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Tomasz Greczyło
Ewa Dębowska *Editors*

Key Competences in Physics Teaching and Learning

Selected Contributions from the International Conference GIREP EPEC 2015, Wrocław Poland, 6–10 July 2015

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Preface

The book presents selected contributions from international conference GIREP EPEC 2015 Wrocław, Poland. The volume’s aim is to acquainting readers with the discussion about problem of looking for strategies and tools to improve physics teaching and learning. Physics educators, university lecturers and physics teachers of various education levels are expected to be the primary audience of the book.

The Conference GIREP EPEC 2015 of International Research Group on Physics Teaching (GIREP) and European Physical Society—Physics Education Division (EPS PED), recognized by EPS as Europhysics Conference, was organized by University of Wrocław (UWr) (Institute of Experimental Physics, Physics Teaching Department and Foundation for University of Wrocław) at the time of the Jubilee of the 70th Anniversary of the Polish Academic Community in Wrocław. It belongs to a series of GIREP conferences organized on regular basis since 1966. The conference was held in Wrocław, in City Haston Hotel and Congress Centre, between 6 and 10 July 2015. This conference was organized and supervised by Prof. Ewa Dębowska (Chair of the Organizing Committee) and Dr. Tomasz Greczyło (Chair of the Local Organizing Committee), both from Institute of Experimental Physics of University of Wrocław in scientific cooperation with the international advisory board. The event was sponsored financially by GIREP, EPS —Physics Education Division, University of Wrocław and Polish Physical Society. The conference was attended by 157 participants representing 36 countries from around the world.

The central theme of the conference was Key Competences (KC) in Physics Teaching and Learning understood as knowledge, skills and attitudes that are fundamental ones for every individual in a society. The essence of KC is that they should be acquired by young people at the end of their compulsory education and training. The KC are all interdependent and intertwine different aspects such as critical thinking, creativity, initiative, problem solving, risk assessment, decision taking and constructive management of feelings. All of them appear crucial in nowadays educational environment. The most impending area to support the process of teaching and learning seems to be directly related to the Information and Communication Technology (ICT). A great impact of ICT in various educational processes is especially visible in physics teaching and learning. Physics is considered as a subject whose main interest is directly and strongly connected not only to digital competence but also to several other Key Competences. The conference offered the opportunities for in-depth discussions of the Key Competences issues such as

- New research approaches: new methods, innovative learning strategies, new models.
- KC changing pedagogy: formative assessment, teacher role, student role, KC oriented assessment, shared pedagogy, KC oriented pedagogy.
- Good practices in KC developing.

The scientific conference's program offered 5 invited talks, 15 oral sessions with 60 presentations, 3 symposiums with 18 presentations, 8 workshops, 2 EPS sponsored Workshops "Specialist Physics Teacher Shortages and the Preparation of School Leavers for Further Study" and 4 poster sessions, grouped 2 by 2, with 32 posters in each group. The EPS workshops were run in conjunction with Horizons of Physics Education (HOPE) and aimed to our understanding of teacher shortages and their effects on pupils across Europe.

Like in previous GIREP conferences, a lot of attention went to engaging teachers in taking part and establish better networks between teachers and researchers. This time the format of a preconference consisted of 6 workshops organized in 3 parallel sessions. They were attended by 35 individuals.

The conference was the unique occasion to provide the participants with an international forum to exchange scientific ideas, inspire new research, and create new contacts for closer cooperation in physics education.

After the conference the Organizing Committee received about 70 submissions, many of which were of a very high quality. Due to diversity of proposals and richness of the subjects suggested by the authors the selection involved some very careful decisions and appeared to be not an easy task. All of that resulted in preparation of two publications—the printed collection of chosen papers and the electronic proceedings. Each paper went through a rigorous review process by at least two reviewers. The papers were subsequently revised by the authors according to reviewers' comments and all accepted papers are reported in this book or in the electronic proceedings. The collection, the one you are reading now, contains about 20 % of contributions recognized as especially 'recommended' for the printed version of the proceedings. It includes the papers prepared by all invited speakers and the ones dealing with more general, not very narrow subjects. All other papers which were accepted by reviewers are available in the electronic version of the conference proceedings.

The organizers are grateful to the authors for their enthusiasm and to all the reviewers for their painstaking work and the time they gave to the evaluation process.

We have tried to do our best to group authors' proposal thematically following both, domains:

- Researching formation of Key Competences in physics teaching and learning—new research approaches, new methods, innovative learning strategies, new models;
- Key Competences changing pedagogy—formative assessment, teacher role, student role, KC oriented assessment, shared pedagogy, KC oriented pedagogy;
- Developing of Key Competences—examples of good practices;

and groups:

- Research (physics education research on the empirical and theoretical levels);
- Research and development, (including classroom ideas, practical issues, development, etc. being more substantial than research);
- Classroom ideas, teaching and learning practices (no or minimal research part).

As a result of the grouping process three chapters were created:

I. Towards Shaping Key Competences,
II. Educational Research and Development,
III. Classroom Ideas and Teaching-Learning Practice.

We hope that the book will offer the reader the opportunity for deep comprehension of the Key Competences to improve physics teaching and learning and to help students to acquire many of them.

Wrocław, Poland

Tomasz Greczyło
Ewa Dębowska

Contents

Part I
Towards Shaping Key Competences

Role of Key Competences in Physics Teaching and Learning

Ewa Dębowska and Tomasz Greczyło

Abstract The paper's aim is to portrait an interpretation of Key Competences in physics education context through some key characteristics of physics teaching and learning processes basing on presentations delivered during the conference of International Research Group on Physics Teaching and European Physical Society—Physics Education Division—GIREP-EPEC Wrocław 2015. The general conference topic was Key Competences in Physics Teaching and Learning. The paper presents the basic roles of Key Competences in science education and technology in the framework of creation of knowledge, gaining skills and developing attitudes, basing on conference presentations and literature review. We have suggested our proposals after careful and critical view on selected findings concerning Key Competences already published (e.g. Rychen and Salganik 2003). The final proposals are presented in a form of statements that might be of interest to both physics education researchers and teachers and serve as an introduction to the entire book.

1 Motivation

The main theme of the conference of International Research Group on Physics Teaching and European Physical Society—Physics Education Division—GIREP-EPEC Wrocław 2015 "Key Competences in Physics Teaching and Learning" underlines the importance of Key Competences (KC) in the shape of knowledge, skills and attitudes appropriate to each context as fundamental ones for every individual in a society. The Key Competences are all interdependent and intertwine different aspects such as critical thinking, creativity, initiative, problem solving, risk assessment, decision taking and constructive management of feelings.

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All of them appear crucial in nowadays educational environments especially that concerning physics as a science domain. KC serve as a reference tool for European Union countries to ensure full integration into their strategies and infrastructures, particularly in the context of lifelong learning. As KC cover wide range of human activity they might guarantee more flexibility in the labour market, supporting adaption to constant changes in the increasingly interconnected world. They are also recognized as a major factor in innovation and motivation of workers as well as in improving a quality of work. The essence of KC is that they should be acquired by young people at the end of their compulsory education and training. This will equip them for adult life, particularly for working life by forming a basis for further learning. In parallel adults should achieve KC throughout their lives in a process of developing and updating skills. The acquisition of KC fits in with the principles of equality and access for all (EUR-Lex 2006).

The conference offered opportunities for in-depth discussions of the Key Competences issues and brought us one step closer to find strategies and tools to improve physics teaching and learning. The volume presents selected contributions which form diversified but consistent collection of articles discussing chosen aspects of KC.

1.1 Key Competences

There are eight Key Competences defined (EUR-Lex 2006):

- communication in the mother tongue (CMT)—the ability to express and interpret concepts, thoughts, feelings, facts and opinions in both oral and written form (listening, speaking, reading and writing) and to interact linguistically in an appropriate and creative way in a full range of societal and cultural contexts;
- communication in foreign languages (CMF)—involves, in addition to the main skill dimensions of communication in the mother tongue, mediation and intercultural understanding;
- mathematical competence and basic competencies in science and technology (MCST)—mathematical competence is the ability to develop and apply mathematical thinking in order to solve a range of problems in everyday situations, with the emphasis being placed on process, activity and knowledge; basic competencies in science and technology refer to the mastery, use and application of knowledge and methodologies that explain the natural world;
- digital competence (DC)—involves the confident and critical use of information society technology (IST) and thus basic skills in information and communication technology (ICT);
- learning to learn (LL)—related to learning the ability to pursue and organise one's own learning, either individually or in groups, in accordance with one's own needs, and awareness of methods and opportunities;

- social and civic competencies (SCC)—social competence refers to personal, interpersonal and intercultural competence and all forms of behaviour that equip individuals to participate in an effective and constructive way in social and working life; civic competence, and particularly knowledge of social and political concepts and structures (democracy, justice, equality, citizenship and civil rights), equips individuals to engage in active and democratic participation;
- sense of initiative and entrepreneurship (SIE)—the ability to turn ideas into action, it is the foundation for acquiring more specific skills and knowledge needed by those establishing or contributing to social or commercial activity;
- cultural awareness and expression (CAE)—involves appreciation of the importance of the creative expression of ideas, experiences and emotions in a range of media (music, performing arts, literature and the visual arts).

They all are elements of the broader constructs—three main categories grouping individual activities concerning use of tool interactively, interplay in heterogeneous groups and act autonomously (Rychen and Salganik 2003). To make sense of and function well in nowadays world, citizens need to master changing technologies and take advantage of large amount of available information. KC play basic role as first guidelines for educators to handle increasingly diverse and interconnected surrounding world and could be broadened to formulate a kind of “statements of action”.

2 Framework

To describe coherently the role of Key Competences in the context of physics teaching and learning it is necessary to draw out some important themes and to explain some aspects in an appropriate framework. The framework consists of three different perspectives on teaching and learning: creation of knowledge, gaining skills and developing attitudes.

2.1 Creation of Knowledge

In constructivist domain the creation of knowledge is understood as a process in which students, as the entity of our actions, always learn on a base of prior knowledge. They possess a large number of knowledge elements that become directly involved in learning physics and an extensive rebuilding of their intuitive knowledge is required to create of new-systematic knowledge “architecture”. This view rules out the possibility that conceptual change is primarily the quasi-rational selection of one alternative among an articulable set of possibilities (Posner et al. 1982). Rebuilding of knowledge takes place in an environment created with particular physics issues—so called “must to know” elements of physics knowledge—

which are rising from teachers (educators) estimation of what is potentially necessary in future learning. Ongoing educational research shows that some new forms and kinds of physics knowledge seem to be most powerful in future learning. More generally, what is the most important physics knowledge is disputable and needs scientific verification (DiSessa 2004).

2.2 Gaining Skills

Gaining skills processes have obvious connections with knowledge. Skills development occurs in strong relation to physics contents even when we consider such basic activities as reading or paper-and-pencil problem solving tasks. The coexistence is even more visible if one considers skills strongly connected to ICT as they have very specific relationship to the problem of rethinking about physics teaching and learning (Greczyło and Dębowska 2015). Software related skills—for example concerning use of measuring devices as well as statistics or algebra oriented programs—are replacing some skills needed to solve problems analytically or obtain data by reading and writing them down. Therefore inquiry approach to gaining skills here is considered as the one in line with constructivism (Knuth and Cunningham 1993).

2.3 Developing Attitudes

The procedure of developing attitudes has its roots in a nature of physics as a subject of people activities centered in a specific domain—universe and its elements—and is making use of specific procedures, methodology of investigations, both experimental and theoretical ones (Veenman et al. 1992). Physicists, like other practicing scientists, are generally concerned about epistemological foundation of their field although they treat it as category of some kind of "philosophy". Knowledge of what and how eagerly and by which means students learn (create knowledge and gain skills at first) brings teachers a feeling of a job well done and allow them to create environment in which developing of the attitudes takes place. The process begins by reducing alienation of physics as a subject and showing close relationship of physics to the social development (Henke and Höttecke 2015).

3 Rules—Statements of Action

The list of basic rules, presented below, understood as statements of action to take, results from the implementation of KC and analysis of topics, approaches and discussions taking place during the conference. The authors have grouped the main research areas in a five element list of core characteristics of teaching and learning physics. The list is supported by presentation of some results of current research included in the very book and additional literature searches.

3.1 Use Language Extensively

The uniqueness of physics language and its specific characteristics have been reported and studied by many researchers (e.g. Redish and Kuo 2015). The awareness of the fact seems to be a crucial point in preparation and carrying on physics activities on different levels. It affects directly both creation of knowledge and gaining skills. The importance of the mother tongue (CMT) as well as foreign language (CMF) is underlined and recognized by researchers in physics teaching and learning. The topic is discussed especially in papers presented in part I—Towards Shaping Key Competences and part II—Educational Research and Development.

3.2 Make Use of Technology

The use of technology is unquestionably one of the main topics in education research nowadays (e.g. Osborne and Hennessy 2003). The authors focus on different theoretical and practical aspects of taking advantages and identifying weaknesses of using new technologies in physics teaching and learning processes. New domains of scientific activities are now ready to be incorporated to the educational processes thanks to use of technology (Dębowska et al. 2013). Such a trend is in line with shaping mathematical competences and basic competences in science and technology (MCST). On the contrary use of technology leads to increasing of armoury of skills and requires more than the mastery of certain narrowly defined skills. The aspects related to the theme are discussed in different ways in papers presented in part III—Classroom Ideas and Teaching-Learning Practices.

3.3 Allow Working in Different Environment

It has already been recognized and reported that when teaching we need to deal with diversities in pluralistic society and in parallel take care of such social values as empathy and the concept of social capital (Rychen and Salganik 2003). To cope with this one should create teaching and learning environment that allows relating well to others, emphasizing co-operation and work in teams as well as managing and resolving conflicts (Veenman et al. 1992). Arrangement taking into account the aspects of working environment are notably important in the process of gaining skills. For the physicists doing research in physics didactics it is a very interesting observation that well known individuals—so called key people in physics—attract others to explore the discipline (Rodd et al. 2013). Such actions are in line with learning to learn (LL) and social and civic competences (SCC). The subject is deeply touched in some papers presented mainly in part II.

3.4 Leave Room for Expression

Expression is here recognized as conditions to realize one's identity, to exercise rights and take responsibilities as well as to understand one's needs and concerns especially the conditions strongly affecting individual teaching and learning processes (Tiberghien 1996). Importance of the aspect is emphasized in the competence of cultural awareness and expression (CAE). The expression plays an important role in developing attitudes (e.g. Henke and Höttecke 2015). The issues related to the theme are discussed in some papers presented in each part of the book.

3.5 Support Teachers

The workshops for physics teachers are continually affected by changes in available tools, successful approaches and preferable methods being the results of globalization and modernization. Technical innovations have placed new demands on individuals inside and outside the workplace. Parallel social and technical advances create new opportunities for teachers to meet demands more effectively in new and different way. This opens a need for extensive support of teachers (e.g. Enyedy et al. 2012). Such needs manifest digital competence (DC) as well as strengthen sense of initiative and entrepreneurship (SIE). This creates a core part of actions developing attitudes. The aspects related to the topic have been discussed in papers presented in part III.

4 Conclusions

The paper presents our perspective of role played by Key Competences in physics teaching and learning based on the presentations made during the GIREP-EPEC Wrocław 2015 conference and literature search. The importance of KC has been broadly recognized and acknowledged. The findings discussed in the very text together with other papers published in this monograph, presented during the conference devoted to physics education issues, underline important role of KC in the shape of knowledge, skill and attitudes. That is why shaping learning objectives delivering the best education for our children is, unquestionably, the main duty of physics teaching and learning community. The reading of the following papers allows one to conclude that, similarly to other disciplines, reflectiveness is the heart of physicists' approaches to shaping Key Competences.

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Competence and Understanding—A Personal Perspective

Gareth Jones

Abstract The differences between competences and understanding are explored and their complementarity is emphasised. As part of this, special attention is given to the communication process in education and to understanding as an internal learning outcome; these are illustrated by reference to difficulties faced by physics students who have autism spectrum disorders. There is discussion of the competences that physics degree course should aim to develop in students with special attention being paid to some basic aspects of communication competence and to the development of personal qualities. Some work done by the EUPEN Network and by the HOPE project is described. The process of degree programme design is described and examples are given of work in (a) developing a package of modules for self-paced flexible learning of mechanics, (b) development of "guided discovery learning" in nuclear physics and (c) Socratic dialogue methods in tutorials. Brief speculations are made concerning some possible implications of applications of artificial intelligence to education. Finally the essence of thinking like a physicist is illustrated by some quotations.

1 Introduction

This contribution to the proceedings of the 2015 GIREP-EPEC conference is a summary of a presentation at the conference which gave a personal perspective on some aspects of physics education based on the author's practical experiences of physics education at a research intensive university. As such, it does not fit into the normal pattern of physics education research (PER) publications; for example it makes little reference to published work on PER. The author does not consider himself to be strongly engaged in PER but rather to be an experimental physics researcher who also has a strong commitment to physics education at all levels and

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has extensive experience of teaching physics and designing physics degree programmes at university and some experience of school-level teaching and of designing teaching materials and methods. This perspective is based mainly on personal experience of university teaching, including the design, organisation and management of degree programmes. Crucially, it is also based on many years of interaction with students of physics, engineering and mathematics. It is also based on many years of cooperation with colleagues in many European countries.

The reader should step back a bit and consider some basic issues in education. Some may seem obvious but they are important and their implications should be considered carefully. There is a focus in this paper on principles which have wide applicability in different contexts and it is hoped that this will be of some interest to physics education researchers and I am grateful to GIREP for inviting me to make this contribution. This paper has two specific purposes: (a) to help clarify the importance in physics university education of combining student understanding with student competences, and (b) to try to pass on the benefits that accrue from a great deal of experience of designing and implementing physics degree programmes including the use of different teaching methods.

The most important thing I should do at the start is to acknowledge the great debt I owe to the students I have been privileged to teach, particularly my tutorial students. My interactions with them have taught me a lot, not just about how young people learn physics but also about physics itself—the questions they have asked me and also their responses to my questions to them have made me think more deeply about physics concepts, techniques and applications. The views and advice presented here are also based on many fruitful discussions I have had over many years with colleagues at Imperial College London and also with colleagues in the Institute of Physics in the UK and within the EUPEN Network of European physics departments. Although my understanding of educational issues has gained most from physics colleagues, I have also gained from discussions with mathematicians, computer scientists, neuroscientists and school teachers.

2 Communicating and Thinking

The essence of good teaching is good communication which is itself perhaps the most important "Key Competences"—the theme of this conference. Good communication depends on receiving as well as on transmitting. It depends on listening, reading, looking and then, crucially, on THINKING. This is the essence of education. Thinking must then be followed by a response. This can be an internal response but more effectively should be creative writing or speech. It is important that the input, the thinking and the response are remembered. I have gently introduced here an analogy to the first basic concept in Computer Science: The elementary Flow Chart INPUT → CPU → OUTPUT plus links to memory. This analogy is revealing. Figure 1 attempts to illustrate these processes. This is given a heading "Communication Flow Chart—Odin's Ravens". Norse legends tell of the

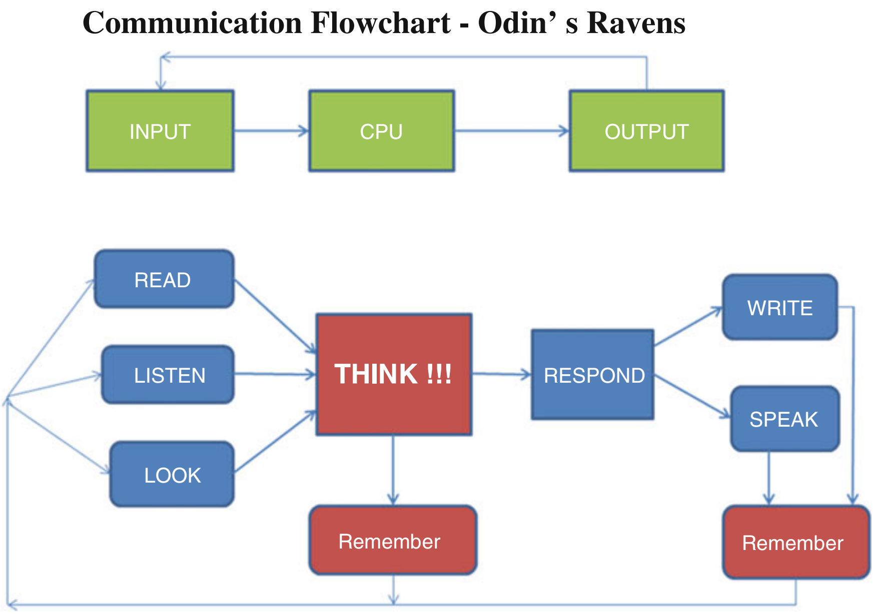

Fig. 1 Communication as a process of Input (Read, Listen, Look) leading to Thinking which in turn leads to a Response followed by Remembering and feedback. "Odin's Ravens" in Norse mythology refer to the key processes of thinking and remembering. The analogy with the basic flow chart of an introduction to Computer Science is shown at the top in green (where the feedback loop is optional). For laboratory based education, a "DO" box should be added before the "THINK" box

two ravens, Huginn and Muginn, that perched on the shoulders of Odin, the king of the Gods. Huginn helped Odin to think and Muginn helped him to remember—just how they did this depends on which account you read. The feedback loop is needed if the process is to result in two-way communication. It is crucial for some educational methodologies, e.g. Socratic dialogues.

