unit (UPERU). They are based on the Model of Educational Reconstruction (MER) revisited by focusing on disciplinary fundamental concepts of the selected topic, aiming at conceptual change with respect to the knots that differentiate common sense from scientific ideas. Learning trajectories are sought in the pathways, with tools, strategies and methods studied for the purpose. The research involves analysis of learning processes using mixed methods. Contexts are scholastic and university ones, as well as formal and non-formal, like the Games Experiments Ideas (GEI) exhibition or theaters. Attention is paid to the disciplinary content and methods that establish physics, in epistemological terms, within a basic culture and in teacher education, with specific studies on the guidance and construction of active citizenship and university teaching innovation. The topics covered are classical physics, quantum mechanics, optical, atomic, nuclear and gamma spectroscopy, relativistic dynamics and superconductivity. For teacher education, the Metacultural-Experiential-Design-Situated (MEDS) model was developed with 20 years of experimentation.

1. – Introduction

International surveys have highlighted the lack of scientific culture at all levels [1, 2]. This posed the problem of how schools can improve the scientific culture of citizens. The European Community has developed recommendations, supported surveys, researches and action projects for this purpose, also focusing on teacher education [3, 4]. But the problem has new aspects today. The complexity of the socio-cultural and working context poses new learning objectives, which require a radical change in teaching methods. The appropriation of scientific concepts and the ability to use them in a differentiated manner, in terms of skills, has become one of the main objectives of education at all levels [5, 6].

This poses the methodological problem of how to operate, so that the student is an active subject and protagonist in the teaching activity. The problem cannot be resolved on a purely pedagogical level: the tools and methods of the discipline must be the basis of the active role of the student, so that they can appropriate the epistemic character of the discipline they face, because it builds competence to use it [7]. On the other hand, scientific education, and in physics in particular, can no longer take place through the approaches followed so far, based on the presentation and explanation of structured knowledge, like answers to unanswered questions [8]. This is particularly important in physics and is an evidence that the great founders of active methods are physicists, like for example: Reginald W. Revans with his pioneering studies of Action Learning [9]; Bonwell and Eison [10], who remained famous for the phrase "*Anything that involves students in doing things and thinking about the things they are doing*"; Marco Antonio Moreira, with his works on meaningful learning and concept maps [11]; Lillian McDermott, mother of the Inquiry Based Learning [12]; Eric Mazur, who founded the peer instruction [13]; Eugenia Etkina [14], and many others. Their work and other extensive long-standing research have shown that, alongside methods, research on the content of physics is needed, precisely because learning is content-specific [15]. It is necessary to improve practice by means of research and to explore Conceptual learning and Lab work role [16, 17], as well as teaching/learning processes for new topics [18, 19]. Therefore, it is necessary to analyse the type of activity in which students are involved, and in particular the role and modality of the laboratory [14, 15, 17, 20]. The internal coherence of the conceptual path [21], and the line of reasoning, are prerequisites for the integration of activities with multi-perspective educational functions, which aim at the appropriation of concepts. Multimedia applications have helped learning processes and fostered new learning objectives, especially in physics [22].

The identification of the influence and persistence of common-sense ideas over scientific learning in exploring reality [21] has produced many studies on common sense ideas and so-called misconceptions (or those interpretative ideas above all, which differ from scientific ones) of children and teachers on all physics topics [21, 23, 24]. Knowledge of misconceptions is not enough to identify how to direct education. Studies are needed on students reasoning [25] and conceptual change [26-29], as well as learning progression [30] in which the evolution of reasoning from common sense to scientific ideas [31] is identified: difficulties and modalities. Above all, in addition to the study of the ways in which reasoning evolves [32], the study of materials [33, 34] and coherent teaching pathways that foster the reasoning and conceptual learning of students at all school levels [35-37], with approaches that take into account theories of reasoning [38]. Alongside intervention modules of this nature, thematic vertical pathways serving as conceptual organisers in curricular pathways are needed [18].

At the same time, there was a need to educate teachers to appropriate and manage the results of research in physics teaching on the study of teaching paths, learning processes and specific strategies [39-41]. This is also a major line of research that seeks to answer the question: how to produce in the teacher the competence to plan effective teaching activities and to create fertile learning environments, monitoring the learning processes of children [4].

This paper presents our research, which fits into the context of content-research supporting education, by building thematic teaching/learning path proposals [42-44] which develop vertically, in the theoretical framework of the Model of Educational

Reconstruction (MER) [45]. The latter is reinterpreted by means of interactive design [46] of learning analytics and Design-Based Research (DBR) [46,47]. Using this approach, the research on teacher education develops a model for the professional education of future teachers with the contribution of physics education research [48].

2. – Theoretical framework and research traits

Our research is placed in the context of content research [7, 18-20, 25-31] and is linked to the construction of skills to produce specific disciplinary learning (learning of Subject Matter). It includes different lines of research to identify conceptual learning paths in physics: coherent thematic hallways where each student can find their own learning trajectory. The main lines of research that are intertwined in this main strand include disciplinary conceptual analysis, the design of educational pathways, the study of learning processes and conceptual change, the design of devices for experimental activity, of headings for data collection and analysis. The theoretical framework is the Model of Educational Reconstruction (MER) [45] revisited: a preliminary focus on the fundamental concepts in the selected theme build the learning objectives, without reductionism or simplifications. In so doing, coherent conceptual paths are searched for in vertical perspective [30,45,46], with an approach that aims at conceptual change and pays attention to interpretive knots [27-29, 31, 44, 49]: those readings and interpretations of common sense of phenomena, that conflict with the scientific view.

The path is developed following a series of Formative Intervention Modules (FIM) [43] with Learning Analytics [47] and Design-Based Research [46] settings, in which different design cycles are carried out: intervention, evaluation, and review of the contents of the FIM [43]. In each FIM, attention is paid to those steps (conceptual and reasoning) on the wayfarer's journey in a vast wooded territory, that aim at the destination of being able to offer a coherent retro-perspective vision of the stages (concepts) of the path, which become tools to be employed in other paths. The development of the path follows two typical phases.