All the above may seem like an excessive analysis of the obvious! But physics is often concerned with thinking deeply about apparently simple but fundamental concepts and an examination of the nature of communication is very relevant to education since good teachers listen to their students and think about what they say. Not everyone engaged in learning, teaching and communicating operates in accordance with this flow chart in a good way. Those who do are the ones who excel. Those who don't are a source of frustration for the teacher (or the student, for often it is the teacher who does not listen!). Of course, the quality of thinking is the key. This doesn't just apply to education. "Listen and think" is better advice than "do this".

Another reason for thinking about the flow diagram for communication and education is that it helps in adapting educational methods to cases where some individual students have difficulties (which we may refer to as disabilities) in understanding certain types of inputs or in producing outputs in a conventional form or indeed in the notion of feedback. These difficulties are often accompanied by an enhanced thinking ability and an internalisation of the process of learning. For example, some students with autism spectrum disorders (e.g. Asperger's syndrome) often have enhanced thinking ability (often unusually precise but lacking reference to context) which shows in high ability in mathematics and mathematical physics although their poor communication and social competence is a problem for both them and their teachers and so they are often regarded as foolish or as an enigma. Such students need special help in developing communication skills and in thinking about context. That can be very hard for them (and their teachers) although their internal understanding may be very good. In 1967, Lennon and McCartney wrote the song "The Fool on the Hill",[1] which epitomizes how the inner world of understanding may not be perceived by others if the thinker has profound communication problems. A physicist reading the lyrics of this song will be struck by the poetic way it portrays how "The Fool on the Hill" goes beyond immediate appearances by thinking deeply about what he sees and is then thought a fool by others because he cannot answer their questions. This illustrates the formidable difficulties that confront autism spectrum disorder students in attempting to interact with teachers.

3 The Concept of Competence

The main key-word of this conference is "Competence" used to signify both an approach to physics education, as in "competence based education", and also the competence of teachers and graduates. But what do we mean by the word "competence"? It can be defined as the ability to do something based on understanding—this combines the two essential qualities of "ability to do something" and "understanding". Thus, competence is more cognitive than a skill. This is widely acknowledged even though the meaning of the word "understanding" is debated. However there are different definitions of the word "competence", e.g. in the Tuning Project.[2]

"Understanding" and the "doing" implicit in competence are complimentary and reinforce each other although these qualities are sometimes seen to be in opposition to each other in the sense that concentration on acquiring competences can be seen as a diversion from understanding. Thus, to be referred to as "competent" can be interpreted as not being a creative or deep thinker. A characteristic driving force of physicists, both young and old, is to understand the physical universe on all scales,

[1]"The Fool on the Hill", Music and Lyrics written by Lennon and McCartney, first recorded Abbey Road Studios, London, 1967. The interpretation given here is due to the present author.

[2]The Tuning Project (Europe) is described in a very large number of papers which can be found at http://tuning.unideusto.org/tuningeu.

i.e. it is an intellectual pursuit. The result of this can be thought of as an internal learning or research outcome, whereas competence is essentially about having the capacity to affect the external world by doing something useful. This can include both communicating understanding and also applying your understanding to solving problems or advancing technology. These competences are particularly valued by employers of physics graduates and constitute one of the most important goals of physics higher education.

The difference between internal and external is also relevant to the psychology of learning and to the assessment of learning. To be assessed, understanding has to be demonstrated—the ability to demonstrate it is a competence but understanding itself is not. The internal-external difference is also relevant to students' medical and psychological conditions (e.g. autism spectrum disorders, sensory and motor problems, personality types).

4 Key Competences for Physics Graduates

There have been many attempts (e.g. the physics special interest group of the Tuning Project) (see footnote 2) to specify the competences that physics graduates should possess. They result in the production of lists such as:

- Ability to analyse phenomena in terms of physics knowledge, principles and mathematical reasoning.
- Ability to pursue a scientific investigation using experimental methods.
- Problem solving ability.
- Ability to apply knowledge to real world problems.
- Ability to work in teams including, interdisciplinary teams.
- Ability to communicate based on the writing of reports, giving presentations and giving general oral explanations to a wide range of audiences both specialist and non-specialist.
- Ability to use information technology, including computer coding, to pursue investigations and to solve problems.

More recently some other competences have been emphasized, such as:

- Ability to make mathematical models and computer simulations of physical processes.
- Ability to show creativity in creating and applying knowledge.
- Ability to innovate and to become an entrepreneur.

All of the above need to be explained and expanded in terms of what they involve. Moreover, they can be expressed using different words. It might help to describe key competences in terms of the basic requirements which they imply. Thus, the key competence of communication ability can be "unpacked" and expressed as guidance for students in terms of:

General principles of the key competence of communication ability:

- Think about your AIMS: *What are you trying to achieve by communicating?*
- Think about your Audience: *Make your communication appropriate for them.*
- Be a good listener and reader: *Do not always be in 'transmit mode'; respond, do not ignore.*
- Acknowledge contributions of others: *Avoid plagiarism.*
- Seek FEEDBACK: *Use it to improve.*

For Report Writing:

- Value clarity: *Write in simple direct sentences. Be precise.*
- Review what you have written: *Be self-critical and make corrections.*
- Take responsibility: *Always put your name and the date on what you produce. Feel responsible.*

Besides developing the above competences, education is also about developing personal qualities. These are crucial for both academic and career development and are also often the basis for decisions on job offers made by potential employers. They are sometimes classed as competences themselves. Through interactions with their students, universities have a duty to help them to develop these personal qualities.

- Ability to think rationally and carefully.
- Ability to learn from others and by one's own efforts and from one's own mistakes.
- Adaptability to new situations and new technology.
- Demonstrating empathy and a cooperative approach.
- Ability to convince others of your ideas and your results
- A willingness to take responsibility for what you do and write.
- To acknowledge the contributions and help of others.
- To guide and support others.
- To practice scientific and personal integrity.
- To have self-confidence when appropriate but also to be self-critical.

5 The Tuning Project and the EUPEN Network

The Tuning Project (see footnote 2) is a major initiative to reform higher education based on a competence approach. It has been funded by the European Commission. It started as a European project in the year 2000 but later became world-wide. It is too large and inclusive to describe here but its emphasis on competences gives it extra economic relevance. It has undertaken major investigations and consultations on competences in a wide range of academic subjects including physics. These have been more detailed and differentiated by type than those presented here. The definition of "competence" used in Tuning is somewhat different to the definition adopted in this paper although there is much in common in the ways of thinking about these issues.

The physics team in Tuning was drawn mainly from the EUPEN[3] network of university physics departments which has an even longer history of investigations into higher education in physics in Europe. This also has been partly funded by the European Commission in a series of specific time-limited projects. Some of these have made extensive investigations on differences in approach to physics education in different European countries. As an example, one provocative conclusion some years ago was "Physics is universal but physics education is not".

The most recent EUPEN project, called HOPE,[4] is underway at the moment. One theme in HOPE is an investigation into the factors that have inspired first year university physics students to study physics. A preliminary conclusion from this is that internal factors dominate over external factors. We see again the importance of the internal world of students. Thus, a wish to understand the world around us, the universe and how things work are the most important driving factors and a wish to learn advanced physics is seen as the key to opening these doors. The least important factors are the influence of friends and family members, visits from university staff, a wish to be a teacher, etc. But the investigation is not yet complete.

6 A Few General Principles of Degree Programme Design

(a) Know your students and make the programme appropriate for them.
(b) Think carefully about (and get agreement on!) <u>purposes</u> and then on aims and objectives.
(c) Design content and methods of teaching/learning to achieve these.
(d) Consider the interests and competences of the academic staff who will deliver the programme.
(e) Think of the students' needs as well as the point of view of the academic staff.
(f) When specifying desired learning outcomes, consider how they can be assessed.
(g) Think about how opportunities for creativity can be provided and motivation increased.

[3]EUPEN (European Physics Education Network) has published a series of books based on the various specific projects it has engaged in. These have mostly been Thematic Network Projects funded in part by the European Commission in various programmes of the ERASMUS, Socrates, and Life-Long Learning Programmes. An example is "Inquiries into European Higher Education in Physics: Volume 7". Universiteit Gent, 2003. ISBN 90-804859-6-9.

[4]HOPE (Horizons in Physics Education) is a project of the EUPEN Network, partly funded by the European Commission in the ERASMUS section of the Life-long Learning Programme (project number Nr 2013-3710_540130-LLP-1-2013-1-FR-ERASMUS-ENW), It is described in http://www.hopenetwork.eu.

(h) Consider how quality can be assured and enhanced.

A basic design principle is to think of things from the students' point of view and to allow them choice. Thus students should be stimulated and stretched intellectually but not overloaded with excessive detail. Opportunities for creativity should be built-in. We should remember that learning is a process of change. It is a change in the students' knowledge and abilities. This means that (at least in physics and mathematics) the change is a change in the brain (or more generally in the nervous system). If physics education is to be universal (like physics itself) then it should be based on cognitive neuro-science. But we cannot expect too much help as yet from this discipline since this branch of science is still struggling with basic questions such as the physical mechanisms of memory and of reasoning. But the relevance of cognitive neuro-science for educational policy is already starting to be recognised.[5]

Students differ, not just in previous education and experiences but also in terms of basic cognitive abilities and ways of thinking. Examples of genius and precociousness in different highly cognitive fields such as mathematics, art, music, chess etc. strongly suggest that these are, at least partly, consequence of differences (perhaps subtle and unknowable) in the neurological structure, connectivity and processes of the brain. The relevance of this for degree programme design is that opportunities for students to excel and to surge ahead must be built-in, just as opportunities for different specialities in the programme should be provided, and that allowance must also be made for students to use different learning methods.

Content is obviously crucial to achieving educational goals and the links, both educationally and logically, between different topics should be part of the design. As well as covering a common core, there should be a range of special topics to be chosen by students.

Teaching and learning methods are aspects of design. A great deal of experience has accumulated on various methods but a key aspect of all is the importance of interactivity between students and teachers. Conventional lecturing, when done well and involving interaction with students, has the advantage of enabling students to get good explanations of difficult topics and to question them. So questions from students should be encouraged and enabled even if this means that less ground is covered.

[5]Presentation of Prof. Sara-Jayne Blakemore, University College London Institute for Cognitive Neuroscience, at the meeting of SCORE at The Royal Society, London, on 24 Feb 2014. http://www.score-education.org/media/15383/final%20annual%20conference%20report%20-%20for%20website.pdf.

7 Improved Teaching/Learning Methods

In recent decades, improved teaching and learning methods have proliferated in response to evidence that conventional university teaching via lectures is not very effective in helping some physics students to understand physics concepts and that methods which generate increased student involvement and active learning are more effective. They also have been stimulated in response to advances in technology and particularly much enhanced capabilities and interactivity of computer based systems. The important point is that they should be embedded in the overall programme design.

There is a long list of teaching/learning methodologies which are used in physics, each with their adherents and each offering particular advantages:

Blended Learning
Flipped Learning
Inquiry Based Learning
Self-paced Learning
Peer Instruction
Flexible Learning
Guided Discovery Learning
Socratic Dialogues
Project Based Learning
Team Based Learning
Etc. …

All are well motivated and in most cases PER has provided evidence of their effectiveness which varies depending on circumstances and targets. However, their impact on university physics teaching has been disappointing. This has often been because there has been resistance from teachers who feel uneasy in adopting them because of a lack of time to learn how to implement a new approach to teaching. Also there is sometimes a feeling that some methods are not appropriate to their particular needs (in terms of student profiles and learning needs) and in particular are only suitable for more basic parts of the curriculum. They are also often difficult to incorporate in the overall teaching/learning design programme. Since they represent somewhat of a revolution, the famous (but unverified) last words of Simon Bolivar come to mind: "*Those who have served the revolution have ploughed the sea!*"

Two different non-traditional methodologies for physics teaching will now be described to illustrate both their motivation and the reasons why they actually made less impact than hoped for. They were carried out by the author and his colleagues at Imperial College London. Also a brief account will be given of the use of traditional Socratic Dialogues in physics tutorials. They are included here because they illustrate some of the above issues and in particular the problems in having new approaches embedded in overall physics degree programmes.

Development of Self-paced Flexible Learning in Mechanics for physics and engineering students

Problem: The reduced but variable mathematical content of school physics caused some physics and engineering students to struggle with classical mechanics in their 1st Year at university.

Proposed Solution: A special supplementary, flexible and self-paced course on Mechanics for Physics and Engineering students.

Method: An interdisciplinary team was formed to design and trial such a course. There was much discussion and much listening to advice from external experts and from students. This resulted, after a lot of work, with the production of a set of about 20 interlinked self-study modules on classical mechanics each consisting of (a) context, (b) pre-test, (c) formative tests, (d) end-of-module competence test.

Trial with students: About 30 selected 1st year students from physics and engineering took part in a trial of 3 of the modules: Particle kinematics, Free-body diagrams, and Newton's Laws. Students worked on the modules individually in a collectively supervised but self-paced manner on different days spread over about two weeks. There were in addition three separate short lectures on cross-module novel applications designed mainly to improve motivation and provide extra interest.

Measurements made and recorded: The times taken for each student to complete each module (completion defined by scoring a high mark in the final competence test) were recorded and also the marks in the formative and end-of-module tests were recorded. The tests were structured to measure achievement of a series of specific learning outcomes.

Results: There was a significant spread in the times needed to complete a module. There was found to be an anti-correlation between time taken and marks (which could be regarded as a proxy measure of the number of learning outcomes achieved), i.e. students who worked more hours achieved lower final marks and hence achieved fewer learning outcomes. This anti-correlation was significant at the probability level for each module of 2×10^{-5}. This confidence level was calculated using the Fisher Z transformation from the correlation coefficient probability density function to a Gaussian.[6]

Discussion of Implications: Students reported their understanding was improved but that the time taken was greater than conventional learning by lectures, books and examples classes. Academic staff who produced the modules reported that the staff time taken to produce the modules was excessive—about 5 × the time for a conventional lecture course including course work and assessments. The academic level reached was lower although basic competence was higher.

Conclusions: Full implementation was not justified although some parts were used as a "Mastery Course" in some engineering departments. The modules were tested using paper-based materials (this was several years ago) although interactive

[6]Course Design for Resource Based Learning: Technology (Case Study 6), Editors F. Percival and G. Gibbs. The Oxford Centre of Staff Development, 1994. ISBN 1-873576-25-0.

computer based modules were planned but not implemented because the considerable extra staff time involved was felt to be not justified. The anti-correlation between time taken (student work-load) and learning outcomes challenges the normal assumption that student progress is proportional to student work-load! All the students involved had satisfied very high entrance standards in maths and physics so it surprising to find this anti-correlation although it suggests that their ways of thinking are different. Although this investigation was done several years ago it is interesting that the basic methodology of flexible, self-paced learning with motivational episodes is similar to the methodology employed in MOOCs.

Trial of "Guided Discovery Learning"

This was a supplement to a 2nd Year lecture course on Nuclear Physics. It used *partly* developed computer programmes which students had to extend to investigate several different topics including (a) numerical solutions of the 3-D Schrodinger equation for modified Yukawa potentials to investigate predicted deuteron properties arising from different forms of the inter-nucleon force, (b) consequences of the Semi-Empirical Mass Formula, e.g. energetics of radioactive decays, and (c) dynamics of radioactive decay chains including branching. Students worked on adding their own code and modifying the programmes in ways that required creativity to investigate specific questions.

In principle this was very effective because of the partly developed nature of the computer programmes for students to extend; it was crucial that it followed a specific course on computer coding. It was limited by demands on computer resources (this was quite some years ago) and particularly by the problem of embedding it in the whole course. Assessment of student performance was also problematic.

Experience of Socratic Method in Tutorials (based on the author's experience of this at Imperial College London)

Small group tutorials were devoted to (a) discussion of student questions in the group (4 students plus tutor), (b) giving students interactive oral feedback on their written work, (c) asking students questions—making them THINK and discussing their responses with them (this is the essential Socratic Method), and (d) helping students to solve problems in real time at the whiteboard.

Students vary in their response but a good tutor will get each individual student to think and particularly to get students to explain their attempts to solve a problem. The crucial advantage comes from the interaction between tutor and students concerning questions from the tutor to the student. Moreover, students really gain from the opportunity to have discussions with experienced physicists and with other students.

8 Possibilities for Application of Artificial Intelligence (AI) in University Physics Education

The author makes no claims of any special knowledge of AI so the following cannot be regarded as authoritative but is intended to draw attention to the nature and possible impact of AI on education. Many educators have speculated that the relevance of AI to education could be profound in the coming decades. The main applications presently envisaged are in distance learning particularly in the context of MOOCs since AI should cope well with different students having different needs. Already starting to be used are methodologies based on adaptive algorithms (exercises, quizzing, feedback), sentiment analysis and machine assessment with individually tailored response to students.

AI raises some fundamental questions about education. Authoritative scientific knowledge is already easily available from the internet to use in self-learning; the problem is to distinguish it from the non-authoritative and also to develop thinking and problem-solving. So university education which is mainly about acquisition of advanced knowledge is questioned. The emphasis should be more on developing understanding and competence. But if AI really becomes pervasive it will call for fresh thinking on the questions of "Who needs to learn physics at university level?", "Who wants to learn and why?" and "Why go to university to study physics?" These are existential questions for physics educators at university.

9 Some Illustrations of the Nature of Physics as a Lifelong Pursuit

One of the goals of physics education is to help students appreciate the nature of physics as a lifelong pursuit to understand the physical universe and the world around them. Although the study of physics at university is partly motivated by its career prospects, young people at the interface between school and university physics tend to be idealistic and the following quote from a high school student is quite typical: '*I'd go to university to study physics because I want to study a subject I'm passionate about, taught by people who are just as passionate. Any positive career impact is simply a bonus.*'[7]

Other insights into how physicists go about this lifelong pursuit can be found in the book "Surely you're Joking Mr. Feynman".[8] There are many passages of this book that eloquently express the essence of thinking like a physicist; for example Feynman relates how he has always been motivated by the drive to solve puzzles in

[7]As told to the author by one of his students

[8]'Surely you're joking, Mr. Feynman!', Richard Feynman (as told to Ralph Leighton), Edited by Edward Hutchings, first published by W.W. Norton 1985 then by Unwin Paperbacks, London, 1986. ISBN 0-04-530023-2.

attempts to understand the universe—he has to keep going until he solves the puzzle.

In one passage, Feynman describes how, as a child, he fixed the radio of a neighbour by thinking about what might be causing it to operate badly; the owner never thought it possible that a little boy could figure out what was wrong by observing and thinking!

In another passage, based on his address to new students at CalTech, he explains the key features of scientific integrity in terms of the need for utter honesty, including thinking about what might be wrong in your theories or experimental results as well as what is new and successful. You must be open about this and also welcome constant questioning and challenge. You must not fool yourself and after that, normal honesty makes it easy not to fool other people. That is crucial.

10 Bibliography

The following three books (intended for a wide readership) give very unusual but enlightening perspectives on some of the issues raised in this paper.

1. "Surely you're joking, Mr. Feynman!", by Richard Feynman (as told to Ralph Leighton), Edited by Edward Hutchings, first published by W.W. Norton 1985 then by Unwin Paperbacks, London, 1986. ISBN 0-04-530023-2. This contains many "gems" which exemplify the essence of the nature and importance of thought processes in physics as expressed by a great physicist. Particularly illuminating passages are to be found in the Chapters, "He Fixes Radios by Thinking" and "Cargo Cult Science" (adapted from his Caltech commencement address, 1974).
2. "Through the Looking Glass, and What Alice Found There", by Lewis Carroll (Charles Dodgson), Published by Macmillan, London, 1871, the sequel to Alice in Wonderland with which it is now often published together. Charles Dodgson was a mathematician at the University of Oxford and there are several passages that indirectly illustrate the nature of mathematical thought and of the problems of giving meanings to words; one particular example which is relevant to the problem of giving meaning to words such as competence is the dialogue between Alice and Humpty Dumpty on "portmanteau" words.
3. "The Curious Incident of the Dog in the Night-Time", by Mark Haddon, published by Jonathan Cape, London, 2003. ISBN 9780099450252. This novel expresses the relation of the internal thought processes of a 17 year old young man with Asperger's syndrome to the external world and how he misunderstands and is misunderstood by those with whom he has to interact. The nature of mathematics as an internal thought process (at which he excels) and also its relation to the physical world are well illustrated. It has been adapted as a moving and highly successful stage play in London and New York and elsewhere.

Acknowledgments As stated at the beginning, I owe a great debt to my students over many years but there are other individuals who have contributed greatly to my understanding of all of the above issues. These include:

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Analysing the Competency of Mathematical Modelling in Physics

Edward F. Redish

Abstract A primary goal of physics is to create mathematical models that allow both predictions and explanations of physical phenomena. We weave maths extensively into our physics instruction beginning in high school, and the level and complexity of the maths we draw on grows as our students progress through a physics curriculum. Despite much research on the learning of both physics and math, the problem of how to successfully teach most of our students to use maths in physics effectively remains unsolved. A fundamental issue is that in physics, we don't just *use* maths, we think about the physical world with it. As a result, we make meaning with mathematical symbology in a different way than mathematicians do. In this talk we analyse how developing the competency of mathematical modelling is more than just "learning to do math" but requires learning to blend physical meaning into mathematical representations and use that physical meaning in solving problems. Examples are drawn from across the curriculum.

1 Mathematics: A Critical Competency for Learning Physics

Mathematics plays a significant role in physics instruction, even in introductory classes, but not always in a way that is successful for all students. As physics students learn the culture of physics and grow from novice to expert, many have trouble bridging what they learn in math with how we use mathematics in physics. As instructors, many of us are distressed and confused when our students succeed in maths classes but fail to use those same tools effectively in physics. Part of the difficulty is that in physics, we don't just calculate with maths, we "make meaning" with it, think with it, and use it to create new physics. Mathematics has been identified as a critical scientific competency both by the European Union

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(EUR-LEX 2006) and the US biology community (National Research Council 2003; AAMC/HHMI 2009; AAAS 2011), so as we think about how we might improve physics instruction it is important to try to understand what role maths play in physics, how that role may be difficult for students, and how we might learn to think about that difficulty. A crucial element is the role that mathematics plays in the epistemology of physics.

The process of science and the development of scientific thinking is all about epistemology—deciding what we know and how we decide that we know it. In physics, mathematics has been closely tied with our epistemology for 300 years, transforming physics from natural philosophy into the mathematical science it is today. For those of us who practice physics, either as teachers or researchers, our knowledge of physics, what we know and what we believe is true is deeply blended with mathematics. This tie is so tight that we may find it hard to unpack our blended knowledge and understand what it is that students find difficult.

My research group has been studying students using math in physics at the university level for more than 20 years in a number of different contexts:

- Engineering students in introductory physics
- Physics majors in advanced classes
- Biology students in introductory classes, both with mixed populations and in a specially designed class for biology majors and pre-health-care students.

Since we have been trying to develop insight into what is going on in our students' minds, our data is mostly qualitative. It often involves videos of problem-solving interviews or ethnographic data of students in real classes solving real homework problems, either alone or in groups. Sometimes we have quantitative data as well, including responses of many students on multiple-choice questions on exams or with clickers in a large lecture class.

We work in the theoretical framework of *Resources*—the idea that student thinking is highly dynamic, calling on multiple smaller bits of knowledge that may be organized in locally coherent, but often changing ways. (Hammer 2000) This framework is built on ideas from education, psychology, neuroscience, sociology, and linguistics research (Redish 2014).

2 Different Languages: Math in Physics Is not the Same as Math in Math

We often say that "mathematics is the language of physics", but what physicists do with maths is deeply different from what mathematicians do with it. Mathematicians and physicists load meaning onto symbols differently and this has profound implications (Redish and Kuo 2015).

In physics, we link our equations to physical systems and this adds information on how to interpret them. Our symbols carry extra information not present in the abstract mathematical structure of the equation. As a result, our processing of equations in physics has additional levels and may be more complex than the processing of similar equations in a math class.

In physics most of our symbols don't stand for numbers (or collections of numbers) but for measurements. Our symbols bring physical properties along with them. As a result, they have *units* that depend on the measurement process. In math terms, this is quite sophisticated. As a result of the arbitrariness in our choice of units, physics equations must have a particular structure. Since the choice of scale is arbitrary, any physically true relation must be true whatever choice of scale is made. This means that every part of both sides of the equation must change in the same way when a scale is changed. Mathematically this means that equations must transform properly—covariantly by an irreducible representation of the 3-parameter scaling group S × S × S for units of mass, length, and time (Bridgman 1922).

What about significant figures? Why do we bother talking about them now that we have calculators? But when we multiply 5.42 × 8.73 in a 6th grade arithmetic class we want something different from what we want when we are measuring the area of a (5.42 cm) × (8.73 cm) sheet of silicon. Every physical measurement has an uncertainty that propagates to the product, leaving many digits shown by a calculator as "insignificant figures", irrelevant to physical silicon.

An elementary example of how the physicist's mapping of physical meaning onto symbols changes the way equations are interpreted is illustrated in the example shown in Fig. 1. This problem was given as a clicker question to a class of about 200 students in algebra-based introductory physics as part of a lecture on the electric field. The topic had been discussed in a previous lecture and the students had been presented with a derivation of the electric field from Coulomb's law for the electric force of many source charges acting on a test charge.

A very small charge q_0 is placed at a point $\vec{r}$ somewhere in space. Hidden in the region are a number of electrical charges. The placing of the charge q_0 does not result in any change in the position of the hidden charges. The charge q_0 feels a force, F. We conclude that there is an electric field at the point $\vec{r}$ that has the value $E = F/q_0$.

If the charge q_0 were replaced by a charge $-3q_0$, then the electric field at the point $\vec{r}$ would be

a) Equal to $-E$
b) Equal to E
c) Equal to $-E/3$
d) Equal to $E/3$
e) Equal to some other value not given here.
f) Cannot be determined from the information given.

Fig. 1 A quiz problem that students often misinterpret

They had seen the equations

$$\vec{F} = \frac{k_c q_0 q_1}{r_{01}^2}\hat{r}_{1\to 0} + \frac{k_c q_0 q_2}{r_{02}^2}\hat{r}_{2\to 0} + \frac{k_c q_0 q_3}{r_{03}^2}\hat{r}_{3\to 0}\ldots + \frac{k_c q_0 q_N}{r_{0N}^2}\hat{r}_{N\to 0}$$
$$\vec{E}(\vec{r}) = \vec{F}_{q_0}/q_0$$

and had pointed out to them that the charge of the test charge factors out and cancels when defining the electric field. When asked, most students could cite the result, "The electric field is independent of the test charge that measures it."

Nonetheless, when asked the question in Fig. 1, nearly half chose answer (c). These students treated the physics as a pure math problem: "If A = B/C what happens to A if C is replaced by-3C?" They ignored the fact that F here is not a fixed constant, but represents the force felt by charge q_0 and therefore implicitly depends on the value of q_0.

A second example illustrates another of the differences between maths and physics classes. Maths classes typically use equations with a small number of symbols, with fixed conventions for what symbols stand for variables and what for constants. Furthermore, introductory maths classes (through calculus) often do very little with parameter dependence. In physics, on the other hand, our equations often involve a blizzard of symbols, some of which may be variables or constants depending on what problem we choose to consider. An example occurred in an introductory physics class for life scientists. One year of calculus was a pre-requisite and most of the students in the class had earned a good grade in that class. Nonetheless, many had trouble knowing how to approach the problem shown in Fig. 2. The problem was presented as a "work together" problem in a large lecture in which I was serving as a facilitator. As I walked around the class, watching and listening to students, I found one group totally stuck.

Student: I don't know how to start. Should I see if I can find all the numbers on the web?
Facilitator: *Well, it says 'Do they ever have the same magnitude?' How do you think you ought to start?*
S: Set them equal?
F: *OK. Do it.*
S: I don't know what all these symbols mean.

When a small organism is moving through a fluid, it experiences both viscous and inertial drag. The viscous drag is proportional to the speed and the inertial drag to the square of the speed. For small spherical objects, the magnitudes of these two forces are given by the following equations:

$$F_v = 6\pi\mu R v$$
$$F_i = C\rho R^2 v^2$$

For an organism (of radius R) is there ever a speed for which these two forces have the same magnitude?

Fig. 2 An example of multiple-parameter use in a physics class for life science students

F: *Well everything except the velocity are constants for a particular object in a particular situation.*
S:…..[concentrating for almost a minute…] Oh! So if I write it….
$Av = Bv^2$… Wow! Then it's easy!

I have seen many introductory students having serious trouble with the multi-parameter equations in physics and have seen that these same students can easily carry out analogous mathematical problems with only variables and numbers.

3 Making Meaning with Mathematics

Our examples suggest that the critical difference in maths-as-pure-mathematics and maths-in-a-physics-context is the blending of physical and mathematical knowledge. A simple model shown in Fig. 3 (Redish 2005) focuses on a few of the main steps: (1) choosing a model to map physical quantities into mathematical structures, (2) processing, using the tools inherited from those mathematical structures, (3) interpreting the results back in the physical world, and (4) evaluating whether the result is adequate or whether the original model needs to be refined.

Often these all happen at once—are intertwined. (The diagram is not meant to imply a step-by-step algorithmic process). In physics classes, processing is often stressed and the remaining elements short-changed or ignored. But in physics, maths integrates with our physics knowledge and does work for us. It lets us carry out chains of reasoning that are longer than we can do in our head, by using formal and logical reasoning represented symbolically. Some of the things we do with maths include:

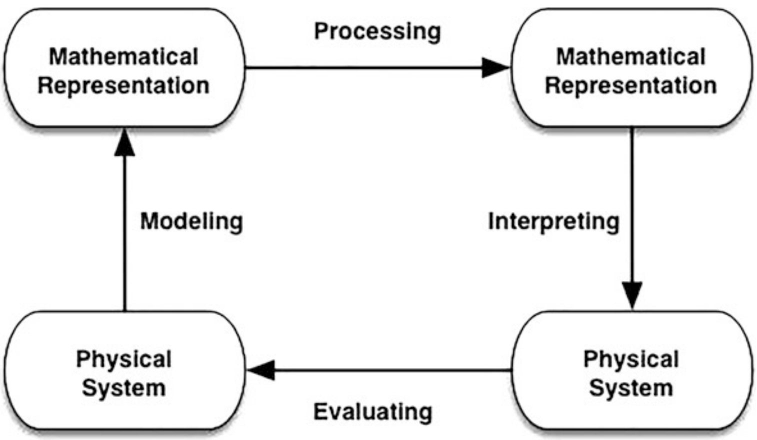

Fig. 3 A model of mathematical modelling

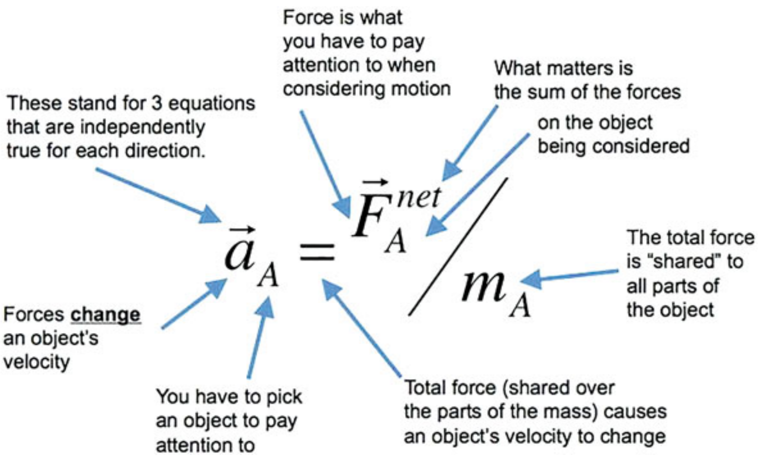

Fig. 4 Conceptual knowledge packed in an equation (From NEXUS/Physics)

- Calculations
- Predictions
- Summary and description of data
- Development of theorems and laws.

But maths in physics also codes for conceptual knowledge, something that is typically not part of what is learned in a mathematics class, such as:

- Functional dependence
- Packing concepts
- Epistemology.

An example of how we use equations to organize and pack our conceptual knowledge is shown in Fig. 4: Newton's second law. When we just write "$F = ma$", our students may see it simply as a way to calculate either F or a and miss the deeper meaning.

4 What Does "Meaning" Mean? Some Advice from Cognitive Science

In physics, we "make physical meaning" with maths. Mathematics is a critical piece of how we decide we know something—our epistemology. What does that mean and how does it work?

To develop an answer, we first ought to consider the question, "How do we make meaning with words?" We'll draw on cognitive semantics—the study of the meaning of words in the intersection of cognitive science and linguistics. Some key ideas developed in these fields are relevant:

- *Embodied cognition*—Meaning is grounded in physical experience (Lakoff and Johnson 1980/2003).
- *Encyclopaedic knowledge*—Webs of associations build meaning (Langacker 1987).
- *Contextualization*—Meaning is constructed dynamically in response to perceived context (Evans and Green 2006).
- *Blending*—New knowledge can be created by combining and integrating distinct mental spaces (Fauconnier and Turner 2003).

One way embodiment allows maths to feel meaningful in maths is with symbolic forms (Sherin 2001; Redish and Kuo 2015): associating symbol structure with relations abstracted from (embodied) physical experience

- Parts of a whole: □ = □ + □ + □…
- Base + change: □ = □ + △
- Balancing: □ = □

A second way maths build meaning is through association via multiple representations

- Equations
- Numbers
- Graphs.

Physicists tend to make additional meaning of mathematical symbology by associating symbols with physical measurements. This allows connections to physical experience and associations to real world knowledge. And that knowledge may be built up as students learn physics.

But just as we saw with introductory students, students at more advanced levels may not apply knowledge they have about the physical world in a math problem. Figure 5 shows an example drawn from an upper division electricity and magnetism class for physics majors. Our data is taken from a video of two students working on a problem from their text (Griffiths 1999).

Students A and B have independently solved the problem and begin to discuss how they did it. Student A thinks there is a net force, student B does not.

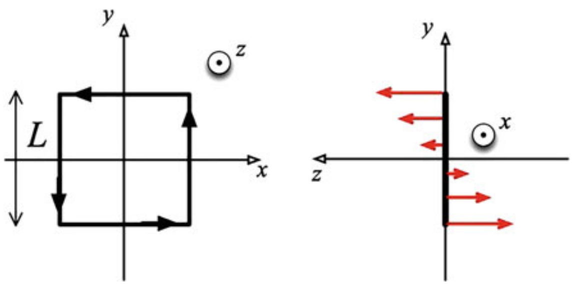

Fig. 5 An E&M problem. Find the force on a current-carrying loop of wire in a space-varying magnetic field, $\bar{B} = B_0 y\hat{k}$ shown in red. (Griffiths 1999)

Student A	*Student B*
Huh! Looks pretty simple—like a physics 1 problem. The sides cancel so I can just do $\vec{F} = I\vec{L} \times \vec{B}$ on the top and bottom where B is constant. Both give "up" so I'm gonna get $\vec{F} = IL^2 B_0 \hat{j}$	I'm pretty sure they want us to do the vector line integral around the loop $\vec{F} = \oint Id\vec{L} \times \vec{B}$ It's pretty straightforward The sides do cancel, but I get the top and bottom do too, so the answer is zero

What do you think happened next?

Student A immediately folded his cards in response to student B's more mathematically sophisticated reason and agreed she must be right. Both students valued (complex) mathematical reasoning (where they could easily make a mistake) over a simple and compelling argument (where it's hard to see how it could be wrong) that blends mathematical and physical reasoning.

The students' expectations that the knowledge in the class was about learning to do complex math was supported by many class activities. They both focused on the "Processing step in the 4-box model," just as the professor had in the lectures.

5 Analysing Mathematics as a Way of Knowing: Epistemological Resources

We can develop a more nuanced view of what is going on. The example shown in Fig. 6 is taken from a homework problem in third year course in the Methods of Mathematical Physics (Bing and Redish 2009).

During this discussion three students are talking at cross-purposes. They are each looking for different kinds of "proofs" than the others are offering. They use different kinds of reasons (warrants[1]) to support their arguments. Eventually, they find mutual agreement—after about 15 min of discussion.

S1: What's the problem? You should get a different answer from here for this… (Points to each path on diagram)
S2: No no no
S1: They should be equal?
S2: They should be equal
S1: Why should they be equal? This path is longer if you think about it. (Points to two-part path) {*Matching physical intuition with the math*}
S2: Because force, err, because work is path independent. {*Relying on authority—a remembered theorem*}

[1] A "warrant" is a specific reason presented to justify a claim (Toulmin 1958).

A rocket is taken from a point A to a point B near a mass m. Consider two (unrealistic) paths 1 and 2 as shown. Calculate the work done by the mass on the rocket on each path. Use the fundamental definition of the work,

$$W_{A\to B} = \int_A^B \vec{F} \cdot d\vec{r}$$

not potential energy. Mathematica may or may not be helpful. Feel free to use it if you choose (though it is not necessary for the calculations required).

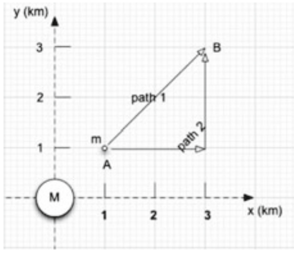

Fig. 6 A mechanics problem to demonstrate that potential energy is independent of path

S1: Well, OK, well is this—what was the answer to this right here? (Points to equation they have written on the board) $\int_{\sqrt{2}}^{3\sqrt{2}} \frac{1}{r^2}dr = \int_1^3 \frac{1}{y^2+9}dy + \int_1^3 \frac{1}{x^2+1}dx$

S2: Yeah, solve each integral numerically {*Relying on validity of mathematical calculation*}

S1: Yeah, what was that answer…I'll compare it to the number of…OK, the y-one is point one five.

A number of different structures are brought to bear here: different kinds of reasons or *epistemological resources*—such as "I know a theorem" or "This is what the calculation tells us" (Elby and Hammer 2001; Hammer and Elby 2003). We've already seen a number of different ways of coming to a conclusion in a physics problem: the students in Fig. 1 who relied on a calculation, those in Fig. 5, one who relied on a physical "hands on" (right-hand rule) intuition learned in an earlier physics class, and a second who relied on a complex calculation. The three students solving the problem in Fig. 6 first called on different resources – looking at the physical structure of the problem, relying on calculation, and calling up a theorem. Some of the resources commonly we have seen used in a physics class include:

1. *Physical intuition*: Knowledge constructed from experience and perception is trustworthy. (diSessa 1993)
2. *Calculation can be trusted*: Algorithmic computational steps lead to trustable results.
3. *By trusted authority*: Information from an authoritative source can be trusted.
4. *Physical mapping to math*: A mathematical symbolic representation faithfully characterizes some feature of the physical or geometric systems it is intended to represent.
5. *Fundamental laws*: There are powerful principles that can be trusted in large numbers of circumstances (occasionally, all).
6. *Toy models*: Highly simplified examples can yield insight into complex calculations.

Except for the first, these typically involve math, even in an introductory physics class. We also identify a meta-epistemological resource:

7. *Coherence*: Multiple ways of knowing (epistemological resources) applied to the same situation should yield the same result.

6 Choosing Resources: Epistemological Framing

Our brains know lots of things, and we have many resources for solving our problems, both in life and in a physics class. But the amount of knowledge that can be held in one's mind and manipulated at any instant is limited (Baddeley 1998). The process by which relevant memories and knowledge are brought to the fore is called *framing* (Tannen 1994). When that framing is particularly concerned with knowledge building or problem solving, I refer to it as *epistemological framing* (Hammer et al. 2005; Bing and Redish 2012). Depending on how students interpret the situation they are in and their learned expectations, they may not think to call on epistemological resources they have and are competent with.

Students' epistemological framing can take many forms:

- "I'm not allowed to use a calculator on this exam."
- "It's not appropriate to include diagrams or equations in an essay question."
- "This is a physics class. He can't possibly expect me to know any chemistry."

These are all conscious and easily articulated. Often (as in some examples above), students are not aware of the epistemological choices they have unconsciously made. Epistemological framing can also coordinate significantly with affective responses (Gupta and Elby 2011).

This epistemological language provides nice classifications of reasoning—both what we are trying to teach and what students actually do. And it can tell us that our assumption that a student failure represents a "student difficulty" with understanding the material may be a misinterpretation of what is going on. There can be epistemological reasons for a student error as well as conceptual ones. But can an epistemological lens provide guidance for instructional design? It can become especially important when students and faculty have different ways of knowing.

7 Case Study: Implications for Interdisciplinary Instruction

Our next examples come from NEXUS/Physics (Redish et al. 2014), an introductory physics class developed to meet the needs of biology and life sciences students (including pre-health care). The class is intended to articulate with the rest of these students' curriculum, so calculus, biology, and chemistry are pre-requisites. This allows us to find places where physics has authentic value for biology students—places where they have difficulty making sense of important but complex issues such as chemical bonding (Dreyfus et al. 2014), diffusion (Moore et al. 2014), or entropy and free energy (Geller et al. 2014). The goals of the course are to (1) create prototype open-source instructional materials that can be shared, (2) focus on interdisciplinary coordination of instruction in biology, chemistry, physics, and math, and (3) emphasize competency-based instruction, building general scientific skills. Since physics uses maths heavily, it's an appropriate place in the curriculum to emphasize how maths are used in science.

The course was built with extensive negotiations among all the relevant disciplines (Redish and Cooke 2013; Redish et al. 2014). One of the important things we learned form these negotiations is that the epistemological resources biology students were comfortable using differed from those expected in a physics class. Some resources common in introductory biology are:

1. *Physical intuition*: Knowledge built from experience and perception is trustworthy.
2. *Life is complex*: Living organisms require multiple related processes to maintain life.
3. *Categorization and classification*: Comparison of related organisms yields insight.
4. *By trusted authority*: Information from an authoritative source can be trusted.
5. *Naming is important*: Many distinct components of organisms need to be identified, so learning a large vocabulary is useful.
6. *Heuristics*: There are broad principles that govern multiple situations.
7. *Function implies structure*: The historical fact of natural selection leads to strong structure-function relationships.

In introductory biology, typically none of these involve any math at all. The resources common to the physics list—physical intuition and authority—usually have a mathematical component in introductory physics (e.g., "authority" is often a theorem or equation) while in bio they do not. Even more problematical, two of the critical resources often used in physics, the value of toy models and the power of fundamental laws (mathematically stated), are not only weak or missing in many bio students, they are seen as contradicting resources they value—life is complex and function implies structure.