1) The first step in our research involves a conceptual reconstruction by means of the MER, that implies rethinking the scientific content in problematic terms, to be reconstructed in a didactic perspective, studying the foundation concepts that make them work as conceptual referents in the learning path. This often involves a critical study of the disciplinary fundamentals for a global framework. Partial simple interpretations and any form of reductionism are renounced, in order to study learning objectives in terms of a coherent theoretical framework, including the associated epistemic character [43, 45, 50].

2) The second step of research design is constituted by the study of learning processes and conceptual change from common sense ideas to individual conceptual elements, often consisting of two parts: a a review of the relevant literature and an inquiry aimed at the thematic conceptual cluster and context. This learning-process research approach aims to identify obstacles to be overcome, in order to reach the scientific level of understanding and the construction of formal thinking, rather than general findings or catalogues of difficulties. We are interested in the internal logic of reasoning, the spontaneous Mental Models [51], their dynamic evolution as a result of problematic stimuli (Inquiry learning) in proposed paths [52]. In addition to specific surveys (Inquiries), research experiments allow us to explore

the contribution to the learning of teaching/learning proposals (T/L) in the FIMs in an operational way.

The path development implies the identification of tools and methods allowing students to operationally master their personal learning trajectories [32]. For this reason, the research of the pathways is integrated with the empirical research on the reasoning of students during learning, with methodologies of Design-Based Research (planning, implementation, data analysis and revision) [46] and Learning Analytics (learners, data, metrics/analytics, intervention) [47] and in the design of FIM and action-research in collaborative school-university dialectics. Here, the aim is to contribute to the classroom practice and/or daily teaching, and develop proposals for vertical teaching paths through different class experiments. We study how to interpret, so to address learning complexity, by building proposals that offer each student room to build personal learning, often very context-related.

Our approaches are therefore not only based on disciplinary content [19, 52], to identify strategies for conceptual change [26-29]. We study operative proposals in a cultural perspective, by focusing on the foundation of basic concepts, methods and applications in physics research, integrated into the physics curriculum and not as special experimentation, thereby offering experience of how physics operates in active research. Integration in the curriculum is a choice and a basic design goal, even for new topics that are not included in the curriculum, such as those of modern physics [53, 54]. We identify vertical paths, which in a learning progression [30] serve as teaching hallways [50]; for individual learning trajectories [55], and study the modalities of step-by-step concepts appropriation [56, 57]. Attention is paid to identifying strategic angles and critical details employed by the knowledge of common sense aimed at phenomenology interpretation, and studying children reasoning in dynamical terms [25, 29, 55, 56] so to find new approaches to physics knowledge [25, 31, 32, 50]. We study ways to build personal learning and skills tools and methods: not just understanding information, interpretive solutions and results or answers to questions not asked (to design learning environments that educate people to manage fundamental concepts).

The research underlies three tasks that are as many research strands: 1) study and validation of specific teaching strategies, such as CLOE [58], Object models, formal thinking construction, history of physics experienced by students [50]; 2) search tools such as tutorials, tests and data analysis sections [33, 34, 59]; 3) R&D research and development for the production of hardware and software prototypes, aimed at precise intellectual challenges that integrate experimental and interpretative activities [60-64].

Figure 1 shows our theoretical framework in the revised MER [45] form.

3. – Methods

The study of foundational concepts makes use of research modalities in the field of physics foundations. This is aimed at identifying and selecting elements and epistemologies, like in the study of a path on quantum-mechanics proposed with the construction of theoretical thinking [65-69], or like in the study of diffraction, proposed as a search of the law ruling the Fourier-like phenomenon and education to interpret the laws within wave-like or light-photons models [70, 71].

Different types of monitoring, also in light of the different reasoning ways, are required to identify tools, strategies and methods to be implemented in FIM and in the global path, to build stimuli working as conceptual referents for conceptual change [26-30] and

Fig. 1. – The research structure.

for the appropriation of individual student learning trajectories [32]. In FIM, we therefore analyse learning processes that use qualitative and quantitative methods [72-76]. We monitor and analyse student discussions with each other and with us, through in-out tests, tutorials, semi-structured [59] and Rogersian interviews [72], written student productions and video recordings.

In-out tests are always the same and are designed to examine students' ideas about the same concept in different forms (written, graphic, formal) and are always made up of interpretation questions about specified contexts. They never have the role of summative evaluation, and contain at most the collection of the learners' experiences by means of questions such as (in primary and low-secondary school) "write 3 sentences containing the word time" or "illustrate what you know about time" or "illustrate equalities and differences between the idea of time and its measurement".

The tutorials are organized as sequences of stimulating questions, which propose to reflect on issues, problems and interpretations, according to the setting of the research group of the University of Washington [33, 34, 38, 77]. They have been produced in very different types, in relation to the characteristics of the research monitoring. Some examples are given below.

Example A. In tables I and II are two examples of stimulation cards, in the case of exploratory experimental activities for students aged 8–15. They are accustomed to reasoning through reflection, experimentation and comparison (table I) or to pay attention to quantitative aspects in a graphic representation, describing and reading its meanings.

Example B. Figure 2 shows a card used to discuss the data collected in real time by a position sensor during the motion of a car that is made running on the table. The real-time visualization (RTL) of the representative data of a phenomenon facilitates the imaginative reduction between reality and its formal description and trains at reading the graphs and their meaning [78].

Figure 3 represents the monitoring of a small group discussion, after using the method developed by Eugenia Etkina [79]. The time devoted to the different issues (Q1–Q10), and the number of interventions, both depend on the specific situation, as the distribution

TABLE I. – *Stimulus card used in experimental explorations, organized in prediction, exploration, comparison.*

THE SCALE

1. Hang the doll on one of the nails on the rod. What will happen?

   ....

2. To restore balance you have to hang another doll, (tick all options you consider appropriate)

   ☐ Of equal weight ☐ Of greater weight

   ☐ Of lower weight

   ☐ On same side ☐ On opposite side

   ☐ At same distance ☐ At greater distance

   ☐ At shorter distance

3. Using as second doll one of double weight, at what distance must be hanged from the suspension point of the rod to restore balance

   ☐ at the same distance as the first one

   ☐ at a double distance than the first one

   ☐ at half distance as the first one

4. For the scale to be in balance, what conditions must be met?

   ....

TABLE II. – *Stimulus card used in the case of exploratory activity in real time lab context* [80] *organized in: reproduction of the observed graph, its description and explanation.*

TERMOGRAFO

Q2 Describe and interpret a process
Work with this card after card
Q1 and having reflected on the experience

Represent the observed temperature graph in the space on the right	
Describe the observed graph	
Explain the observed graph	

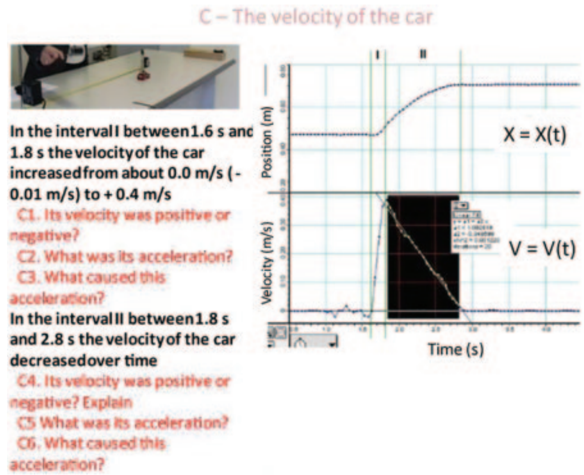


Fig. 2. – Example of a tutorial card.

of answers does. Looking at the color of the students' interventions, it is evident how the simple answers (green color) almost disappear, leaving room to the discussion of experimental situations (blue) and the discussion/argument (orange) [79]. The cognitive evolution of the group is so evident.

Example C. In the pathway on quantum mechanics [59, 61], students are stimulated to analyse the transition probability of a photon state with given allowed direction between two polaroids, examining the relationship between the vectors of state before and after transition, and correlating it with the macroscopic Malus law.

Data analysis is carried out on large samples only when general inquiries are made. This is displayed, *e.g.*, in fig. 4, where the curriculum established by the institutions is investigated, acted by teachers and experienced by students in 10 European countries through the theoretical frame of Spider Web [81].

It is seen that most 8-years-old school students mainly listen to the teacher, and carry out individual work or learn to do homework. In Italy, they seem to carry out a bit more

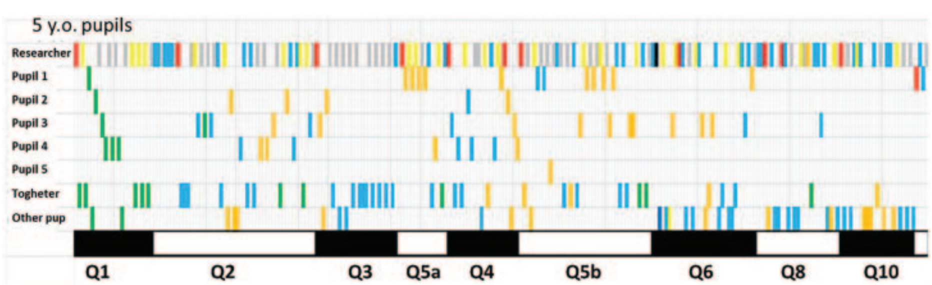


Fig. 3. – Monitoring of the response categories of 5 five-year old children (pupils 1–5) and of other children around whom questions Q1-Q10 at the bottom bar have been posed. Different colors represent different aspects as in the legend below. Red: key issues. Yellow: promotion of further discussion. Blue: refers to, or introduces, situations and examples, experiences. Grey: waiting for further answers. Green: simple assertive answers. Orange: discussion and arguments.

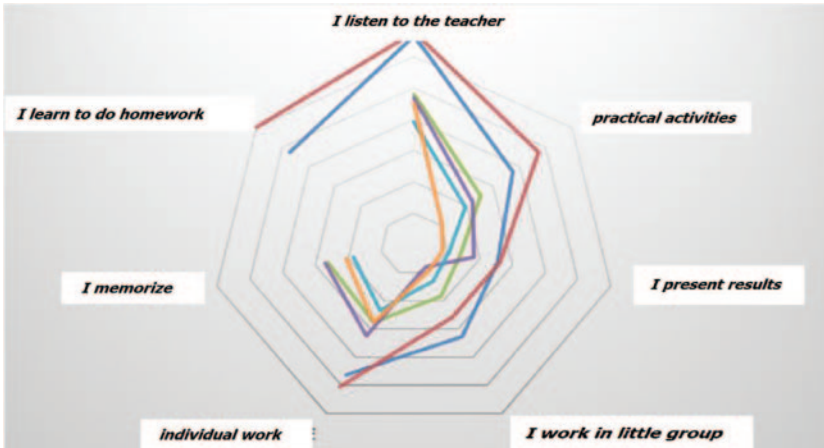


Fig. 4. – Answers from of 8198 pupils, among whom 2666 are aged 8 (red line EU, blue line Italy), 2797 aged 11 (green lines EU, purple in Italy), and 2735 aged 13 (blue line EU, orange line in Italy). From the Science Education Curriculum (SECURE) project of the FP7 Program [82].

practical work than in the rest of Europe. At the age of 11 and 13, the situation is not very different, and memorization activities are added. In Italy, there seems to be greater interactivity, because pupils present their works to their classmates [83].

In most FIM, samples are a few, from 1 to 3 classes (25–75 students). In addition, data are richer and analysed in operational terms, building classes of answers to the individual open tutorial questions. They are then transformed into multiple-choice questions by using the answer classes after at least two cycles of testing with different classes.

Example D. Figure 5 shows an example of data analysis for the answers to one single question of a tutorial on electromagnetic induction, in a path on electromagnetism with three classes for each of the two testing sites [84].