This difference between student and teacher's expectations requires some dramatic changes in our instructional approach from that taken in a traditional physics class. We cannot take for granted that students will value toy models. We have to justify their use. We cannot take for granted that students will understand or appreciate the power of principles (Newton's laws, conservation laws of energy, momentum, or charge). We have to teach not just the content but the epistemology explicitly. We have to create situations in which students learn to see the value of bringing in physics-style thinking with biology-style thinking in order to gain biological insights ("biologically authentic" examples) (Watkins et al. 2012).

Example: Disciplinary Epistemological Framing: Why do Bilayers Form? One goal of NEXUS/Physics was to design lessons that explicitly demand a resolution between epistemological resources emphasized in introductory biology and physics. An example of this is a recitation activity on membrane formation. Recitations in this class are done as group work and often require that students bring in their knowledge of biology and chemistry. In this lesson, the question is raised: "Given that the electrostatic attraction between water molecules and a lipid (oil) molecule is stronger than the attraction between two lipid molecules, why does oil and water separate, and, important for biology, how can lipid membranes form?" A videotaped discussion of a student group illustrated not only the mixing of epistemological resources from physics and biology, it shows that the students perceive the mixing of kinds of reasons.

S1: In terms of bio, the reason why it forms a bilayer is because polar molecules need to get from the outside to the inside.
S2: If it's hydrophobic and interacting with water, then it's going to create a positive Gibb's free energy, so it won't be spontaneous and that's bad. [proceeds to unpack in terms of positive (energetic) and negative (entropic) contributions to the Gibbs free energy equation.]
S1: I wasn't thinking it in terms of physics. And you said it in terms of physics, so it matched with biology.

The first student argues that it has to form because the end result is needed—a typical structure-function argument used in biology. The second student brings in the equation for free energy, $\Delta G = \Delta H - T\Delta S$, presented and analysed both in physics and chemistry, and sees, guided by the structure of the equation, that there is a competition between two effects—energy (here, enthalpy) and entropy. The attraction, being a potential energy, contributes to the enthalpy term, ΔH. But the entropy term involves both lipids and water, and the change of the entropy of the water overcomes the enthalpy term. The students' use of multiple (and interdisciplinary) epistemological resources is illustrated in Fig. 7.

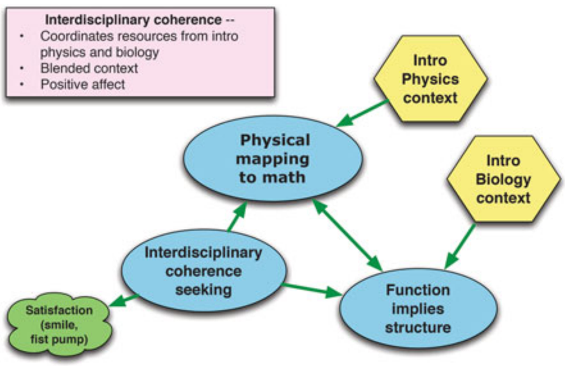

Fig. 7 The interdisciplinary epistemological resources used by students in the NEXUS/Physics lesson on membrane formation

Example: Interdisciplinary Instruction or Teaching Physics Standing on Your Head

Both students and faculty may have developed a pattern of choosing particular combinations of epistemological resources in their framing of tasks within a particular class. This leads us to our third epistemological structure: the *epistemological stance*. By this we mean that particular patterns of epistemological framing may become "comfortable" for an individual, with the result that they are likely to frequently activate it as their "normal" or "go-to" knowledge-building approach. The epistemological stances chosen by physics instructors and physics students may be dramatically different – even in the common context of a physics class.

In Fig. 8, I show an example that illustrates this. This task was given as a clicker question in a NEXUS/Physics lecture in a discussion meant to extend what the students had learned about potential energy to the case of atom-atom interactions and chemical bonding.

I served as facilitator in two different classes. Two different professors explained it this way when students got stuck: "Remember! $\vec{F} = -\vec{\nabla}U$, or in this case, $F = -dU/dr$. At C, the slope of the U graph is positive. Therefore the force is negative—towards smaller r. So the potential represents an attractive force when the atoms are at separation C." They built on the equation that generates Fig. 8b, though both wrote the equation on the board but not the figure.

Wandering around the class while students were considering the problem, I got a good response using a different approach. "Think about it as if it were a ball on a hill [as in Fig. 8c]. Which way would it roll? Why? What's the slope at that point? What's the force? How does this relate to the equation $F = -dU/dr$?"

A conflict between the epistemological stances of instructor and student can make teaching more difficult. Physics instructors seem most comfortable beginning with familiar equations—which we use not only to calculate with, but also to remind us of conceptual knowledge. The chain of epistemological resources being used by the professors is something like the following:

$$\textit{By trusted authority} \Rightarrow \textit{Calculation can be trusted} \Rightarrow \textit{Physical mapping to math.}$$

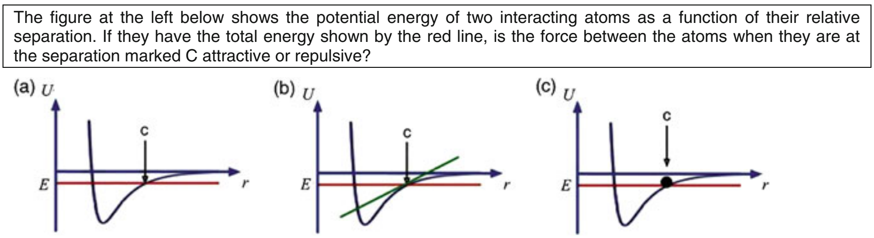

Fig. 8 Three figures illustrating different epistemological approaches to an explanation. **a** The figure shown in the problem; **b** an explanation based on a formula; **c** an explanation based on a physical analogy

Most biology students lack experience blending math and conceptual knowledge. They were more comfortable starting with physical intuitions, like, “How does a ball roll on a hill?”

$$\textit{Physical intuition} \Rightarrow \textit{Physical mapping to math} \Rightarrow \textit{Mathematical consistency}$$

For physicists, math is often the “go to” epistemological resource—the one activated first and the one brought into support intuitions and results developed in other ways. For biology students, the math is decidedly secondary. Structure/function relationships tend to be the “go to” resource. Part of our goal in teaching physics to second year biologists is to improve their understanding of the potential value of mathematical modelling. This means teaching it rather than assuming it.

8 Conclusion

I have presented an analysis of how mathematics is used in physics, including both an unpacking of what professionals do and an analysis of how students respond. I have shown that this can both can give insight into student difficulties reasoning with mathematics and potentially provide guidance for how to focus on epistemological issues that might create barriers between what a physics instructor is trying to teach and what the students are learning.

We have developed three ways to talk about how students use knowledge, and mathematical knowledge in particular. (1) *Epistemological resources*—Generalized categories of “How do we know?” warrants; (2) *Epistemological framing*—The process of deciding what e-resources are relevant to the current task (NOT necessarily a conscious process); and (3) *Epistemological stances*—A coherent set of e-resources often activated together. But be careful! These are NOT intended to describe distinct mental structures. Rather, we use them to emphasize different aspects of what may be a unitary process: activating a subset of the knowledge you have in a particular situation. A *warrant* focuses on a specific argument, using particular elements of the current context. (“Since the path integral of a conservative force is path independent, these two integrals will have the same value.”) A *resource* focuses on the general class of warrant being used. (“You can trust the results in a reliable source such as a textbook.”) *Framing* focuses attention on the interaction between cue and response. (“You need to carry out a calculation here.”)

Such an analysis has implications for how we understand what our students are doing, what we are actually trying to get them to learn, and (potentially) how to better design our instruction to achieve our goals.

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Introduction of Current Scientific Results to Education: Experiences from the Case of Liquid Crystals

Mojca Čepič

Abstract Introduction of current scientific research results into education requires an in-depth knowledge of the topic, experiences regarding the methodology of teaching physics and practical experiences in the classroom. Several serious considerations have to be done before the development of the teaching module, they should be well reflected throughout the module's evolution, and several actions accompany already developed model, in addition. In this paper, we briefly discuss the module on liquid crystals, its content, the methods and the activities. We reflect on the development of the module and based on this reflection we suggest a general approach to developments of new teaching modules on current research results.

1 Introduction

New topics are topics that are not included into the curriculum at present. Due to the limited time devoted to physics in various schools, one can always find several such topics. The absent topics can be classified into three groups:

- Topics, that are not considered due to the lack of time, although students have enough preliminary knowledge to comprehend them (for example "the elliptical polarization of light" and "the optical activity");
- Topics, that are included as fundamental for a physicist's education, however they are considered as too difficult or irrelevant as a general knowledge (for example "quantum mechanics" or a "general relativity");
- Topics, that allow for an insight into an on-going fundamental research.

These topics have several common properties. They are often considered as too difficult to understand. Very often teachers have no in-depth knowledge related to them, as well. For the most of such topics is typical that they were not presented and

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studied thoroughly during the pre-service training, they were not considered in details in compulsory courses or teachers were not even able to obtain the information during their studies as the science was discovered after they have already finished the in-service training. For that last group of topics one cannot expect that teachers investigate, learn and develop teaching materials for an introduction of such topics into the classroom.

In this contribution, we limit the meaning of "new topics" solely to the topics that are concerned with novel results of contemporary fundamental research. However, we believe that the approach for introduction of novel research results into the classroom is easily adapted and used for other topics from the list above, as well.

What is, according to my opinion, the main motivation for an introduction of a new topic into education? The introduction of a new topic in the physics classroom allows for a positive response of education to several open problems. It is well known that topics in physics are considered as boring, not correlated to students' experiences, irrelevant for everyday life and old from students' perspective (Osborne et al. 2003). Examples studied in the classroom are very often highly idealized (massless, frictionless, ideally rigid, …) in contrast to everyday experiences, where an effort to maintain the motion is always needed, for example. In addition, the relevance of the classroom knowledge for everyday life is often not argued. Therefore, even as being a passionate physicist, I can understand that the physics is often not considered credible.

Students seldom get in contact with scientists. They sometimes visit laboratories but there students usually meet a sophisticated measuring equipment or research institutions organize science shows that do not offer an insight into an on-going research and to the everyday life of scientists. Therefore, an impression that physicists are extremely clever but also weird people and the research is something so advanced that a general student could not even hope to grasp any of new ideas is substantiated. Could an introduction of novel research results to students send them a different message?

On the other hand, communication of novel scientific results to lay public has become a requirement in applications for several research funds. Also tax-payers become more and more demanding regarding information on research results for which the taxes were spent. Therefore, to learn the methods of communication the scientific results to lay public becomes an imperative for researchers as well.

Finally, we believe that the introduction of new topics into physics education may increase or at least lessen a decrease of students' motivation for physics. An appropriate approach that allows students to construct their own understanding based on their personal experiences of new topics is therefore a necessity. If presented topics are relevant for everyday life, it is even better.

The paper is organized as follows. First I briefly present a teaching module on liquid crystals. Next I discuss reflections on its development. Finally, in conclusions important steps necessary for the introduction of new topics into education are resumed.

2 Our Experience: The Teaching Module on Liquid Crystals

The teaching module on introduction of liquid crystals to introductory physics courses at the introductory level and the high-school physics courses consists of three parts. The introduction part is the 90 min standard lecture accompanied by basic demonstration experiments, followed by the 90 min chemistry lab for the synthesis of a liquid crystal called MBBA and 90 min physics lab for studies of the liquid crystal synthesized during the chemistry lab (Pavlin et al. 2013a; Verbit 1972). Let us briefly review the content of each part of the module.

2.1 The Lecture

The study of preliminary students' knowledge regarding liquid crystals has shown that students actually do not know anything about them except they are vaguely familiar to the name in connection to displays (Pavlin et al. 2011). Therefore, the basic information on liquid crystals are given as a traditional lecture accompanied by several experiments vital for understanding of the most characteristic properties and phenomena related to them.

The light motif of the lecture is the operation of the liquid crystal display. The lecture starts with an introduction of a basic element that determines the colour on the liquid crystal display—the pixel (Fig. 1). The pixel properties for different screen colours are analysed and the conclusion, that one needs a mechanism that allows for the control of transmission of light through each colour component (the green, the red and the blue) in the pixel is needed. This control is enabled by

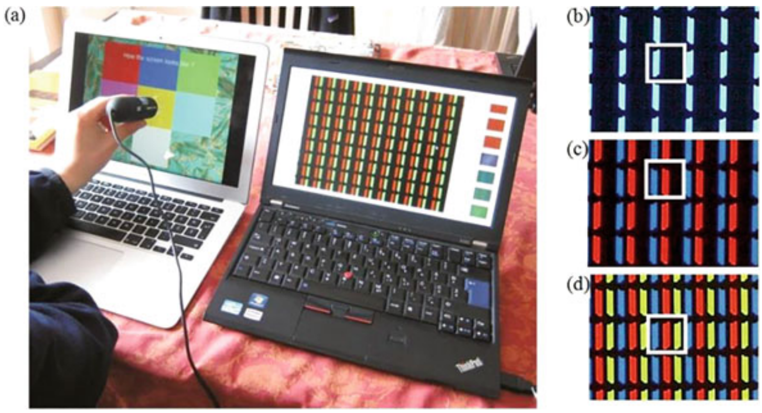

Fig. 1 **a** The structure of the screen is enlarged by an USB microscope (USB microscope provider 2015). **b** The *blue area* enlarged. **c** The *magenta area* enlarged. **d** The *white area* enlarged. The *white rectangle* marks the pixels in (**b**)–(**d**)

peculiar properties of the liquid crystal, which introduces the motivation for learning about liquid crystals.

The discussion of phases and phase transitions for an example of water, the material that everyone experiences in all three phases, starts this discussion. The three states of the liquid crystal: the solid, the liquid crystalline and the isotropic liquid, are shown and how their appearance changes upon heating. It is additionally stressed that an opaque appearance of a liquid crystalline phase is very similar to the appearance of the mixture of crushed ice and the liquid water. The appearance does not change upon heating and cooling for several tenths of degrees, which is a strong indication for an additional phase between the solid and the transparent liquid phase (Fig. 2a). The basic difference between regular liquids and liquid crystals is the structure at the microscopic level. Liquid crystalline phases are formed of elongated molecules in general and long molecular axes are on average parallel although centres of molecular masses form a liquid-like order. In addition, rotation around short molecular axes is hindered but molecules are free to move (Fig. 2b). The consequence of such complex ordering is the anisotropy. Therefore, the concept of anisotropy and examples of anisotropic materials from everyday life are introduced (Čepič 2012; Ziherl et al. 2010, 2013).

As the most of the applications are based on optical properties of liquid crystals, the emphasis of the lecture is on the anisotropic optical properties of liquid crystals. The concept of optical anisotropy is introduced for polarizers (Fig. 3a), it is shown that transparent anisotropic materials allow the transition of light through crossed polarizers (Fig. 3b) and finally this phenomenon is demonstrated for a liquid crystal in the cell (Fig. 3c) as an evidence of anisotropic properties of liquid crystals in the liquid crystalline phase.

The double refraction on the wedge cell filled with a liquid crystal is shown and directions of polarization are determined for both beams. The introductory lecture is concluded with an explanation and a demonstration of the mechanism for the control of the brightness of the liquid crystal display.

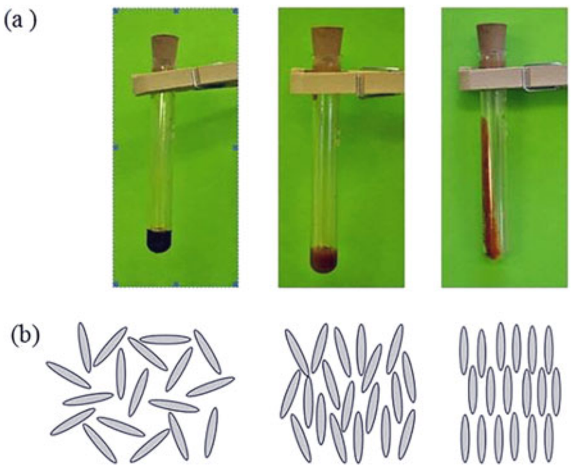

Fig. 2 **a** From *left* to *right*: the appearance of the liquid crystal MBBA in the isotropic phase, in the nematic phase. **b** Corresponding structures of the phases. *Ellipses* symbolise elongated molecules that form a liquid crystal

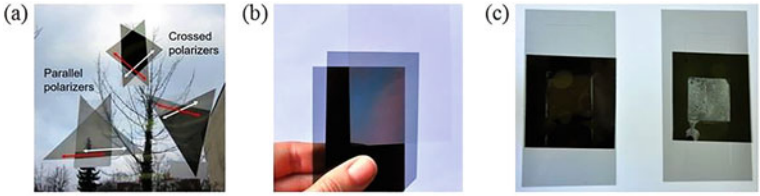

Fig. 3 **a** Polarizers parallel, crossed and under a general angle. **b** Anisotropic regular transparency between crossed polarizers. **c** A cell between crossed polarizers filled with a liquid crystal in the isotropic phase (*left*) and in a liquid crystalline phase (*right*)

2.2 The Chemistry Lab

Students combine the synthesis of a liquid crystal and a synthesis of another material from the spectrum of organic chemistry laboratory work. The synthesis is rather straightforward although some chemicals require a special care and a part of the procedure requires a fume hood. The synthesis takes around 60 min and it is considered as successful if the newly synthesized material is transparent at around 40 °C and becomes opaque upon cooling to the room temperature. Details regarding the synthesis can be found elsewhere (Čepič 2014; Pavlin et al. 2013a; Verbit 1972).

2.3 The Physics Lab

Properties of liquid crystals are studied in the physics lab and the liquid crystalline material from the synthesis is used. Four experiments are performed: (a) Students measure the *temperature of phase transition from the opaque liquid crystalline phase to the transparent isotropic phase*. Results of this experiment are used for the control of the success of the synthesis. If the transition temperature is close to the temperature reported in journals, that is 40 °C, the synthesis was successful. For not enough pure samples (sloppy purification, contamination of the material) the transition temperature is lower, although the material can still be used for most of the experiments. Our experiences were that even pre-service primary school teachers were successful in the synthesis of the liquid crystal in a very high percentage, actually only one group out of 40 failed.

The second experiment *introduces polarizers and how polarizers are used for distinction between isotropic and anisotropic transparent materials*. These experiences are then used to recognize *anisotropic properties of a liquid crystal in a cell*. For this purpose students construct a liquid crystalline cell constructed by simple means (Fig. 4a–d). As glasses for the cell students use regular object and cover slides that are needed for observations of biological samples under the microscope. Ordering of liquid crystalline clusters is obtained by rubbing. Observation of such

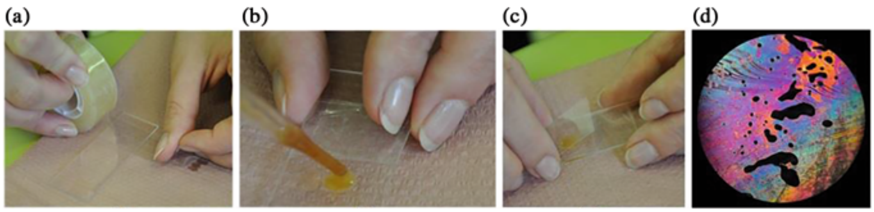

Fig. 4 Assembling the liquid crystal cell. **a** For spacers few layers of an adhesive tape are placed on an object glass approximately 1 cm apart. **b** A drop of a liquid crystal is placed between the spacers. **c** The cover glass is put on the top of the liquid crystal bridging the two spacers. **d** The cell is inserted between crossed polarizers and is observed through the microscope. *Colours* indicate that the layer of a liquid crystal is relatively *thick*, *dark areas* are bubbles of an isotropic air

cells between crossed polarizers under the microscope shows that liquid crystals are anisotropic. Heating the cell above the transition temperature to the isotropic phase during the observation of the cell between crossed polarizers under the microscope reveals the sudden change of optical properties at the phase transition. The sample becomes black at one point, usually at the edge of the cell and the black non-transparent area indicating the isotropic phase spreads very fast across the whole sample. The transparency of the liquid crystal is re-established upon cooling below the transition temperature, the clear evidence that anisotropic properties are related to the liquid crystalline phase and not to the material in general (Fig. 5).