The students carried out explorations designed by themselves, with a large U-shaped magnet (with polarities at the ends of the U) and small coils with a different number of coils of different sizes connected to a galvanometer or voltage sensor [83, 85].

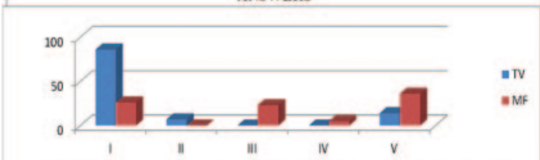
In the 6 classes, the same activities were carried out following different conceptual approaches. On TV, magnetic field lines were used to interpret all phenomena, while in the three MF classes a classical electrodynamic approach was followed. A large majority of TV students (81%) interpret their observations by relating the parameters explored to magnetic field lines (CAT I, CAT II), 25% of them use magnetic field flux (CAT III), and only 1 student remains at the level of the local phenomenon description (CAT IV). Only 26% of the MF students are in CAT I, almost as many refer to the flow of the magnetic field, and 36% of them do not make interpretations. The electromagnetism path of 6 tutorial cards, each with 5–6 questions, allowed us to identify the magnetic field lines as a strategic direction of a fertile approach for conceptual change and the construction of formal thinking in electromagnetic phenomena.

Example E. In table III is reported one more example of data analysis in a class where the following question has been posed: "*Explain to your classmate what is meant by mutually exclusive property and what is meant by incompatible properties (and in what they differ)*" [86].

The main categories identified through the students' responses are reported. Only

Q III.1 Individuate a general rules that allows you to interpret all the observation you did.

ANSWERS



I	proportional to the speed of the variation of the number of the field lines (TV 86%, MF 26%)
II	proportional to the number of windings and the speed of field lines variation through the coil (TV 7%, MF 0%)
III	flux interlaced to the coil (TV 0%, MF 23%)
IV	placing and pulling out the coil from between the magnets generate a current (TV 0%, MF 5%)
V	NR (TV14%, MF 36%)

Fig. 5. – The five response classes for two groups of 86 (TV) and 75 (MF) students, who were required to identify a general rule for interpreting the effects of the interaction of different coils with the magnetic field of a U-magnet [84].

the 17/38 responses dealing with both properties were considered. Some examples of responses refer to the iconography used during the course, to indicate a given polarization property [86].

Example F. Figure 6(a) shows an example of the score distribution in the input and output tests from a FIM on optical polarization for a class of 20 students [87].

The input-test data (magenta) show a narrower distribution around a low score (11/20), while the output data (blue) display a wider and less peaked distribution, though clearly shifted towards higher scores (14/20) [87].

Figure 6(b) shows the distribution of the scores obtained by each student in the 20 items of the input test (magenta) and of the output test (blue), from which we see the intervention effectiveness on the conceptual learning of individual students [87].

Example G. One other data-analysis method in input and output to a quantum mechanics FIM [88, 89] is shown in fig. 7. Here, the Müller & Wiesner method was used [90] with in and out tests to analyse the conceptual change of the students from a classical to a quantum vision of the examined phenomena [91].

One other analysis method used in our research is the phenomenographic one [91], as in the case in which students express their ideas on quantum physics.

4. – Research contexts

Research contexts can be classified into two types: formal and non-formal. The formal ones concern: 1) kindergarten and primary school but in some case also low secondary school, in which we studied FIM on the following topics: measurement, motion, thermal phenomena, fluids, light and optics, energy, electrostatic and electrical circuits, magnetic phenomena and the concept of field sound [56, 92-95](1); 2) the upper secondary school on the following topics: force and motion, oscillations and waves [78, 96-99], thermal phenomena [80, 100, 101], energy [94, 102], geometric and physical optics [103-106], spectroscopy [64, 107, 108], electrodynamics and electromagnetism [83, 84, 109-111], and the

(1) Here we report only some examples of publications, including 25 booklets in Italian.

TABLE III. – *Data analysis of data of 17/38 students, who were asked: Explain to your classmate what is meant by mutually exclusive property and what is meant by incompatible properties (and in what they differ)* [86].

	Category		N	Examples of students' answers
	Exclusive	Incompatible		
A	One excludes the other	There is a measurement procedure whereby a system loses one and acquires the other	7/17	"*Mutually exclusive properties are those properties that if present together cancel each other out (e.g., pol. Horizontal and pol. Vertical). The incompatible properties are those for which there is a measurement operation in which the system can lose one of them and acquire the other*".
B	May not be possessed simultaneously	If a system has one, it cannot have the other, they cannot coexist	6/17	1. "*The mutually exclusive properties are those that a photon cannot have at the same time [..]. The incompatible ones are those that the photon cannot have at the same time*". 2. "*Incompatible if you have one, you cannot have the other. Mutually exclusive = they cannot happen together*".
C	They cannot coexist and only up to the measurement	They cannot manifest themselves together	2/17	*Incompatible properties are those properties that cannot be manifested at the same time, whereas mutually exclusive properties manifest themselves only at the moment of measurement*".
D	They cannot be possessed together	Each property is not a mixture of other properties	2/17	"*Triangle vertical polarization; ∗ pol. horizontal; rhombus polarization 45 degrees. The diamond and asterisk or triangle properties are incompatible because a rhombus cannot also have ∗ and triangle properties. The rhombus state cannot be considered a mixture of the asterisk and triangle states. These two properties are then mutually exclusive as they cannot happen together (transmission result equal to 0).*"