The third experiment shows that *the non-polarized incident light splits into two mutually perpendicularly polarized light beams* that have different speeds of propagation and consequently different refraction indexes. To show this

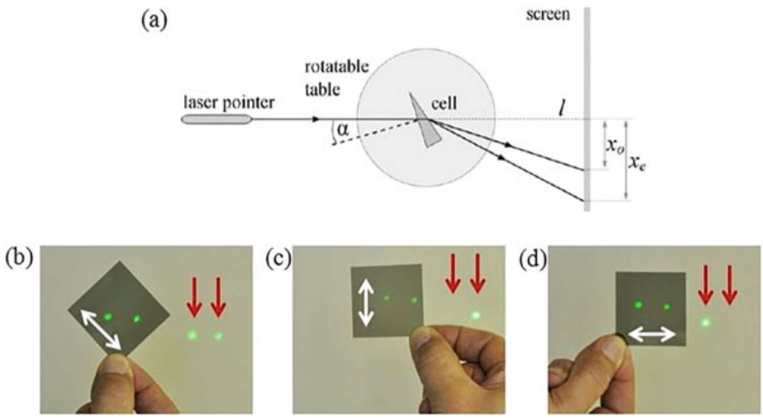

Fig. 5 **a** The setup geometry for demonstration of double refraction. **b** Both beams are partially absorbed if passing the polarizer oriented in general directions. **c**, **d** Beams are polarized perpendicularly to each other. *Double arrows* indicate the orientation of the polarizer, *red arrows* serve as a guide to the eye indicating positions of *light spots* on the screen that appear due to the splitting of the incident light beam

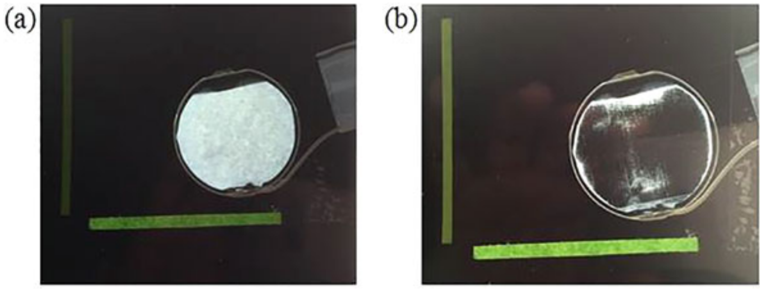

Fig. 6 **a** The cell with conductive layers on the glass surfaces filled with a liquid crystal between the crossed polarizers. No voltage applied. It is transparent. **b** The same cell with the voltage of 9 V applied. It is *dark*. *Green lines* indicate transmission direction of polarizers

phenomenon, the liquid crystal is filled in a wedge cell rubbed along the wedge. The rubbing guarantees the orientation of long molecular axes parallel to the wedge, which controls experimental circumstances and allows for conclusions based on experimental results that relate polarization, refraction index and the structure of the liquid crystal in the cell.

While the first three experiments are oriented toward the study of liquid crystalline properties, the last experiment simulates the function of the pixel. Students use cells with transparent but conductive surfaces filled with well oriented liquid crystal (Fig. 6a). Application of the voltage across such a cell changes the structure of the liquid crystal within the cell and when such a cell is put between crossed polarizers, it becomes dark with the voltage applied but it is transparent if there is no voltage (Fig. 6b).

The whole module with the set of experiments during lab works allows the students to get the basic knowledge and hands-on experiences with liquid crystals, to study their properties and to construct a comprehension on how liquid crystalline properties are used in application.

3 Reflections on the Module

What have we learned from the experience of introducing the liquid crystals into the classroom? Let us consider the problems we had to solve and let us try to consider if our solutions were specific and topic related or they can serve as suggestions or guidelines for introduction of other new research results to education.

(a) *Why would one want to consider the whole work related to introduction of novel scientific results into classroom?*

There are general reasons already given in introduction but they are usually not strong enough to stimulate researchers and educators for a job. The literature search have shown that introductions of on-going research results into the classroom are rather rare. Papers usually report research that does not consider many different issues. The reports are either limited to suggestions of experiments (for example: Besson et al. 2007; Pearson and Jackson 2010), some are accompanied with suggestions to teachers, how to use the reported materials (for example: Etkina and Planinšič 2014; Planinšič and Etkina 2014, 2015a, b), but additional experimental testing of suggested units is extremely rare (Pavlin et al. 2013a; García-Carmona and Criado 2009). The systematic study of an influence on students' motivation for science that is expected for such activities was, to my best efforts, not found. Reports on other possible studies that may accompany introduction of the on-going research into the classroom, for example, how students in late teens obtain new knowledge without former experiences, have not been found as well. The motivation for such a work may arise from a different perspective of a researcher, as was the case for our example.

The author is the theoretical physicist working on a theoretical modelling of liquid crystals with an emphasis on antiferroelectric liquid crystals and polar liquid crystals in general (Takezoe et al. 2010). A personal fascination with a beautiful world of liquid crystals, the richness of phenomena related to them and a number of devices with liquid crystals we use every day, resulted in a desire to share this fascination with students and other audiences. First ideas on construction of experiments that evidently demonstrate to students some of their peculiar properties date in late nineties, some even later (Shenoy 1994; Oswald and Pieranski 2006; Pavlin et al. 2013b). The teaching module on liquid crystals that includes a series of experiments, teaching materials and the teacher training was developed and tested recently (Pavlin et al. 2013a). Another issue is important. Not only, who is motivated for the introduction of novel scientific results into the classroom, but also, what is the necessary expertise such a person or group should possess?

It seems that the answer lies in a simple lack of motivation, but it might be as well be the case that instructions or a guide for such work are actually missing. Therefore, the question of motivation is certainly important for an introduction of any new topic.

(b) *Who should work on the problem of adaptation of novel research results for communication to students?*

Although the teachers are motivated to introduce new topics to students, even the best and the most active teachers that after several years of teaching often search for new challenges, have no opportunities to achieve the expert level of knowledge related to new topic. The teacher usually does not have an access to scientific journals, but even if they have it, the articles are usually written in a topic specific language, the equipment relevant for experimental results is highly professional and the relevance of several problems is often either exaggerated or neglected. In addition, to introduce the new topic to students, the person has to have a serious in-depth knowledge on the subject that usually develops through years of working in the field.

Therefore the most appropriate person is an active researcher that has a comprehensive knowledge on the subject and is actively involved in its research. However, such a person is usually motivated for education at advanced levels when students are included directly into the research through PhD programs or even later. Some stimulations for the effort of communication of new topics to lay public and students at lower levels of education came recently from requirements of funding. Many project calls require direct communication of novel results to lay public.

The most effective is the combination of a researcher, who is positively motivated for such a work, of an educator, who enjoys in obtaining new advanced knowledge also outside of his field of research, and the teacher that is enthusiastic enough to be willing to learn and test the new ideas in the classroom. The researcher takes care on the choice of important messages and their scientific correctness, the educator suggests the teaching methods, together with the researcher designs the experiments that provide experiences to students and prepare the materials for teachers and students. The teacher provides experiences from the classroom with respect to the level of students, the placement of the topic to the curriculum, availability of the resources and the testing of the teaching of the new topic in reality.

I believe that these aspects are valid for consideration of any new topic.

(c) *Which activities are important before a development of a new module?*

Here we will discuss only few questions, but they are probably the most important.

- *Is it possible to include the new topic directly into the curriculum?*

Although the aim of our work from the very beginning was a development of the module for students at the Faculty of Education, University of Ljubljana, ambitions to introduce liquid crystals to the high school audience have stemmed from the first experiences at introductory level for the first year university students. We have analysed the high school curricula in details to determine topics for inclusion of liquid crystals. A closer look has shown that liquid crystals are very appropriate for illustrations of various phenomena that are already included in Slovenian physics curriculum for high schools. Liquid crystals can illustrate phase transitions, optical properties like refraction and the polarization of light, and properties of materials in an electric field. They provide context for the learning because they are used in devices used every day.

If the topic is very distant to the curriculum goals or it is rather time consuming, it is more than likely that teachers will not include it in their regular teaching.

- *Do students already possess a necessary preliminary knowledge? On the other hand, do they have to comprehend several new concepts to be able to understand the new topic?*

This issue is very relevant for the time that has to be allocated for the new topic. In addition, if the introduction of novel scientific results into the classroom requires learning the concepts that are not included into the pedagogical contents or learning standards, the management of the school but also, very often, the students will not appreciate additional efforts. In some countries, even parents can influence the decision of a teacher and stop the activities. Therefore, to be on the safe side, one should carefully consider if the preliminary students' knowledge obtained within the curriculum satisfies.

- *Are simple, quick, mostly hands-on experiments for practical work of students providing them experiences for the new topic, available or possible to develop?*

Our guess was that the knowledge about liquid crystals is very limited. We expected that students hardly possess experiences and preliminary knowledge to base the construction of the new knowledge on them. The study on preliminary knowledge confirmed this guess (Pavlin et al. 2013a; Pavlin et al. 2011). Therefore, the teaching unit have to provide personal experiences by different means, through information, by experimental demonstrations and students' personal involvement in laboratory experiments.

Many lectures for the lay public are limited to a show demonstrating interesting and shocking experiments, but for education purposes, this is not enough. Experiments have to illustrate phenomena that are studied in the curriculum evidently. For the case of liquid crystals, some experiments were already discussed in the literature (Shenoy 1994; Ciferno and Marroum 1995; Oswald and Pieranski 2006), but most of the experiments were constructed with the specifics of the pedagogical content and learning goals in mind (Čepič 2014).

The issue of providing personal experiences related to the new topic is very important for any new topic. If a student has no possibilities to repeat an experiment that was not clear to her/him or if she/he is not able to discuss some details related to it, it is highly unlikely that the new topic would be attractive. Learning by listening or observing is much less efficient and if a student is lost, her/his motivation is lost as well.

- *To determine learning goals that allow testing the learning outcomes.*

Although it is believed, a determination of learning goals is the starting point for a development of a module, it is hardly so in reality. We have designed several experiment to satisfy our curiosity and our not very well articulated desire to show students some interesting phenomena. Additional motivation for this work was a problem of adaptation of several experiments that require high tech equipment in the professional laboratory. No such equipment exists in a students' laboratory. Experts in the research field considered the task impossible at the very first moment. However, experimenting in students' labs can often be limited to observations and very accurate measurements are not so important as in the professional laboratory. Design of experiments using simple means is an interesting but demanding task by itself. Sporadic inclusions of such experiments, informal discussion with students regarding their interest for a new topic, the effects of experiments on understanding and comprehension of the new knowledge etc. has stimulated a serious work on the consistent module with verifiable learning goals. Therefore, a discussion on learning goals followed preliminary not well articulated experiences on the topic. The process was very similar to the regular scientific method: observations and data first (the play with experiments), hypothesis (learning goals) next, and the test at the end. Having fun with design of new experiments and showing them to students, is not enough. One has to measure the learning outcomes, otherwise the lecture on the new topic may miss the target audience without recognition. Although one could think that the construction of the teaching goals is straightforward, it is far from it. The researcher is ambitious and she/he would like to explain the subtle details. The educator finds problems in the preliminary knowledge and experiences, in the cognitive level of students, in the comprehension of concepts and experiments that illustrate the new topic. The teacher is occupied by possible lack of students' motivation and the lack of effort students are willing to invest in the new topic, the time allocated for the new topic and other aspects of a practitioner. For a teacher is also very important issue how to include the new topic in a regular testing although the topic is not strictly a part of curriculum. The final goals were results of several iterations of the teaching module and the testing of new knowledge provided the fit back that has influenced the structure of the module as well.

(d) *Which activities are important after a new module is developed?*

The work is obviously not finished when the content of the lectures and laboratories is determined, and the lecture and experimental work is prepared. In most of the studied reports on introduction of new topics this part was missing. If the developer of the new module is its performer at the same time, she/he can respond to fit-backs directly. If the researcher, a faculty and a lecturer is not interested in the physics education research, she/he will probably not consider serious measuring of teaching intervention effects. However, if the aim of the introduction is that teachers, non-experts in the field, teach the topic, several additional steps are needed.

- *The testing of the learning outcomes.*

Although the testing of learning outcomes is for a researcher in physics or science education obvious, it is usually not the case for researchers in fundamental research that are lecturers at the same time. They usually include the topic in their regular lecture, they include some questions related to the subject into final tests and student's answers contribute to the final mark. The answers are not seriously analysed, the lecturer considers them as an information only. This is probably a reason that the majority of papers on introduction of new topics does not report on testing and evaluation. But for an introduction of the topic to a high school a serious evaluation of intervention effects is necessary. The teacher, a non-expert, should be aware of expected outcomes already before the introduction of a new topic. In addition, the testing gives a set of tested questions and provides a standard for learning outcomes. In a serious study, the researcher consider questions at the same time as the learning goals. Examples of evaluations are given in (Garcia-Carmona and Criado 2009; Pavlin et al. 2013a).

- *Accompanying materials for students.*

To allow for a successful introduction of a new topic to a high school classroom, the researcher in collaboration with an educator should prepare instructions for the experimental work, working sheets, questions for self-assessment, and the study materials adapted for a cognitive level and the preliminary knowledge of students.

- *In-service and pre-service training for teachers and students, respectively.*

A serious training in a form of a seminar with the workshop that is longer than the module for students provides more in-depth knowledge to teachers, personal experiences with demonstration and laboratory experiments and considerations of adaptations for students with lesser preliminary knowledge and skills. The training should provide also the literature for teachers that is more detailed as the materials for students but is not at the level of scientific journals. In addition, the training should be extended through ICT means providing a direct communication link between a teacher practitioner and the module developer allowing a support when technical problems in the classroom related to experiments appear or questions by motivated and/or talented students that go beyond the experiences of the teacher occur. One cannot expect that teachers could be willing to try an introduction of a new topic without a serious upgrading of their personal knowledge and experiences in a new topic and without a serious backup of experts.

It is clearly seen that even a development of a short, few hours long module requires serious efforts, many working hours and a rather long period of development. According to my opinion, the task of introduction of a single new topic should be considered as a serious research problem, which requires a devoted researcher and a significant allocation of a regular research time, if the funding expects also such "outreach" outcomes.

4 Conclusions

Our experiences regarding an introduction of new topics into educations are: one serious attempt - the liquid crystals (Pavlin et al. 2013a), one earlier preparation of materials for the superconductivity (Earle et al. 2004), and a new topic—the aqua gels that is an on-going research (Pavlin 2014). We briefly presented the module on liquid crystals and reported reflections on important steps related to its development. Based on those experiences and reflections we suggest a phenomenological model for the introduction of novel scientific results into the science classroom. Let us quote the tasks i.e. activities we found important for an introduction of a current research into the classroom at a specific level, briefly again:

- Choose the topic;
- Determine the level;
- Define the goals;

- Determine the preliminary knowledge;
- Verify the curriculum;
- Determine the place in the curriculum;
- Decide for the methods;
- Design experiments;
- Design the teaching module;
- Prepare the accompanying materials;
- Test and evaluate the module;
- Design the teachers' education and materials;
- Train the teachers;
- Make experiments available to teachers.

During the design of communication of current scientific results into education, several problems and obstacles are met. Some of them are considered in this contribution and how to overcome them is discussed. Our experience does not substantiate the opinion often given by scientists involved in a fundamental research, and the same opinion was even heard from our colleagues, lecturers of subject knowledge "the real science is too difficult for students". It is not. However, one needs to invest a serious effort to develop an effective communication of new scientific results to students at various level.

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The Influence of Epistemic Views About the Relationship Between Physics and Mathematics in Understanding Physics Concepts and Problem Solving

Ileana M. Greca and Ana Raquel Pereira de Ataíde

Abstract From all the difficulties students have while trying to understand physics, the ones with mathematics are of the more remarkable, at least for physics teachers. Although the problem is explicit, its solution becomes complex due to the lack of clarity about the characteristics of the relationship between maths and physics. If for the teacher these relationships are unclear, it is probable that their students will not realize their character and assume a naive attitude, believing that knowing the equation and how to resolve it will result in success in solving physics problems, forgetting the conceptual part. We investigated how these relationships were perceived by two consecutive groups of undergraduate students in a physics degree that educate high school physics teachers and how this way of understanding is reflected in their conceptual learning and their attitudes when they are asked to resolve problems of thermodynamics. We will discuss how their perceptions would influence their teaching in middle school.

1 Introduction

At higher levels of education, the need to describe the physical phenomena or solve problems, requires both the understanding of theory and its mathematical formulation. Nevertheless, this is a quite difficult task and often students tend to a mechanical learning of concepts and algorithms (Greca and Moreira 2001), a fact that appears markedly in problem solving. In general, the difficulties faced in problem solving eventually lead the students to show a resistance in face of this activity. On the other hand, if the student understands how physics relates to

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mathematics in the construction of concepts, she/he will have a more appropriate image of the use of the mathematical models for physics, which for most students only represent abstract relationships between variables.

Throughout history, mathematicians and physicists had divergent ideas about the role of mathematics in the development of physics. The French philosopher Paty (1995), highlights three forms of mathematics to be used in the construction of physical knowledge. The first form is the analog vision, inherited trait from Scholastics, exemplified by the historical episode of the "invention" of what are now called kinematics, by scholars of Merton college in Oxford. The second form is the vision of mathematics as a language that reflects the real, that can be identified in the writings of Galileo, where, according to Paty, Galileo invoked the idea that the "book of nature" is written in the language of figures and numbers (Paty 2001). The third vision is mathematics as a language that is intrinsically linked to the construction of physical thinking, a characteristic that appears in the XVIII century with the explicit drafting of physical concepts mathematically thought that reaches its peak in the XX century with the Theory of the Relativity and of the Quantum Mechanics. In this way, mathematics can be conceived in its current use in physics as an instrument that builds or isolates structures and not as a language that translates itself (Paty 1995).

Regarding the implications for the teaching of physical relations between these two school disciplines, Pietrocola (2010), proposes the notion of mathematics as structuring of physical knowledge, such as the "skeleton" that holds the "body" of physics. Treating mathematics as a language, and thus bringing out its interpretative character, may differentiate the scientific knowledge and common sense knowledge, once the used language is an important differentiation form between those two forms of knowledge and science usually makes use of mathematics as a way of expressing itself. In this sense, mathematics as a language lends its structure to scientific thought to make the physical models of the world, and its choice as structuring of science lies, among other things, in its characteristics of accuracy, universality and deductive logic (ibid.). This position corresponds with the third of the views presented by Paty, because the sense of language adopted by Pietrocola is not that of translation, but rather as part of the construction of the knowledge that it expresses. This idea is also similar to the Feynman's statement: "Mathematics is not just another language. Mathematics is a language plus reasoning; it is like a language plus logic. Mathematics is a tool for reasoning" (Feynman 1989).

Thus, being the language of physical knowledge, mathematics should take an important role in physics learning, as it has in the process of building this knowledge. However, physics teachers, when they think that the biggest problem for the learning of their discipline are the weak mathematical skills students have, show a naïve epistemological positioning. Usually, they present math only as a tool to be used by physics to solve their problems and this view spreads among students leaving in them the impression that knowing the mathematical expression and how to resolve it is enough for doing very well in physics. This position has characteristics of the two naïve visions explained by Paty: the analog vision and the vision of mathematics as a translator of physical phenomena, and may constitute pedagogical obstacles (Pietrocola 2002), for the learning of physical concepts, because they result in a concern of the students to only know the equation and how to resolve it without having the objective of understanding the concepts. The naïve view is partly fueled by textbooks, since they rarely present a display of content, activities and problems escaping from the mathematical instrumentalism already consolidated in the teaching of physics. Therefore, it is possible that the "instrumentalism" which is observed in many students during problem solving is not due solely to the cognitive difficulties that this task requires, but also to an epistemological perspective.

Thus, the focus of this work is to find how pre-service physics teachers conceive the relationship between mathematics and physics and if their vision influence their understanding of physics, especially during problem solving.

2 Methodology

For answering our research question, we investigate, in a qualitative study, how students of two groups from the last year of a Physics degree to train high school teachers at the State University of Paraiba (N = 22) perceive these relationships and how this way of understanding is reflected in conceptual learning and their attitudes when asked to resolve problems of thermodynamics.

As objects of research we chose five different types of materials:

- The annotations accomplished during the attendance of the classes.
- A questionnaire with direct questions about the view that these students have about the role of mathematics in solving physics problems.
- Two evaluation activities for each student, related with the first law of thermodynamics, with two problems and five conceptual questions each one.
- Individual interviews, aiming to clarify the difficulties detected in solving problems (during the classes and the evaluation activities) and to determine the strategies that these students use to solve them, as well as their view of some mathematical important concepts for understanding the concepts of thermodynamics.
- Academic grades in the calculus study modules in previous semesters.

With this material we first classified the students according to categories related with their strategies for problem solving; their view on the role of mathematics in the construction of a physical theory; their skills in mathematical understanding of basic differential calculus and their understanding of them for problem applications in physics; their academic performance in the subject, and their conceptual understanding of central physics concepts related with the first law of thermodynamics. After that, we converted these categories in variables and performed a contingency analysis and a multiple correspondence analysis.

Categories (a detailed analysis can be found in Ataíde and Greca 2013):

(a) The most striking feature in the strategies used in problem solving:

- Operational Mathematics (OM)—Student who uses mathematics as a technique and tends to solve problems by trial and error.
- Conceptualization (C)—Student who favours the conceptual understanding and tries, not always successfully, to make a link of the concepts with math to be used in solving problems.
- Mathematical Reasoning (MR)—Students who uses mathematical reasoning coherent with the situation outlined in the resolution of problems, although they may not work properly with the mathematical techniques.

(b) The students' view on the role of mathematics in the construction of a physical theory, adapting the classification proposed by Karam (2007).

- Tool: mathematics is used by the physics as a facilitator of the numerical calculations.

The calculation was initially created by Newton to solve physical problems. Thus, mathematics is used as an object used to facilitate the resolution of the proposed problem. (E8)

- Language: mathematics is a translator of the physical thought to the world, a mere manifestation of physics, with the task of representing it in an understandable way.

The mathematics, in physics, plays the role of a language that is used to model and describe the physical phenomena. (E1)

- Structure: the mathematics appears as a physical structuring of thought itself:

Mathematics has a fundamental function in physics it is the structural basis, it is like the skeleton of our body. (E5)

(c) Their skills in their mathematical understanding of basic differential calculus and their understanding of the concept of differential calculus for problem application in physics. In these cases we used the code 'Y' for "yes, he/she understands it" and the code 'T' for "he/she shows technical skills only".
(d) Their academic performance in the subject, considering a high academic performance when the students approved the discipline with good grades (more than 6.5/10); a medium one when they just approved (grades between 5 and 6) and low, when they failed.
(e) Their conceptual understanding of central physics concepts related with the first law of thermodynamics.