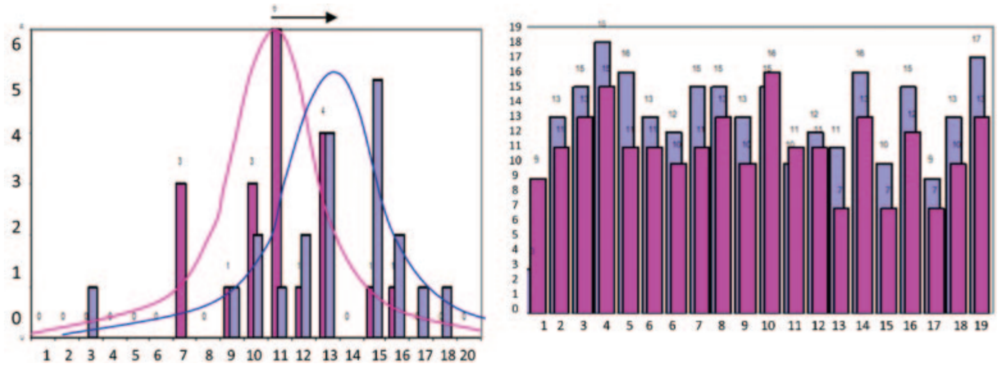


Fig. 6. – (a) Distribution of the scores for the input test (left bin) and the output test (right bin) following a 6-hour optical polarization FIM. (b) Scores obtained by each student in the input test (front bin) and in the output test (back bin) following a FIM on the 6-hour optical polarization.

use of informatic technologies and mobile Applications (APP) for acceleration measurements, optics, acoustics, optical spectroscopy [2, 61-64, 78, 80, 101, 112, 113] the first two years of university, on the problem of didactic innovation in Italy in general, and in particular of physics for non-physicists, with studies related to course degrees in the biotechnological area, and agriculture, food and environment areas [114-120]; 4) the initial education of prospective primary teachers [48, 121-124] and secondary school teachers [125, 126] and the professional development of in-service primary [127] and secondary teachers [128-132], both in terms of model research and of curricular design and teaching proposals, or learning monitoring.

The non-formal contexts concern 1) the exhibition Games Experiments Ideas (GEI) [133]: an environment of experiments made with common materials proposed for exploratory hands-on/minds-on; 2) the scientific theatre that has seen us engaged as collaborators in initiatives related to the Copenhagen play, by Frayn [134], as consultants for the production *Mileva Maric* [135] and *Mysteries of Light*, in which we implemented our path on quantum mechanics [135] with experiments and virtual reality in more than one representation, including ESOF International 2020 [136]; 3) school-work experiences and pathways for transversal skills and guidance in which, proposing ourselves as em-

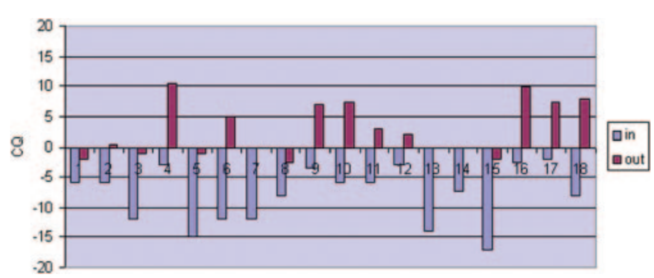


Fig. 7. – For each student (horizontal index) the QC index (computed according to Müller & Wiesner [90]) for pre-test (IN) and post-test (OUT) (QC > 0: quantum mechanics ideas; QC < 0: classical ideas). [89].

ployers for the development of mobile APP with classes of students aged 16–18, we have offered a working strategy that engages students themselves in responsible design challenges and cognitive analysis for learning [102, 113]; 4) theoretical and operational proposals for citizenship education and formative guidance to encourage the construction of future ideas in young people [137]; 5) studies on methodologies for the in-service professional development of teachers in physics [128, 129, 132, 133, 138], paying attention to the disciplinary content and methods that underpin the epistemic physics within a basic culture and teacher education, with specific studies on the guidance and construction of active citizenship [137-139].

5. – Findings

The outcomes of our research approach, which includes several integrated lines, are of different natures. In addition to entire courses, there is evidence of learning processes, specific strategies, hardware and software prototypes for experimental activity, teaching materials made available both in local language publications and on our website (`https://urdf.uniud.it`), that are widely used by teachers and students. We consider the latter products to be both working tools and relapses of the research itself. We therefore present here only the strategies, the prototypes and selected paths.

5·1. *Developed strategies*. – The developed and most experienced strategy to date is that of the Conceptual Labs of Operative Exploration (CLOE) [140].

Strategy CLOE. This was developed in the context of the GEI exhibition to create exploration-based FIMs by using the exhibition materials [56, 134, 140] and it was also used in the path for quantum mechanics [59]. The CLOE are conducted in a learning environment in which children have an operational role, proposing problem-situations on specific subjects. Semi-structured interviews and worksheets are used with phases of individual explorations of the posed problem, as well as debates within small groups followed by collective discussion and co-construction of conceptual maps. It offers a context in which one is left with free exploration, then asked to make a prediction, and finally to test and compare the results of the tests with the predictions. As an example, table IV shows steps 2 and 3 in the exploration of the interactions of a magnet with different objects and with different metals: as one can see, for each step the problem, the stimulus questions to students, and research questions are identified.

In the data analysis we examine the answers to construct operational definitions of classes of answers for each stimulus question and each research question. The answers are analysed in two ways: a) by classes of meanings, b) by classes of typology: descriptive, assertive, evocative of experiences, interpretative.

CLOE's strategy in the GEI context has allowed us to study the role of operational capability, personal involvement in the exploration of phenomena and of the context in learning processes, and the role of identifying the reasoning in phenomena interpretation, formalization types, and analysis levels: from the descriptive to the interpretative one, and the models used in the various situations [50, 66, 83, 92, 96].

Strategy OM. The strategy of object models (OM) consists of a concrete object representing the system in its physical behavior and, in it being concrete, allowing exploring the model characteristics, while realizing its bias and therefore its limits, examining the predictions that can be compared with reality [50, 60, 104]. For example, we have filmed and looked at the individual frames of a transparent box (Einstein lift) in free fall, containing an object hanging from a spring, to discuss reference systems and weight [50, 140].