- Good (G) Student presents, in all of his answers, an acceptable understanding of the physical concepts compared to scientifically accepted concepts.

- Regular (R) Student does not show a clear understanding of physics concepts, although he can resolve some problems.
- Poor (P): Student does not understand or master the necessary physical conceptualization of the studied subject.

3 Results

In Table 1 we present the summary of all the categorizations described above. From the table it is possible to separate students in three groups. Students E4, E5, E6, E14, E15 seem to have the mathematical knowledge required for this area. They also have very good conceptual understanding of the physics concepts. They seem to solve problems using what we defined as mathematical reasoning for problem solving and assume a structural role in physics; nevertheless their perception of this it is somewhat vague. These students are among those that showed better performance in the area under study. On the opposite side, students E7, E8, E9, E10, E11, E20, E21, E22 have the poorer performance in this area, dominate the mathematical "techniques", but have neither a proper understanding of physical concepts, nor of the relationship between mathematics and the construction of these concepts. Their main approach to problem-solving is 'operational mathematics'. It is interesting to note that all these students have a view of mathematics as a tool for the study of physics. In an intermediate position are students E1, E2, E3, E13, E16, E17, E18 and E19. All of them have an average performance and mathematical skills. However, although a majority of them (five students) seemed to show that conceptualization was of great theoretical value, their average understanding of physics concepts left mathematization in the background; the other three students showed the characteristic of operational mathematics and a regular understanding of physics concepts.

As for the view of the relationship between mathematics and physics, for three of the students, mathematics permitted the translation of physical phenomena; two considered that the only function of mathematics is to be a tool for physics; the other five considered mathematics as the structure of physics. Nevertheless, for students E1, E2, E3, E13, E16, E17, E18 and E19, it appears not to contribute to a differentiated attitude during problem solving. For example, two of them applied operational mathematics as their main strategy. This might well indicate a lack of coherence between their epistemological view of mathematics and physics and the way in which they apply that view to problem solving.

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Table 1 Summary of categorization of students

Student	Understanding of physics concepts	Mathematical understanding of basic differential calculus	Understanding of the concept of differential calculus for problem application in physics	Most remarkable characteristic in problem solving	Epistemic view of the role of mathematics in physics	Academic performance in the subject
E1	Regular	Y	Y	C	TRANSLATOR	M
E2	Regular	T	T	C	TRANSLATOR	M
E3	Regular	Y	T	C	STRUCTURE	M
E4	Good	Y	Y	MR	STRUCTURE	H
E5	Good	Y	Y	MR	STRUCTURE	H
E6	Regular	Y	Y	MR	STRUCTURE	H
E7	Regular	T	T	OM	TOOL	L
E8	Poor	T	T	OM	TOOL	L
E9	Poor	T	T	OM	TOOL	L
E10	Poor	T	T	OM	TOOL	L
E11	Poor	T	T	OM	TOOL	L
E12	Regular	T	T	OM	TOOL	M
E13	Good	Y	T	C	TOOL	H
E14	Regular	Y	Y	MR	STRUCTURE	H
E15	Good	Y	Y	MR	STRUCTURE	H
E16	Regular	Y	T	OM	STRUCTURE	H
E17	Regular	T	Y	OM	TOOL	H
E18	Good	T	T	C	TRANSLATOR	M
E19	Regular	T	T	OM	STRUCTURE	M
E20	Poor	T	T	OM	TOOL	L
E21	Poor	T	T	OM	TOOL	L
E22	Poor	T	T	OM	TOOL	L

Codes Y—yes; T—technical skills only; C—conceptualization; MR—mathematical reasoning; OM—operational mathematics; H—high; M—medium; L—low

As for the view of the relationship between mathematics and physics, for three of the students, mathematics permitted the translation of physical phenomena; two considered that the only function of mathematics is to be a tool for physics; the other five considered mathematics as the structure of physics. Nevertheless, for these students, it appears not to contribute to a differentiated attitude during problem solving. For example, two of them applied operational mathematics as their main strategy. This might well indicate a lack of coherence between their epistemological view of mathematics and physics and the way in which they apply that view to problem solving.

In order to better understand these results, we used two techniques from descriptive statistics, which enable studying categorical variables. We used contingency tables, which serve to record and analyse the relationship between two or more categorical variables. After that, we used a Multiple Correspondence Analysis, which is a technique that applies over the results of the analysis of contingency tables. The goal of this technique is to summarize several data in a limited number of dimensions, with the least possible information loss. Thus, the analysis of multiple correspondence has a similar goal to the factor analysis, but applying to categorical variables. The correlation analysis constructs a Cartesian representation based on association between the variables analysed, in which the proximity between points represents the level of association between the variables. Although we don´t have a big sample, these analysis are useful for seeing tendencies in the data. So, the results we obtained by the use of these techniques are intended to be suggestive and to guide further research.

To perform these analyses we converted the previous categories in categorical variables and calculate the coefficient of contingency between the same with SPSS software, version 18. In Table 2 we present the coefficients for those variables in which there is an association in a level of significance of 5 % ($p < 0.05$).

We observe that all variables are interdependent with different levels of dependency. To better visualize the relationships between them we applied the multiple correspondence analysis. Figure 1 shows the graphic result of this analysis, where the six variables in study appear discriminated in two dimensions.

Dimension 1 seem to show that the variables *Understanding of physics concepts*, *Mathematical understanding of basic differential calculus; Understanding of the concept of differential calculus for problem application in physics* have strong contingency coefficients and are the ones that contribute the most for explaining the variation in the data. On the other hand, dimension 2 seems to be related to *Academic performance*. The distance between this variable and the ones over dimension 1 (*Mathematical understanding of basic differential calculus* and *Understanding of the concept of differential calculus for problem application in physic)* seems to show that knowing mathematic techniques for this area it is not enough for being successful in the subject. Between both dimensions, appear the variables *Most remarkable characteristic in problem solving* and *Epistemic view of the role of mathematics in physics,* with a very strong relationship between them. Their position seems to indicate that both contribute for the students' academic performance and also for their understanding of physics concepts.

Table 2 Contingency analysis

	Understanding of physics concepts	Mathematical understanding of basic differential calculus	Understanding of the concept of differential calculus for problem application in physics	Most remarkable characteristic in problem solving	Epistemic view of the role of mathematics in physics	Academic performance in the subject
Understanding of physics concepts						
Mathematical understanding of basic differential calculus	0.46					
Understanding of the concept of differential calculus for problem application in physics	0.46	0.71				
Most remarkable characteristic in problem solving	0.60	0.55	0.55			
Epistemic view of the role of mathematics in physics	0.57	0.54	0.54	0.72		
Academic performance in the subject	0.57			0.69	0.66	

All the variables have significant coefficients ($p \leq 0.05$)

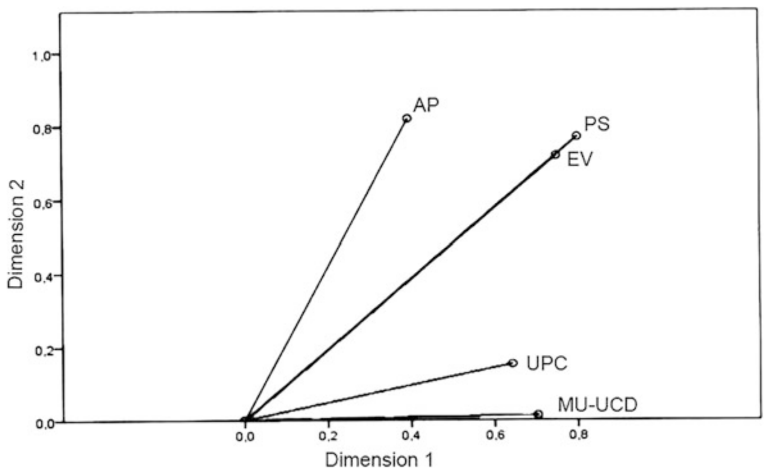

Fig. 1 Result from the multiple correspondence analyses. *Codes UPC* Understanding of physics concepts; *MU* Mathematical understanding of basic differential calculus; *UCD* Understanding of the concept of differential calculus for problem application in physics; *AP* Academic performance; *PS* Most remarkable characteristic in problem solving; *EV* Epistemic view of the role of mathematics in physics

4 Conclusion

The main finding of this study is that a close relationship appears to exist between the way students solve physics problems in thermodynamics and the epistemic view they hold of the role played by mathematics in physics. By extension, their epistemic view also seems to influence the learning and understanding of physical concepts, since problem solving is the main activity in the physics classroom. So, epistemic views on the role of mathematics in physics seem to be a contributory factor for student to successful learning in this discipline.

Otherwise, our results also show that having technical skills in mathematics are not enough to know how to solve physics problems neither to understand physics concepts. In this sense, the usual complaint that students do not understand physics because their fragile math skills seem to be a poor answer of a quite complex problem.

Considering the more successful students, it is important for them to understand not only the physical and mathematical concepts separately, but the mathematical formalization related to the construction of the physics concepts, for a more effective learning. This point is interesting because it seem to indicate that for a conceptual understanding of physics concepts, or at least for some of them, it is also necessary to understand their mathematization for fully grasp them.

It is worth pointing out that the subjects of this study are in their final year of teacher training to become high school physics teachers. Their views on the relationship between physics and mathematics that have been observed in this paper will probably dominate their teaching of the discipline in high school. For example, students that hold that math is only a tool for physics, may propagate this view, emphasizing only formula application in problem solving and not stressing the role of mathematics in the construction of physics concepts.

Nevertheless, as stressed in the previous section, these results have to be seen as tendencies that have to be explored with bigger samples.

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Part II
Educational Research and Development

Eyetracking in Research on Physics Education

Roman Rosiek and Mirosława Sajka

Abstract The paper discusses new opportunities to carry out research on physics education, specifically from a neurodidactical point of view. It shows the possible ways of applying new tools and technologies in didactics of physics. Emphasis was placed on analysing eyetracking as a research method. Examples chosen from an analysis of empirical research results are provided to illustrate the diagnostic possibilities of the tool as well as to point out their strengths and weaknesses. Eyetracking technology was used to examine the strategies and difficulties faced by high school students, university students, and scientists in the process of problem solving.

1 Introduction

The development of the theory of psychology, psychophysiology, and neuroscience, as well as the increasingly common use of the advancements of cognitive science which is presented as an interdisciplinary field concerned with the observation, analysis, and modelling of the activity of the senses, brain, and mind encourages attempts at making use of this knowledge in physics education. Cognitive science, as a multidisciplinary and interdisciplinary science, is situated on the border of many fields: cognitive psychology, neurobiology, philosophy of mind, artificial intelligence, and physics (Varela et al. 1991). The increasing availability and ease of use of measuring interfaces as well as very precise electronic devices, the aim of which is to non-invasively monitor changes in psychophysiological parameters not only in laboratory conditions but also during everyday activities, encourages us to attempt at making use of these theories and methods in physics

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education. The factor that led us to undertake this type of research is the increase in interest and availability of biofeedback techniques which are commonly used in psychology, medicine, or sports. This research approach allows us to try to supplement and combine traditional research methods, e.g. observation, interview, or analysis of the written work of pupils and students while monitoring the changes in their psychophysiological parameters. Attempts are made at combining e.g. the descriptions of the level of stress and motivation with the correctness and efficiency of solving tasks and problems, and their achievements in learning, e.g. in the context of the *Yerkes–Dodson law* (Anderson et al. 1989; Lupien et al. 2007).

The aim of the research is defining the usefulness of using psychophysiological methods in physics education, as well as defining the possible ways of use and analysing their advantages and disadvantages. However, due to the very wide scope of theoretical knowledge required for the research, the following study emphasises eyetracking and omits the analysis of the following methods of parameter monitoring: heart rate variability, respiratory variability, brainwave amplitude changes, and skin conductivity changes.

Eyetracking methods are defined as the use of non-invasive wireless methods of measuring eyeball movement while solving physics tasks. This research makes use of a 1250 Hz eyetracker with a high-speed, high-resolution camera and infrared illuminators. It allows for high-precision ($<0.5°$) recording of the position of the eye in the presented scenarios. The most important parameters in eye movement are the measurement of visual scene path analysis, known as *scan paths*, locations in which the eye stopped on specific visual scene elements, called *fixations*, eye movement, known as *saccades*, and the direction and distance between consecutive fixations. Eyetracking research also includes the analysis of pupil size changes.

2 Eyetracking for Research on Physics Education: Usefulness and Limitations

Eyetracking is becoming increasingly popular as a modern test and research method (Soluch and Tarnowski 2013). Lower cost of equipment as well as its increasing variety and availability allow for eyetracking to be used in education more often. Moreover, the use of eyetracking technology for the analysis of the learning process already caused an emergence of partial summaries by Lai, Tsai, Yang, Hsu, Liu, Lee et al. (Lai et al. 2013).

The type of eyetracking research on physics education is run more frequently worldwide (e.g. Kekule 2014; Madsen et al. 2012, 2013; Ohno et al. 2015; Smith et al. 2010) as well as in Poland among interdisciplinary research group (e.g. Andrzejewska et al. 2015).

The following segment of this paper contains an analysis of the usefulness of eyetracking and different types of eyetracking data visualization methods in physics education. Emphasised is placed on presenting an example of application of the method as well as presenting its advantages and disadvantages supplemented with examples from our research. The keynote of this paper is the question: *What type of analysis can be done by using eyetracking software in order to research types of specific task-solving strategies and to establish a way of researching and measuring the hypothetical reasons for the success and failure of the solution?*

3 Methodology of Empirical Research

3.1 Participants of the Research

104 people were invited to take part in the study, one person was excluded due to technical problems. This includes: 24 second year students from one of the high schools in Cracow, 66 students from the Pedagogical University of Cracow, 9 doctoral students and 4 scientists (three in physics and one in mathematics).

3.2 Theoretical Tool: Stone Problem

The task chosen for this analysis in regards to its substantial content is related in the Polish education system to the overall goals and physics education in middle school (13–15 year-old students) and high school (16–18 year-old students) as well as fulfils the goals of mathematics education in Poland related to functions at a middle school and high school level (Fig. 1).

The task can be solved by using various strategies. There are two main groups of them:

I. *Strategy based on knowledge gained at school*

In order to properly solve this task, the subject should have knowledge of the changes of velocity in a vertical projection. The first phase of the movement, the

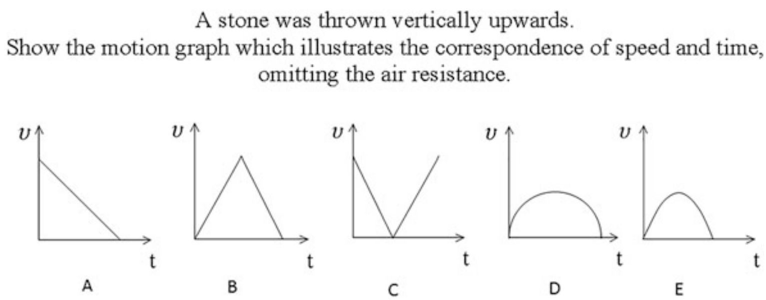

Fig. 1 *Stone problem* with translation from Polish to English

climb phase, involves uniform decelerated motion, and the second phase involves uniform accelerated motion in free-fall, while remembering to skip air resistance in all of the phases. Both cases involve, though simplified, a linear change of velocity as a function of time:

$V(t) = V_0 - gt$, where g—gravitational acceleration, t—time, V—velocity. This problem regards speed, which is the value of the velocity vector.

II. *Strategy based on common knowledge*

An important aspect of this task is that a skilled use of common knowledge allows the task to be properly solved. Just visualising the fact that the velocity of a rock thrown vertically upward decreases at first, until it stops, and then rises, is enough. Only one of the available graphs shows such changes in velocity.

In both of the aforementioned groups, the task can be solved in two ways—either by choosing a graph in line with one's visualization, or by elimination.

The elimination of incorrect graphs can also be done in different ways—by choosing several features of the movement—e.g. having two phases of the motion: rising and falling, as the stone has to fall (elimination A) and another selected characteristic, e.g. the value of initial velocity, the monotonicity of the function, the zero point of the function, etc.

4 Types of Data Visualization

Modern eyetrackers provide many different types of data. The measurement speed which can go as high as 1250 Hz allows for precise and varied methods of analysis and data visualization. Emphasis below is on the usefulness of the following types of eyetracking data visualization in physics education:

- *Heat map* or its black and white negative: *focus map*, either as picture or video, present the areas of the screen along with the average fixation time of the participants' eyes. On a *heat map*, the slide displayed on the computer screen is covered with different colours—in our examples from white (lack of fixations) through blue, green, yellow, orange, to red, which represents the longest fixation time (colours can be fixed in different ways). It can be useful not only for illustrating the general tendency of the observations of all participants, but also for group and individual analysis.
- *Scan path* as a picture or video allows to analyse the students' looking paths. It presents a clear graphic interpretation of data, showing successive fixations (using circles where the greater the diameter of the circle, the longer the fixation) and saccades, i.e. paths of displacement between two consecutive fixations (using segments).
- *Gridded AOI* (*Area of Interests*) presenting e.g. the average or total dwell time, average or total fixation count, average or total number of revisits, and other

data, automatically, for every rectangle defined by a chosen number of rows and columns for the whole screen.
- *Defined AOI* (*Area of Interests*) are areas of the slide defined by a researcher depending on the aim of the study. They can be shaped in various ways. For defined AOI, full data (average or total) is provided, also in percentages. Their possible analysis: *Key Performance Indicators* (*KPI*) as a picture or video, *sequence charts*, or other.

Exemplary usage for the visualizations above for research analysis will be presented alongside the advantages and disadvantages of particular methods based on empirical studies.

Due to restrictions regarding the amount of text, a complex and in-depth analysis of empirical studies for determining an eyetracking-based strategy for solving the *Stone problem* as well as the reasons for failure in its resolution cannot be the subject of this work.

5 Chosen Results and Excerpt from the Analysis Thereof

In the context of presenting the overall trends of looking at the slide presenting the *Stone problem*, a *heat map* is a more precise way of presenting the average fixation time as it can be scaled, (see Fig. 2, left—the last two shades of red represents the range of 1600–2000 ms) rather than a *focus map* (Fig. 2, right).

Mouse clicks at the selected options are visible in the maps as square symbols: ♦. The *heat map* can provide information regarding which areas of the slide were observed by the subjects and which areas of the slide had the maximum time of fixations, which are most likely to be indicators of which elements the participants were interested in. However, due to the fact that *heat maps* are used to present average values, they do not present data regarding the number of subjects or total time spent observing a slide, which could lead to misuse or errors in interpretation. For instance, in the case of our research, a *heat map* generated for four experts would neither show the average trends of the group, nor the time spent or strategies used to solve the task, which is confirmed further. However, these strategies can be

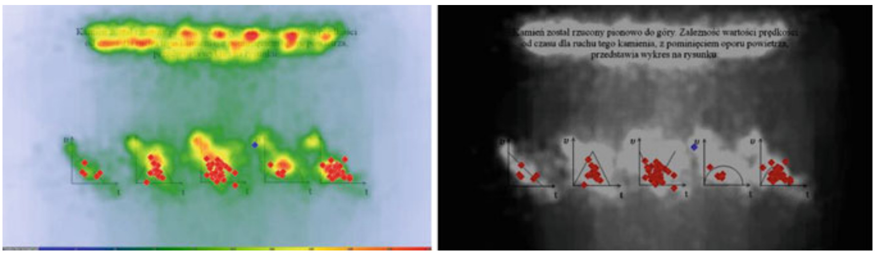

Fig. 2 *Heat map* and *focus map* for all 103 participants

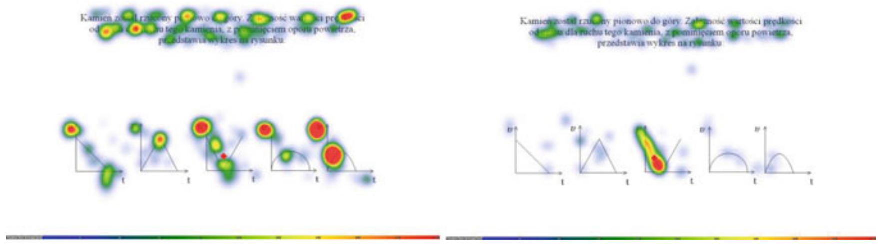

Fig. 3 *Heat map* for experts P21 (*left*) and P59 (*right*)

preliminarily observed on individual *heat maps*. Exemplary data is shown for experts P21 and P59 (Fig. 3).

On this basis, it can be concluded that expert P21 paid attention to the task, having the most fixations on the keywords related to the type of relation ("relation between the value of speed and time") and closely examined all graphs, particularly concentrating on the description of ordinates on every graph. In terms of the curves on the graphs, he mainly observed the second and last ones. The zeroes and extrema of functions as well as the initial speed of the rock were also analysed. However, expert P59 mainly concentrated his eyes on the middle graph. This does not mean that their *heat maps* are to be directly compared to conclude that he paid less attention to the task than P21. His *scan path* shows his in-depth analysis of the task (see Fig. 4, middle).

Based on the presented *scan paths* (see Fig. 4), three different task-solving strategies can be observed in the three subjects:

P21: The strategy of analysing all graphs and eliminating incorrect ones.
P59: The strategy of imagining the correct shape of the graph of the relation described in the task based on the wording of the problem, followed by choosing that graph.
P62: The strategy of combining knowledge related to the relation of the speed of the stone to time during its movement, as well as knowledge of linear functions in segments - the analysis exclusively graphs of piecewise linear functions (A, B, C). P62 was a scientist of mathematics.

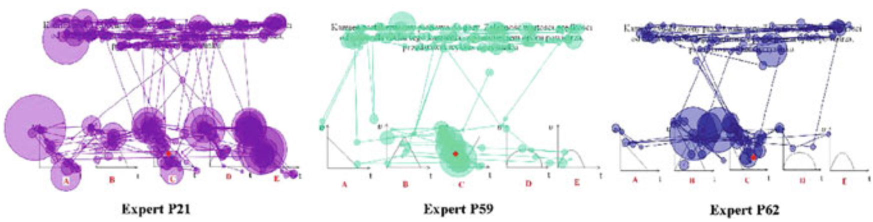

Fig. 4 *Scan paths* for experts P21 (*left*), P59 (*middle*) and P62 (*right*)

However, only a *defined AOI* and an analysis of eyetracking data allows to understand the differences between the approaches of the subjects to solving the task. The analysis includes e.g. data related to time spent working on the task.

Sequence charts (see Fig. 5) for scientists P21, P59, P62, and P104 show the order of looking at the defined AOI in time. Beside the charts is a thumbnail of the way of defining AOI. The *sequence chart* of the work of expert P21 shows, for instance, how much time he spent on the analysis of all graphs, particularly B, D, and E. The fixation time on the text in the task equals 40 % of the total time spent on the task, on option C—11.6 %, on option B—4.7 %, D—16.4 %, and E—12.4 %. A total of 33.5 % of time of working on the task was spent in the areas of answers B, D, and E. The average fixation values of all subjects are respectively: text of the task—45.8 %, option C—10.1 %, B—8.2 %, D—9.6 %, E—7.6 %, which is presented by the data regarding defined AOI (Fig. 6)

A question is raised of how much the number of fixations of the expert differs from the average number of fixations of all subjects. In which areas of the slide are the expert's fixations recorded and what is the difference with respect to the areas and average number of fixations of all participants? Another analysis is attempted by using *gridded AOI*. The following figures present the number of fixations of

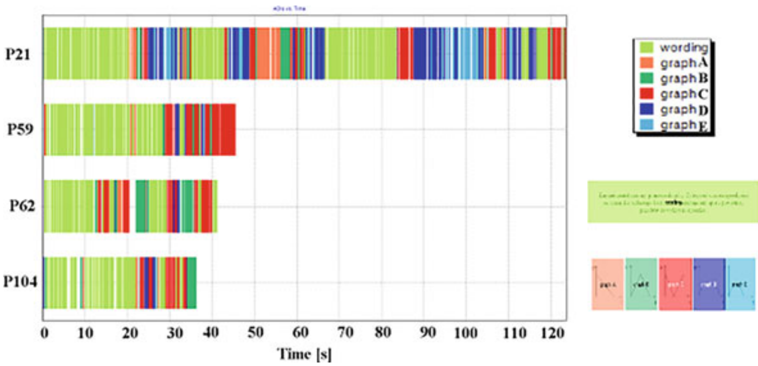

Fig. 5 *Sequence charts* for scientists P21, P59, P62, and P104

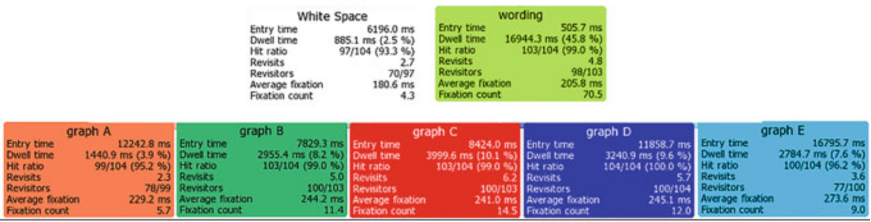

Fig. 6 *KPI* for all participants

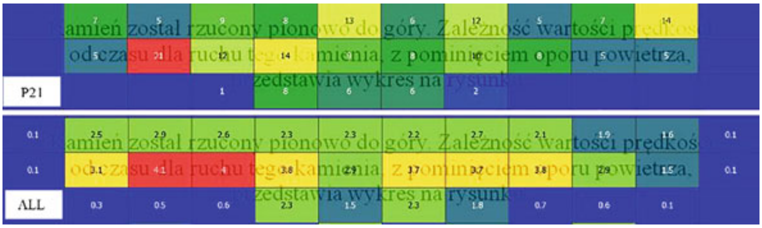

Fig. 7 Gridded AOI with the fixation count of Expert P21 and the average fixation count for all 103 participants in the area of the text of the problem

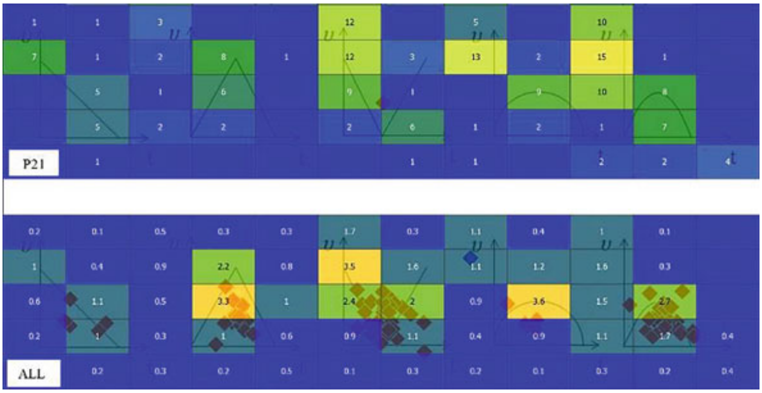

Fig. 8 Gridded AOI with the fixation count of Expert P21and the average fixation count for all 103 participants in the area of the graphs

expert P21 and the average number of fixations of all subjects for task text analysis (Fig. 7) and the graphs analysis (Fig. 8) respectively.

Significant differences can be observed in the number of fixations, e.g. the phrase "relation of speed to time" counted 64 fixations of the expert, while the average number of fixations of all subjects is four times lower at 15.7. Similarly, the number of the expert's fixations for the phrase "vertically upward" is 27, while for all subjects it is four times lower at 6.8. Similar differences can be observed in the graphs analysis (see Fig. 8).

To continue the in-depth analysis, other AOI are defined and the eyetracking parameters of subjects are analysed in areas the significance of which regarding task resolution has been discovered with the help of *gridded AOI*. On the basis of the *defined AOI*, more correlations can be observed between groups of students, pupils, and experts, as shown in Table 1 (Fig. 9).

Table 1 Chosen average eye-tracking values for the analysis of specific AOIs defined for the following graphs for pupils, students, and experts

		A	B	C	D	E
Average percentage dwell time in AOI of distractors	Pupils	3.7 %	7.2 %	10.5 %	9.3 %	6.5 %
	Students	4 %	8.8 %	6.9 %	7.1 %	7.5 %
	Experts	2.9 %	8.2 %	15.3 %	4.4 %	2.9 %
Average number of revisits in AOI of distractors	Pupils	2.3	5.4	7.3	6.2	4.1
	Students	1.4	3.4	3.6	3.6	2.2
	Experts	1.5	4	5.5	2.8	0.5
Average number of fixations in AOI of distractors	Pupils	5.7	11.3	17.3	14.7	10.8
	Students	3.9	8.5	7.1	7.3	6.2
	Experts	5.8	11.3	21.3	7	4

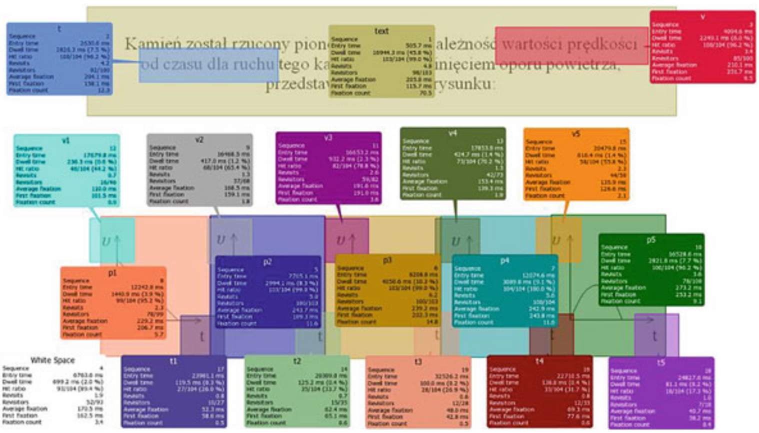

Fig. 9 Average results for the *defined AOI* for all participants

6 Summary

On the basis of empirical research we can conclude that eyetracking method allows to:

- distinguish those who read the text of the task attentively and those whose answers are random,
- objectively and precisely document all stages of task analysis, beginning with the text of the task up to choosing the answer,
- distinguish the words, sequences of words, sentences, and symbols that were the subject of in-depth analysis,
- study individual differences in methods of physics problem solving,
- distinguish unique strategies of solving tasks and choosing answers,

Table 2 Uses of eyetracking data analysis methods

Application	Scan path	Heat map	Gridded AOI	Defined AOI
Analysis of quality and method of reading	+	±	+	+
Distinguishing words and symbols responsible for information processing (number and duration of fixations, revisits, and dwell time)	+	+	+	+
Distinguishing task solving strategies	+	±	+	+
Comparing task solving strategies	+	±	+	+
Comparison of results can be individual	+	±	+	+
Comparison of results can be in groups	−	±	+	+
Distinguishing the sequence of analysis of particular areas of the screen	+	−	−	+
Providing precise numeric data (e.g. number and duration of fixations, number of revisits, and dwell time used to distinguish areas which trigger the process of processing information or interest)	−	−	+	+

- learn the differences in the strategies of solving tasks and choosing answers between beginners and experts,
- indicate hypothetical causes for choosing incorrect answers.

Table 2 presents suggested and empirically tested uses of the specified eyetracking data analysis methods. The “+” symbol indicates verified diagnostic capabilities, “−” indicates a lack of such capabilities, and “±” indicates a possibility of significantly restricted use. Table 3 presents the advantages and restrictions of eyetracking as a research technique.

The presented results show a very short snippet of the research we are conducting by using eyetracking techniques. Despite this, multiple advantages and possibilities can be observed by the uses of the described research in the scope of science education. The research in this work was carried out in a laboratory on a stationary device. However, it is worth noting that many of the described research

Table 3 The advantages and restrictions of eyetracking as a research technique

Advantages	Disadvantages
• Accuracy of measurement • Accuracy of method • Precision of video capture in time • Possible analysis of areas causing interest or cognitive strain • Easy to compare work of different people • Analysis can be individual or in groups • Possibility of doing an in-depth analysis of the strategy of reading the text of a task • Individual and comparative analysis available	• Time consuming of study and analysis • Calibration difficulties, especially for subjects with visual impairment • Difficulty in selection of data analysis methodology

proposals do not require powerful stationary equipment. The wide availability and low prices of mobile devices allow to carry out this type of research on a wider scale, including school conditions.

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Analysing the Conceptions on Modelling of Engineering Undergraduate Students: A Case Study Using Cluster Analysis

Claudio Fazio, Onofrio Rosario Battaglia, Benedetto Di Paola and Dominique Persano Adorno

Abstract The problem of taking a set of data and separating it into subgroups where the elements of each subgroup are more similar to each other than they are to elements not in the subgroup has been extensively studied through the statistical method of Cluster Analysis. This method can be conveniently used to separate students into groups that can be recognized and characterized by common traits in their answers, without any prior knowledge of what form those groups would take (unsupervised classification). In the last years many studies examined the consistency of students' answers in a variety of situations. Some of these papers have tried to develop more detailed models of the consistency of students' reasoning, or to subdivide a sample of students into intellectually similar subgroups by using Cluster Analysis techniques. In this paper we start from a description of the data coding needed in Cluster Analysis, in order to discuss the meanings and the limits of the interpretation of quantitative results. Then a method commonly used in Cluster Analysis is described and the variables and parameters involved are outlined and criticized. Section 3 deals with the application of this method to the analysis of data from an open-ended questionnaire administered to a sample of university students, and discusses the quantitative results. Finally, some considerations about the relevance of this method in Physics Education Research are drawn.

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1 Introduction

Many qualitative research studies involving open-ended questionnaire analysis have provided instructors/teachers with tools to investigate students' conceptual knowledge of various fields of physics. Many of these studies examined the consistency of students' answers in a variety of situations. Others looked at problems where the underlying physical systems are similar from the point of view of an expert. In recent years, some papers have tried to develop more detailed models of the consistency of students' reasoning, or to subdivide a sample of students into intellectually similar subgroups. Bao and Redish (2006) introduced model analysis as a framework for exploring the structure of the consistency of the application of student knowledge, by separating a group of students into intellectually similar subgroups.

The problem of taking a set of data and separating it into subgroups where the elements of each subgroup are more similar to each other than they are to elements not in the subgroup has been extensively studied through the statistical method of Cluster Analysis (ClA). ClA can separate students into groups that can be recognized and characterized by common traits in their answers, without any prior knowledge of what form those groups would take (unbiased classification).

ClA, introduced in Psychology by Tyron (1939), has been the subject of research since the beginning of the 1960s, with its first systematic use by Sokal and Sneath (1963). The application of techniques related to ClA is common in many fields, including information technology, biology, medicine, archeology, econophysics and market research. For example, in market research it is important to classify the key elements of the decision-making processes of business strategies as the characteristics, needs and behavior of buyers. These techniques allow the researcher to locate subsets or clusters within a set of objects of any nature. These have a strong tendency to be homogeneous "in some sense". The results of the analysis should reveal a high homogeneity within the group (intra-cluster), and high heterogeneity between groups (inter-clusters), in line with the criteria chosen.

ClA techniques (Everitt et al. 2011) are exploratory and do not necessarily require a priori assumptions about the data, but they do need actions and decisions to be taken before, during and after analysis. The selection of variables, the choice of the criteria of similarity between the data, the choice of clustering techniques, the selection of the number of groups to be obtained and the evaluation of the solution found, as well as the choice between possible alternative solutions, are particularly important. It is also important to bear in mind that different choices can lead to separate and somehow arbitrary results (as they heavily depend on the criteria used for the selection of the data). Subjectivity is common to all multivariate analysis methods, and is typical of the processes of reduction and controlled simplification of information.

In the literature concerning research in education, some studies using ClA methods are found. They group and characterize student responses by using open-ended questionnaires (Wittmann and Scherr 2002; Fazio et al. 2012, 2013) or multiple-choice tests (Ding and Beichner 2009).

A recent paper (Stewart et al. 2012) analyses the evolution of student responses to seven contextually different versions of two Force Concept Inventory questions, by using a model analysis for the state of student knowledge and ClA methods to characterize the distribution of students' answers. This paper shows that ClA methods are an effective way to examine the structure of student understanding and can produce significant subgroups of a data sample. The authors conclude that the ClA method is an effective mechanism for extracting the underlying subgroups in student data and that additional insight may be gained from a careful, qualitative analysis of clustering results. In fact, each cluster is characterized by means of a careful reading of the typical trends in the answers of the individuals that are part of the cluster. Other studies (Fazio et al. 2012, 2013), on the other hand, find clusters of students by comparing each student with researcher-built ideal profiles of student behavior. These profiles are often known from previous research and the related sets of characteristics are related to well defined answering strategies.

It is well known that there are inherent difficulties in the classification of student responses in the studies mainly involving open-ended questionnaires. In fact, the problem of quantifying qualitative data has been widely discussed in the literature for many years (Green 2001), and it has been pointed out that, very often, a small or even unconscious researcher bias means that the categories picked out tend to find those groups of students that the researcher is already looking for. A recent paper (Hammer and Berland 2014) points out that researchers "*should not treat coding results as data but rather as tabulations of claims about data and that it is important to discuss the rates and substance of disagreements among coders*" and proposes guidelines for the presentation of research that quantifies qualitative data. Another paper (Chi 1997) discussed the need to describe the process of developing a coding scheme, by outlining that in the process of quantifying qualitative data, *data* means the qualitative records supplied by students and not the result of the coding scheme. If we call these records "*raw data*" we have to take into account that the data being quantitatively analysed, which is obtained through the process of data reduction (Hammer and Berland 2014) contained in the coding scheme, is biased by the subjective interpretation of researchers. It is important for this to be taken into account in the interpretation of the results of the subsequent quantitative analysis.

In this paper we start from a description of the data coding needed in ClA, in order to discuss the meanings and the limits of the interpretation of quantitative results. Then a method commonly used in ClA is described and the variables and parameters involved are outlined and criticized. Section 3 deals with the application of this method to the analysis of data from an open-ended questionnaire administered to a sample of university students, and present the quantitative results. In the last section we discuss the meaning of our results for the physics education researcher and outline some points of strength and limits.

2 Quantitative Analysis

2.1 Data Setting

Research in education that uses open-ended questions and is aimed at quantifying qualitative data usually involves the development of coding procedures. This requires an accurate reading of student answers in order to reveal (and then examine) patterns and trends, and to find common themes emerging from them. These themes are then developed in a number of categories, which can be considered the typical "answering strategies" put into action by the *N* students tackling the questionnaire items. Therefore, it is possible to summarize the whole set of answers given to the questionnaire into a limited number, *M*, of answering strategies, making the subsequent analysis easier. Some details are supplied in Sect. 3.1. Through coding and categorization we produce a set of *M* data (the answering strategies) for each of the sample subjects (the *N* students doing the questionnaire). As a consequence, each subject, *i*, can be identified by an array, a_i, composed of *M* components 1 and 0, where 1 means that the subject used a given answering strategy to respond to an item, and 0 means that he/she did not use it. Then, a $M \times N$ binary matrix (the "matrix of answers") modeled on the one shown in Table 1, is built. The columns in it show the *N* student arrays, a_i, and the rows represent the *M* components of each array, i.e. the *M* answering strategies.

For example, let us say that student S_1 used answering strategies AS_1, AS_2 and AS_5 to respond to the questionnaire questions. Therefore, S_1 column in Table 1 will contain the binary digit 1 in the three cells corresponding to these strategies, while all the other cells will be filled with 0.

The matrix depicted in Table 1 contains all the information to describe the sample behavior with respect to the questionnaire items. However, it needs some elaboration in order to make this information understandable. ClA classifies subset behaviors in different groups (the clusters). These groups can be analysed in order to deduce their distinctive characteristics and point out similarities and differences among them.

It is worth noting that, from an educational point of view, the end of the clustering procedure does not mark the end of the study on the selected sample. The problem of characterizing the clusters on the basis of the common trends that allow cluster construction (for example, the different use of answering strategies to a questionnaire) still has to be discussed, and is the duty of educational researchers.

Table 1 Matrix of data: the *N* students are indicated as S_1, S_2, … , S_N., and the *M* answer strategies as AS_1, AS_2, … , AS_M

Strategy	Student			
	S_1	S_2	…	S_N
AS_1	1	0	…	0
AS_2	1	0	…	1
…	0	…	…	…
AS_M	0	1	…	0

2.2 Distance

ClA requires the definition of new quantities that are used to build the grouping, like the “similarity” or “distance” indexes. These indexes are defined by starting from the $M \times N$ binary matrix discussed above.

In the literature the similarity between two subjects ***i*** and ***j*** of the sample is often expressed by taking into account the distance, d_{ij}, between them (which actually expresses their “dissimilarity”, in the sense that a higher value of distance involves a lower similarity).

The distance index can be defined by starting from the Pearson’s correlation coefficient. It allows the researcher to study the correlation between subjects i and j if the related variables describing them are numerical. If these variables are non-numerical variables (as in our case, where we are dealing with the arrays a_i and a_j containing the binary coding of the answers of subjects i and j, respectively), we propose a modified form of the Pearson’s correlation coefficient, R_{mod}, similar to that defined by Tumminello et al. (2011) as,

$$R_{mod}\left(a_i, a_j\right) = \frac{p\left(a_i \cap a_j\right) - \frac{p(a_i)p\left(a_j\right)}{M}}{\sqrt{p(a_i)p\left(a_j\right)\left(\frac{M-p(a_i)}{M}\right)\left(\frac{M-p\left(a_j\right)}{M}\right)}} \tag{1}$$

where $p(a_i)$, $p(a_j)$ are the number of properties of a_i and a_j explicitly present in our subjects (i.e. the numbers of 1’s in the arrays a_i and a_j, respectively), M is the total number of properties to study (in our case, the possible answering strategies) and $p(a_i \cap a_j)$ is the number of properties common to both subjects, i and j (the common number of 1’s in the arrays a_i and a_j).

By following (1) it is possible to find for each student, i, the $N - 1$ correlation coefficients R_{mod} between him/her and the others students (and the correlation coefficient with him/herself, that is, clearly, 1). All these correlation coefficients can be placed in a $N \times N$ matrix that contains the information we need to discuss the mutual relationships between our students. The similarity between subjects i and j can be defined by choosing a type of metric to calculate the distance d_{ij}. Such a choice is often complex and depends on many factors. If we want two subjects, represented by arrays a_i and a_j and negatively correlated, to be more dissimilar than two positively correlated subjects (as is often advisable in research in education), a possible definition of the distance between a_i and a_j, making use of the modified correlation coefficient, $R_{\text{mod}}(a_i, a_j)$, is:

$$d_{ij} = \sqrt{2\left(1 - R_{\text{mod}}\left(a_i, a_j\right)\right)} \tag{2}$$

This function defines a Euclidean metric (Gower 1966), which is required in order to use it for the following calculations. A distance d_{ij} between two students equal to zero means that they are completely similar, while a distance $d_{ij} = 2$ shows that the students are completely dissimilar. By following (2) we can, then build a new $N \times N$ matrix, D, containing all the mutual distances between the students. The main diagonal of D is composed by 0s (the distance between a student and him/herself is zero). Moreover, D is symmetrical with respect to the main diagonal.