TABLE IV. – *Protocol example of the CLOE strategy for research on the reasoning of students in the exploration of a magnet interacting with different objects and metallic materials.*

CLOE protocol	Stimuli questions for students	Research questions
2. Identifying a magnet, having a collection of objects in a box	Q2.1 How do you operate in order to individuate the magnet? Q2.2 How do you identify it? Explain	RQ2.1 What types of procedure are put in action? RQ2.2 What types of reasoning are used and how do reasonings play the role of conceptual referents? How do they evolve? RQ2.3 Are poles used as a referent to identify a magnet?
3. Interactions of metals with a magnet	Q3,1 Explain how to identify which metal interacts with the magnet	RQ3,1 How are the basic properties of magnetic interactions used? RQ3,2 Is the phenomena exploration organized in a conceptual framework?
A-Type of interaction B-Nature of interaction	Q3.2 How do the interactions occur?	RQ3.3 How are the phenomena presented: in terms of description or does some interpretation emerge? RQ3.4 Which are the perspectives adopted in looking phenomena? Pole interactions and/or field perspectives? RQ3.5 Is the reciprocal interaction emerging in spontaneous exploration?

We realized the mesoscopic model of fluids with foam balls, predicting Stevino's law [50]. We used a stretch cloth attached to a box to visualize the gravitational field model, and discuss the free fall and orbit of a system around the Earth [50, 140]. We have created APP graphics allowing loading the image of a situation, use it to draw the physics model of a phenomenon, and then transform the initial image of reality [113]. Figures 8(a) and (b) show the images of the two last phases of construction for the explanation of multiple images in flat mirrors displaced with an angle.

This OM strategy has demonstrated to be fertile in gaining appropriation of the system meaning, physical model and the way in which the latter is built and used in physics.

Strategy role-playing games. In studying the modalities in which the interpretations are constructed and the formal thinking developed, we often make use also of strategies known as role-playing games [141], the graphical and iconographic representations [78,86,142,143]. Two examples illustrate how we implement the latter. In the study of electrical and electrodynamic phenomena, we asked 8 year-old children to imagine becoming very small, and entering objects or inside the conducting wire, and representing the inside of the system in various situations. Ideas that often coincide with historical interpretative models have emerged, and their discussion among peers has given room to ideas for conceptual change to evolve [58, 95, 111]. In the path for quantum mechanics instead, the symbolic language for the properties (for example, a triangle for vertical photon polarization, a star for horizontal and a rhombus for 45° angle), distinguished from that referring to the state vector, occurred to be fertile to understand the distinction between mutually exclusive and incompatible properties, the superposition principle, and its consequences [65, 66, 89].

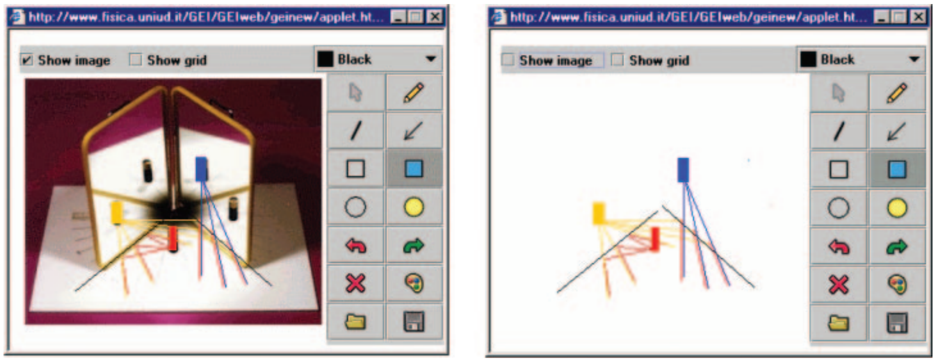


Fig. 8. – (a) Screenshot of a stick that forms multiple images in front of two corner mirrors is captured. The incident and reflected rays can be drawn on it, predicting the position of the virtual image and its reflection in the other mirror. (b) Sketch of reality, where the explanation of multiple images can be identified, with the optical-ray model and the laws of reflection from geometric optics.

Strategy for guidance. The strategies put in place for research on educational guidance, are based on an education vision of guidance, which is seen as a responsible action of young people to build their identity in a vision of the future, giving an important role to the action and the intellectual and operational challenges that make the subjects play [129-136]. Scientific activity in this context develops soft together with hard-scientific skills, promoting the construction of the cultural foundations of the discipline.

In university teaching innovation, through research and implementation [114-119], we have founded a strategy based on the following principles: i) teaching innovation concerns university, the department and the course of studies for a multiplicity of elements that are functional to the education of the enrolled students, and must therefore be shared and asked for the needed supports; ii) the contents of each physics course, even when basic, must be redesigned by bending its role and characteristics with respect to the course of studies in which it is inserted; iii) the course must be based on differentiated activities of almost the same hourly weight: lectures, laboratory, exercises and problems, to which one has to add insights on the role of physics in the professional degree where one is located and conducts their research (for example biophysics for biotechnology), with reading and discussion of two articles; iv) the laboratory activities are of a design nature; v) the exercises are offered with an extensive database, and regular tutoring meetings promote their discussion; vi) monitoring in the learning process must be continuous and have an impact on the ongoing learning process.

5·2. *Developed prototypes*. – Research on the new objectives with the use of information and communication technologies (ICT) has allowed studying new ways to enrich the learning process [71, 78, 101, 105, 106]. In physics, multimedia, simulations, web environments of communication, modelling, and measurements using computers are part of the nature of disciplinary research. When in students hands, they represent new opportunities to build disciplinary skills. It is therefore natural to include in education research their search and development: in this field, as in many applied-physics contexts, physicists must build prototypes for the tools deemed to be important. The main original developed prototypes and used in the didactic pathways, are here simply mentioned, referring for details to specific publications.

TERMOCRONO is a hardware and software system consisting of 4 temperature probes that capture, represent in a graph and tabulate data in real time, producing the imaginative representation of a phenomenon in the formal language of the graph [63, 142, 143]. It has been used with both primary school children [80, 92] with a process-like approach to thermal phenomena, and students of all ages, in particular university ones [100, 101, 142].

LUCEGRAFO has been developed to acquire position-related light intensity data in optical diffraction experiments, aimed at making students 1stto take advantage of the experimental investigation modalities for a genuine theoretical interpretation [61, 71, 104-106].

SPETTROMETRO returns optical emission and absorption spectra by integrating a camera with diffraction gratings and filters placed directly in the camera holder [64]. The software calibrates the RGB signal to return reliable values, in energy or wavelength, within a graph that can separate the chromatic components. It has played an important role in the path about optical spectroscopy, already implemented in different contexts [107, 108, 115].

R&H acquires Hall resistivity and coefficient data for samples placed on a thermostat plate for measurements performed at thermal equilibrium between −200 °C (at liquid nitrogen temperature) and room temperature. Samples for resistivity measurement can be metals, semiconductors, and superconductors [62]. The path of superconductivity [57, 62, 68, 144, 145] has motivated its realization, but its flexibility and reliability have turned it as a central system for research on the role of the laboratory in the formation of physical identity.

JQM is a simulation environment [146] at the heart of our pathways on quantum mechanics [66, 89]. It is designed so as to put in the students hands the theoretical exploration and the research plan. The student can choose the projector-source of a chosen number of photons of given polarization, can place on their way a number of polarizers of chosen allowed direction, as well as birefringent crystals. The detector is a counter, which selected polaroid filters can be placed in front of. Such a simple, flexible and open environment, forces the student to design theoretical exploration, having in mind hypotheses and interpretations.

5˙3. *Developed pathways*. – The development of vertical thematic paths is the main objective of our research. As illustrated above, it has required s a long work for several years for each path, and involves a complex interweaving of studies, implementations and revisions.

In classical physics, we have developed paths centered on the use of ICT to overcome conceptual knots (the common sense ideas in relationship with specific physics concepts) in the study of motion and the role of friction in Newtonian dynamics, on oscillations and waves [97-99], on thermal phenomena with a thermodynamic approach [80, 100, 101], which has led to different paths in primary school [101] often associated to teachers education at the same school level. Vertical paths about optics have been studied starting from primary school, paying special attention to the phenomena of diffraction and optical polarization with secondary and university students [61, 71, 89, 120]. Similarly, the path on fluids, starting in kindergarten with fluids at equilibrium, have been the subject of a vertical path, which has involved numerous experimentations even at university level and for teacher education.

To modern physics (MP) we have devoted continuous research over many years since 1995 [53, 60, 66, 69, 89]. During the last 15 years MP has been included in all textbooks, even though in the last chapter and in fragmented and non-consistent manner, with special relativity and quantum physics as favorite subjects. The historical approach is privileged, when it is not the prevailing content. Epistemological aspects are considered important but not treated much. Quantum physics is characterized by the following topics: discretization of energy levels, light-matter interactions, particle-wave duality, de Broglie wavelength, technical applications, Heisenberg uncertainty principle, probability nature of measurement. The Born approach prevails, although in literature many different ones can be found [147]. In this field, we have tackled the challenge of education rather than of science communication and dissemination, thus giving up on results storytelling to offer instead learning opportunities and not only information understanding (that is mastering the fundamentals and concepts) with the appropriation of tools and methods. We paid attention to different dimensions: looking at physics as a discipline that offers citizens with a broad culture, integrating the subject treatment with reflections on the ways of looking at conceptualizations (disciplinary identity) and of gradually building formal thinking.

The history of physics has often contributed to our research, especially in three ways: 1) it has instructed the analysis of students' interpretations, which are often similar to those used by scholars of the past [106, 140]; 2) it has inspired stimulus issues, such as that of the weight of objects in the elevator in free fall [140] or the mesoscopic model for fluids [116]; 3) it has offered a methodological training ground for the formulation of laws in diffraction and in the interpretation of the spectrum of the hydrogen atom [131, 148].

The carried out research has led us to develop coherent didactic proposals on the following ten main topics.

T1-Discussion of some *crucial and transversal concepts* both in classical and in modern physics, such as those of *state, measurement, cross section*, that are widely used in research. This is the first series of elaborated didactic proposals, looking at the role and generality of concepts in physics [54].

T2-Bridging-phenomena between optics theories, with particular attention to diffraction [61] and polarization [66, 89]. Experimental explorations and measurements are the conceptual references of challenges aimed at identifying conceptual and formal interpretations, in which students are the protagonists responsible for the construction of reasoned explanatory proposals of phenomena.

T3-T4-T5-Spectroscopies. The research on *optical spectroscopy (T3)* has allowed us to develop three possible paths, following implementations performed in 11 classes for a total of 2208 students of class IV or V of upper secondary school (mainly scientific lyceums) [108]. Two other paths are the result of educational research on *atomic Rutherford backscattering spectroscopy (T4)*- RBS and nuclear [149], and finally *(T5) gamma* [150]. Questions stimulate experimental investigation, often conducted with self-built equipment [150] or research laboratories [149], in which students analyze the data in a similar manner as in our laboratories, to derive structural information and gain tools and methods of physical investigation, as the learning data have given us evidence of [90, 101, 108].

T6-T7-The physics of modern analysis techniques proposes a laboratory-based approach and the analysis of experimental data as in the case of spectroscopy, in which students are engaged in interpretive challenges and in laboratories that are managed by themselves. They are only given indications of the open problem, so that they can appropriate the physicist way of working and realize how intertwining theory and experiments in the physics of matter. Besides the already mentioned RBS spectroscopy *(T4)*, in which students showed how to interpret the spectra of measurements obtained from research laboratories [149], we addressed the *Time Resolved Reflectivity (T6)* for the study of the epitaxial growth of a solid material on a sample and the electrical transport properties in solids *(T7)*, with the prototype we developed as a measuring apparatus [62], and addressing the cases of metals, semiconductors and superconductors. From experimental data, the students identified the type, number and mobility of charge carriers, associating the structural characteristics for semiclassical and quantum interpretations.

T8-Explorative approach to superconductivity, in fact of phenomenological type, with semi-classical interpretations has been widely tested, using low and high tech experiments developed within 4 EU projects (Supercomet I, II, Mosem I, II). Many interesting outcomes on learning processes result from the educational path implementation. The path was developed after implementing it in single classrooms of 15–20 students, for a total of 1580 students from 51 schools in 21 cities [57, 145].

T9-Mass-Energy: the path tackles the basic concepts of relativistic dynamics, aimed at understanding the meaning of $E = mc^2$ [151].

T10-Foundations of theoretical thinking with the Dirac approach to quantum mechanics (QM). This approach to the theory is motivated by quantum physics being the cultural reference paradigm and theoretical foundation of current descriptions of microscopic phenomena [65]. In fact, quantum-mechanical thinking is a new cultural approach to physics that has important implications in many branches of science. In 2002, there were more proposals for teaching quantum physics in secondary school than classical physics, but no consensus has been reached on the aspects to be taught or the approaches to be adopted [66, 88, 89]. The proposed educational paths are based on the different QP formulations and interpretations (see our review [147]). In currently available proposals [147] physics of quanta, quantum physics, and quantum mechanics are often confused. The proposed narrative hypotheses (not emerging from students' reasoning) prevail over the disciplinary aspects.

While the descriptive dimension is acceptable for information, it is not satisfactory for education: awareness should be produced of the reference assumptions, offering indications on the adopted formalism, since QM formalism takes on a conceptual role. In more than 30 publications since 1996 [65, 66], we have developed a path based on the strategy of starting from simple in-context experiments. These studies have involved 1298 students from 44 classes, 1028 conducted by our researchers in collaboration with teachers of 32 schools/classes, and 270 implementations conducted by teachers in 12 classes in 12 different cities (3 of them being non-Italian). At the disciplinary level, we have chosen to focus on the superposition principle and its consequences, whereas at the didactic level to discuss in depth specific situations with light polarization as a quantum property, starting from ideal experiments where single photons interact with polaroids and bi-reflective calcite crystals. While referring to our more recent work [86] for details, table V summarizes the pathway's rationale. Here, we remark that students face the challenge of conceptual change from classical physics with methodologies of the theoretical physicist, also thanks to the JQM software [146].

In a more recent pilot study [152] conducted in a high school, with a compact FIM followed by quantum-game playing, we have explored the use of quantum games as tools and found that students were able to effectively grasp the concepts of superposition and entanglement through playing the game. We believe that further research efforts are needed on this emerging topic.

Table V. – *Rationale of the pathway on Quantum Mechanics (QM).*

- Malus' law is valid after reducing the intensity -> polarization is a property of the single photon
- Polaroid-polarized photon preparation: role and modality
- Exploring the interaction of polaroid-polarized photons, identifying:
  - mutually exclusive properties
  - incompatible properties and the uncertainty principle
- The state identified with a vector and the superposition principle in QM $\mathbf{w} = \mathbf{u} + \mathbf{v}$
- Distinction between state (vector) and properties (icons) living in different spaces
- Measurement in QM as transition to a new state: the collapse of the system in the measured one and its genuinely stochastic nature
- Interaction of polarized photons with bi-reflective crystals to understand
  - denial of state trajectory and state spatial entanglement
  - non-locality
- FORMALISM-Probability of transition from a state **u** to a state **w**, as projector
- Quantitative interpretation of interference, entangled states.

5˙4. *Teacher education.* – Just for the sake of completeness, we recall here that the research work carried out in our unit on the education of primary and secondary-school teachers, and the professional development of in-service teachers, has been parallel, and as much important and relevant as that on the educational pathways, in fact much benefitting from it. Publications in this field are more than forty. For reasons of available space, we recall here only three classes of them: those on the development of the MEDS model for the initial education of primary teachers [4, 47, 121-133], those in the context of the National Plan for the Scientific Degree (PLS -Piano Nazionale Lauree Scientifiche) PLS, and those also within the IDIFO National Master, shared by 20 Italian universities for in-service teachers education [129, 130, 132, 133, 153].

6. – Concluding remarks

In this work we have offered a report on the research carried out at UPERU from 1992 to present days. The reported work has been carried out with the support of 10 European, 25 National projects, 12 IDIFO, and 20 regional projects, and many young PhD students and researchers who have today a position in other institutions, but yet form a live collaboration network. The collaboration at national and international levels has allowed us to compare and improve the work in the contexts of the mentioned projects: within the International Research Group in Physics Education (GIREP), the Physics Education Commission of the European Physical Society (EPS-PED), the Multimedia Physics Teaching and Learning (MPTL), the International Commission on Physics Education of the IUPAP (ICPE), the American Association for Physics Teaching (AAPT), the European Scientific Education Research Association (ESERA) and international collaborations with the universities of Washington, San Sebastian, Dresden, Paris, Budapest, Ljubljana and many others in the frameworks of EPS-PED, MPTL, and ESERA.

The research was composed of two content-research strands: that about teacher education and that on the proposal of educational paths. Here, only the second strand has been referred to, that has allowed us to build an original line of research: starting from the theoretical framework of the modified Model of Educational Reconstruction

(MRE), this original research line intertwines and integrates research strands on conceptual change, and on research and development, which have allowed developing teaching strategies and hardware and software prototypes to become an integral part of conceptual learning paths in a vertical perspective.

The research topics concern classical and modern physics and formal and non-formal contexts. Attention to the boundaries of the curriculum prevails: primary and kindergarten school, and upper secondary school and university. The role of ICT in overcoming conceptual issues is the prevailing focus of research also for intermediate school levels. The social role of physics education has engaged us since 1994, in studies and research on future scaffolding and on citizenship soft-skills building and physics identity, by means of examples in the framework of action research and problem solving.

The university teaching innovation is instead a line of research of the last 8 years, in which we are placing in use the coherent proposals of the developed paths.

The originality of the research carried out in its whole complexity has consolidated a way of working that we wish will be fertile especially for the new generations of PhD students and researchers, besides than for ourselves, and that we wish it will be supported by institutions to become a wide resource for the quality of physics education at all levels.

* * *

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