2.3 Clustering Technique

In this paper we use a technique known as *Non-Hierarchical Clustering* (*NH-ClA*), that basically allows us to partition the data space into a structure known as a *Voronoi diagram* (a number of regions including subsets of similar data). Among the many NH-ClA algorithms, we use here the *k-means*, which was first proposed by MacQueen (MacQueen 1967). In this method, the final result is a bi-dimensional Cartesian plane containing points that represent the students of the sample placed in the graph according to their mutual distances. As said before, for each student, *i*, we know *N* distances. It is, then, necessary to define a procedure to find two Cartesian coordinates for each student, starting from these *N* distances. This procedure consists in a linear transformation between a *N*-dimensional vector space and a 2-dimensional one and it is well known in the specialized literature as *multidimensional scaling* (Borg and Groenen 1997).

The starting point is the choice of the number of clusters one wants to populate and of an equal number of “seed points”, randomly selected in the bi-dimensional Cartesian plane representing the data. The subjects are then grouped on the basis of the minimum distance between them and the seed points. Starting from an initial classification, subjects are transferred from one cluster to another or swapped with subjects from other clusters, until no further improvement can be made. The subjects belonging to a given cluster are used to find a new point, representing the average position of their spatial distribution. This is done for each cluster and the resulting points are called the cluster *centroids.* This process is repeated and ends when the new centroids coincide with the old ones. The spatial distribution of the set elements is represented in a two-dimensional Euclidean space, creating what is known as the *k-means* graph (see Fig. 2).

NH-ClA has some points of weakness and here we will describe how it is possible to overcome them. The first involves the a priori choice of the initial positions of the centroids. This can usually be resolved by repeating the clustering procedure for several values of the initial conditions and selecting those that lead to the minimum values of the distances between each centroid and the cluster elements. Furthermore, at the beginning of the procedure, it is necessary to arbitrarily define the number of clusters. A method widely used to decide if the number of clusters, *q*, initially used to perform the calculations is the one that best fits the sample element distribution is the calculation of the so-called *Silhouette Function, S.* (Rouseeuw 1987). The *S* values allow us to decide if the partition of our sample subjects in q clusters is adequate, how dense a cluster is, and how well it is differentiated from the others.

For each selected number of clusters, q, and for each element, j, a value of the *Silhouette Function*, S_{qj}, is calculated. It gives a measure of how similar that element is to the other elements in its own cluster, when compared to points in other clusters. $S_{q,\ j}$ ranges from −1 to +1, and a value near +1 indicates that j is well-matched to its own cluster, and poorly-matched to neighboring clusters. If most elements have a high silhouette value, then the clustering solution is appropriate. If many points have a low or negative silhouette value, then the clustering solution could have either too many or too few clusters.

Subsequently, the values S_{qj} can be averaged on each cluster k, to find the average silhouette value, $<S_k>$ and on the whole sample, to find the average silhouette value, $<S(q)>$. Large values of $<S_k>$ are to be related to the cluster elements being tightly arranged in the cluster k, and vice versa (Rouseeuw 1987). Similarly, large values of $<S(q)>$ are to be related to well defined clusters (Rouseeuw 1987). It is, therefore, possible to perform several repetitions of the cluster calculations and to choose the number of clusters, q, that gives the maximum value of $<S(q)>$.

The clusters Cl_k (with k = 1, … , q) obtained can be characterized by their relative centroids, C_k. Particularly, if for each centroid we can find an array c_k with the same number of components associated to the arrays, a_i, that identify the real subjects, (i.e. the number M of answering strategies to the questionnaire) and composed by 0 and 1 values, we can say that c_k summarizes the cluster characteristics. We then study the answering strategies that make up the c_k array and make sense of the typical features of the cluster subjects.

In order to do this, we devised a method that consists of repeating the *k-means* procedure in reverse by using the iterative method, described as follows. For each cluster, Cl_k, we define a random array c'_k (composed of values 1 and 0, randomly distributed and corresponding to a supposed virtual centroid) and we find the following value

$$\sum_i \left| d_{ik} - d'_{ik} \right| \tag{3}$$

where d'_{ik} is the distance between this virtual centroid and the cluster element i (in the same cluster Cl_k) and d_{ik} is the distance between the real centroid and the same cluster element.

By using an iterative procedure that permutes the values of the random array c'_k., we minimize the value in (3) and we find the closest array representation of the real centroid. It can be shown that at the end of the iterations c'_k contains 1 values exactly in correspondence to the answering strategies most frequently given by the cluster elements. In fact, since a centroid is defined as the geometric point that minimizes the sum of the distances between it and all the cluster elements, by minimizing this sum, the correlation coefficients between the cluster elements and the centroid are maximized and this happens when each centroid has the largest number of common strategies with all the subjects that are part of its cluster.

In order to analyse how well, for each cluster Cl_k, the centroid characterizes its cluster, a coefficient r_k, defined as the centroid *reliability*, is calculated as follows

$$r_k = \frac{\langle S_k \rangle}{(1 - \langle S_k \rangle) n_k} \tag{4}$$

where n_k is the number of subjects contained in cluster Cl_k and $<S_k>$ is the average value of the *S-function* in it.

Since each value $<S_k>$ is a measure of how tightly the data are grouped in the cluster, its ratio with the number of subjects in the cluster relates the cluster density to its dimension. High values of r_k indicate that the centroid characterizes the cluster well, as this happens for dense clusters or for clusters with a low number of subjects. In fact, considering two equally dense clusters, the one with a lower number of subjects involves smaller cluster dimensions, i.e. a lower variability of subject properties.

Finally, in order to have comparable reliability values between the different centroids, we normalize the values r_k, by referring each of them to its average value and variance, i.e.

$$r_k^{norm} = \frac{r_k - \langle r_k \rangle}{\sigma(r_k)}.$$

3 Example of Quantitative Study

In this section we analyse the answer strategies to an open-ended questionnaire supplied by a sample of university students, using the techniques discussed above.

3.1 The Questionnaire and the Sample

The questionnaire is made up of four-items that focus on an understanding of the modelling concept (see Appendix A). They are part of a more complex questionnaire, which has already been used, in previous research (Ding and Beichner 2009; Lederman et al. 2002; Fazio and Spagnolo 2008). We have chosen to analyse a questionnaire with a low number of questions, and consequently a relatively low number of answers, since we are also interested to the study of the relationship between qualitative and quantitative analysis.

The four items selected refer to: (I) the definition of a physics model, (II) the subjects' beliefs about the representational modes of physics models, (III) their main characteristics and (IV) the subjects' beliefs about the modelling process.

The questionnaire was administered to 124 freshmen of the Information Technology and Telecommunications Engineering Degree Course at the University of Palermo, during the first semester of the academic year 2013/2014. The students were given the questionnaire during the first lesson of general physics, before any discussion on the model concept had started.

3.2 Categorization of Student Answers

After the questionnaire had been submitted to our student sample, three researchers independently read the students' answers in order to identify the main characteristics of the different student records (the raw data). Then, they agreed to construct a coding scheme through the identification of keywords that were relevant for an understanding of these records. During the first meeting, the selected keywords were compared and contrasted, and then grouped into categories based on epistemological and linguistic similarities.[1] These categories were also re-analysed through the researchers' interactions with the data, and taking into account the existing literature about models and modelling (Grosslight et al. 1991; Treagust et al. 2002; Pluta et al. 2011; Van Driel and Verloop 1999). As a third step, the researchers read the student records again and applied the new coding scheme, by assigning each student to a given category for each question. Given the inevitable subjectivity of the researchers' interpretations, the three lists were compared and contrasted in order to get to single agreed list. The inter-rater reliability of the analysis was good. Discordances between researcher lists were usually a consequence of the different personal decisions of the researchers to divide the student answers into a more or less restricted number of typologies. In some cases, discordances were due to different researcher interpretations of student statements. This happened 14 times when comparing tables of researchers 1 and 2, 9 times for researchers 2 and 3, and 12 times for researchers 1 and 3. Hence we obtained very good percentages of accordance (97 %, or higher) between the analysis tables of each researcher pair. When a consensus was not obtained, the student answer was classified in the category "statement not understandable".

It is worth noting that very often the researchers' discussions while assigning each student to a given category produced a more refined definition of these categories. The complete list of 20 categories shared by researchers with respect to the four questions can be seen in Appendix A. As a result of the coding and

[1]For example, students that defined models as *simple phenomena* or *experiments* or *reproductions of an object on a small scale* have been put on the same category since the three definitions have been intended as giving a ontological reality to models.

categorization, we obtain a matrix like the one depicted in Table 1, where $N = 124$ and $M = 20$. This matrix of data represents a set of properties (the categories to which student answers have been assigned) for each subject (the student being analysed).

3.3 Data Analysis

All the clustering calculations were made using custom software, written in C language, for the NH-ClA (*k-means* method) as well as for H-ClA where the *weighted average linkage* method was applied. The graphical representations of clusters in both cases were obtained using the well-known MATLAB software.

In order to define the number q of clusters that partitions our sample well, the *S-function* $<S(q)>$ has been calculated for different numbers of clusters, from 2 to 10 (see Fig. 1). The figure shows that the best partition of our sample is achieved by choosing four clusters, where $<S(q)>$ has its maximum.

Figure 2 shows the representation of this partition in a 2-dimensional graph, where the x and y axis simply show the values needed to place each subject according to mutual distance in relation to the other subjects after the multidimensional scaling. The four clusters show a partition of our sample into four groups made up of different numbers of subjects (see Table 2).

The four clusters Cl_k ($k = 1, \ldots, 4$) can be characterized by their related centroids, C_k, which are the four points in the graph whose arrays c_k contain the answering strategies most frequently applied by subjects in the related clusters (see Table 2). The codes used refer to the answering strategies for the questionnaire items described in Appendix A. Table 2 also shows the number of subjects in each

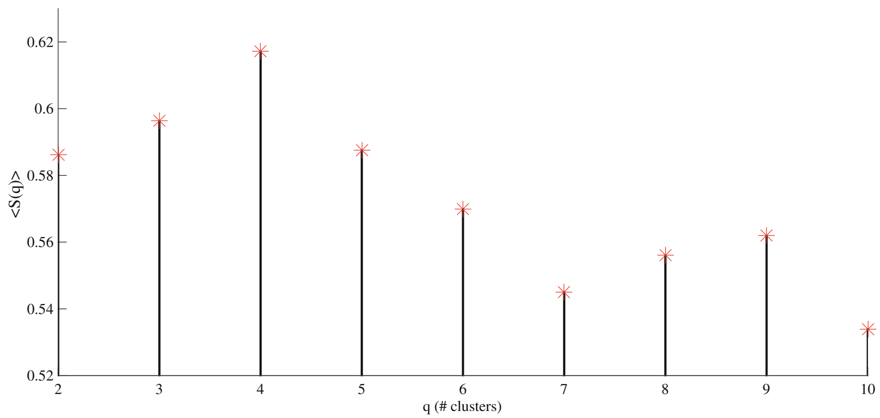

Fig. 1 Average Silhouette values for some partitions of our sample in a different number of clusters

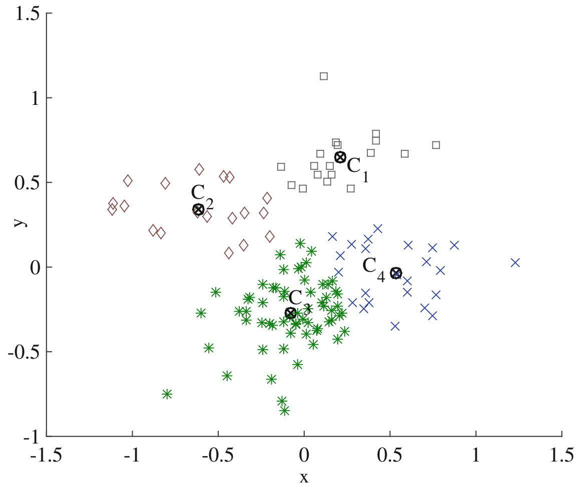

Fig. 2 K-means graph. Each point in this Cartesian plane rapresents a student. Points labeled C_1, C_2, C_3, C_4 are the centroids

Table 2 An overview of results obtained by NH-ClA method

Cluster centroid	C_1	C_2	C_3	C_4
More frequently given answers	1B, 2C, 3B, 4A	1B, 2B, 3E, 4A	1C, 2B, 3A, 4A	1C, 2C, 3B, 4B
Number of subjects	18	19	63	24
$<S_k>$	0.75	0.62	0.60	0.56
r_k	1.4	-0.02	-0.92	-0.46

cluster, the mean values of the *S-function* $<S_k>$ ($k = 1, \ldots, 4$) for the four clusters and the reliability index r_k of their centroids.

We can see that cluster Cl_1 is more compact than the others, and Cl_4 is the most spread out. Furthermore, the values of r_k show that the C_1 centroid represents its cluster best, whereas the C_3 centroid is the least representative and characterizes the cluster less well.

4 Discussion

To give meaning to results of ClA involves to identify the typical features characterizing the subject answers as well as differences and for similarities in answering strategies of subjects belonging to different clusters.

The four questions in our questionnaire mainly refer to: (I) the definition of a physics model, (II) the subjects' beliefs about ways of representing physics models, (III) their main characteristics and (IV) the subjects' beliefs about the modelling process. We have classified student answers into categories, also called answering strategies, that explain student reasoning strategies.

Looking at the results of NH-ClA, the four clusters identified are characterized by the related centroids and each centroid is represented by one array c_k, which describes the different answering strategies categorized for each question. These strategies are defined as follows: c_1: (1B, 2C, 3B, 4A), c_2: (1B, 2B, 3E, 4A), c_3: (1C, 2B, 3A, 4A), c_4: (1C, 2C, 3B, 4B), where the codes in brackets refer to the questionnaire answer strategies reported in Appendix A. We have already pointed out that the array describing the cluster centroid describes to the answers more frequently given by the subjects in the cluster, and in this sense we can identify at what frequency each answering strategy is shared by the cluster subjects.

In particular, cluster Cl_4 is mainly composed of subjects that use higher level answering strategies to deal with the concepts in the questionnaire. In fact, these students recognize that a model *is a mental representation of a real object or phenomenon, which takes into account the characteristics that are significant for the modeler* (1C). They also think that models *are creations of human thought and their creation comes from continuous interaction with the "real" external world and from its simplification* (2C) and that a model *must highlight the variables that are relevant for the description and/or explanation of the phenomenon analysed (or the object studied) and their relationships* (3B). *The modelling process is seen as a construction where the model can still contain errors or uncertainty connected with the possibility (or ability) to carefully reproduce the characteristics we are interested in* (4B).

Subjects in cluster Cl_2 show a low-level understanding of the model concept. They refer to a model as *a simple phenomenon or the exemplification of a phenomenon through an experiment or a reduced scale reproduction of an object* (1B), and believe that *models are simple creations of human thought like mathematical formulas, or physics laws and/or they are what we call theories or scientific method* (2B), and give answers regarding the main characteristics of a model that are confused and unclear (3E). For these students *every natural phenomenon can be simplified in order to be referred to a given model* (4A).

To sum up, we can say that the subjects in cluster Cl_4 seem to share many conceptions connected with an epistemological constructivist view. Subjects in cluster Cl_2, on the other hand, often held beliefs that correspond with a "naïve realist" epistemology, i.e. they usually considered models to be exact copies of reality, albeit on a different scale.

Subjects in clusters Cl_1 and Cl_3 can be placed at an intermediate-level, but in different ways. The subjects in cluster Cl_1 state that *physics defines models as a simple phenomenon or the exemplification of a phenomenon through an experiment or a reduced scale reproduction of an object* (1B). However, they also say that they *are creations of human thought and their creation comes from continuous interaction with the "real" external world and from its simplification* (2C). Furthermore, subjects from clusters Cl_1, Cl_3 and Cl_4 seem to share the idea that in a modelling process it is important *to highlight the variables that are relevant for the description and/or explanation of the phenomenon being analysed* (*or the subject being studied*) *and their relationships* (3B). Subjects from clusters Cl_1, Cl_3 and Cl_2 apparently share the idea *that every natural phenomenon can be simplified in order to be referred to a given model* (4A). In short, subjects from clusters Cl_1 seem to share with subjects of cluster Cl_2 the ideas concerning the definition of physics models and the modelling process, but they also share their beliefs about the function as well as the characteristics of physics models with the subjects from cluster Cl_4.

The subjects in cluster Cl_3 share the idea that a model is a *mental representation aimed at describing a real object or a phenomenon, which takes into account the characteristics that are significant for the modeler* (1C). However, they also think that *models are simple creations of human thought, like mathematical formulas or physics laws, and/or they are what we call theories or scientific method* (2B). These ideas are not completely consistent with each other, the characteristics assigned to the model or the subjects' ideas about the modelling process.

On the other hand, it must be taken into account that the value of the reliability, r_k, of the C_3 centroid is the lowest, showing that the array c_3 is not very significant in representing the answering strategies of the subjects in the cluster. Also, looking in detail at the c_3 array, the answering strategies are not easily understandable from the point of view of consistency. Although the array c_3 contains the answers most commonly given by the Cl_3 subjects, these do not have very high frequencies (no more than 38 % (answer 1C)), and other answers were given by a large number of subjects, for example answering strategy 1B (*A physics model is a simple phenomenon or the exemplification of a phenomenon through an experiment or a reduced scale reproduction of an object*) was selected by 30 % of students in Cl_3. In our opinion, this may show that a substructure is present in cluster Cl_3, and this should be analysed through different analysis methods, like, for example Hierarchical Cluster Analysis (Everitt et al. 2011), that can point out a higher number of clusters and help to make sense of them.

5 Conclusions

In this paper, we discussed the problem of quantifying qualitative data in order to analyse how to identify groups with common behavior, ideas, beliefs and conceptual understanding in a sample of students. We presented a method of cluster analysis (NH-ClA) and analysed definitions, variables and algorithms in detail, in order to understand the possibilities offered by such a method and its limits. We gave an example of their application in order to demonstrate the necessary approximations and the different ways of interpreting results. The example is an analysis of the answers to a questionnaire given to a sample of university students.

It is worth remembering that data that are quantitatively analysed are the results of a categorization of raw data (the individual student answers) and this reduction of the initial data can be subject to errors, which obviously influences the final evaluation and the inference about the reasoning strategies supporting students' answers. Such errors can only be reduced (through a clear process of coding and subsequent categorization) and not eliminated, and this must be taken into account when we try to infer typical students' reasoning strategies.

Looking at the meaning of the concept of a physics model as understood by the students in our sample, our results are consistent with those described in the literature, which illustrate a continuum of ideas/beliefs ranging from naive conceptions to constructivist ones (Grosslight et al. 1991; Treagust et al. 2002; Pluta et al. 2011; Van Driel and Verloop 1999). Our analysis gives details of student conceptions about the function of a physics model and its properties, by identifying features of intermediate conceptions as well as groups of students sharing such conceptions, in a continuum of this type. Furthermore, the results of this study provide important hints and insights for teaching methods that may improve students' model-based reasoning, and provide teachers with information about their students' level of understanding, with which they can make instructional decisions.

Appendix A: Questionnaire and Answering Strategies

Q1. The term "model" is very common in scientific disciplines, but what actually is the meaning of "model" in physics?

(1A) A set of variables or rules or laws or experiments and observations that simplify reality and represent it in a reduced scale.
(1B) A simple phenomenon or the exemplification of a phenomenon through an experiment or a reduced scale reproduction of an object.
(1C) A mental representation aimed at describing a real object or a phenomenon, which takes into account the characteristics significant for the modeler.
(1D) A simplified representation describing a phenomenon aimed at the understanding of its mechanisms of functioning (or at explaining it or at making prediction).
(1E) No answer or not understandable answer.

Q2. Are the models creations of human thought or do they already exist in nature?

(2A) Models really exist and are simple, real life situations or simple experiments and humans try to understand them, sometimes only imperfectly.
(2B) Models are simple creations of human thought like mathematical formulas, or physics laws and/or they are what we call theories or scientific method.
(2C Models are creations of human thought and their creation comes from continuous interaction with the "real" external world and from its simplification.
(2D) Models are creations of human thought aimed at explaining natural phenomena and making predictions.
(2E) No answer or not understandable answer.

Q3. What are the main characteristics of a physical model?

(3A) It must contain all the rules or all the laws for a simplified description of reality and/or it must account for all the features of reality.
(3B) It must highlight the variables that are relevant for the description and/or explanation of the phenomenon analysed (or the object studied) and their relationships.
(3C) Their characteristics can classify models as descriptive or explicative or interpretative.
(3D) Their main characteristics are simplicity and/or uniqueness and/or comprehensibility.
(3E) No answer or not understandable answer.

Q4. Is it possible to build a model for each natural phenomenon?

(4A) Yes, every natural phenomenon can be simplified in order to be referred to a given model.
(4B) Yes, but the model can still contain errors or uncertainty connected with the possibility (or ability) of carefully reproducing the characteristics we are interested.
(4C) No. There are phenomena that cannot be described or explained with a model and/or that cannot be defined in terms of precise physical quantities.
(4D) No. There are phenomena that have not been still explained and these, perhaps, will be in the future.
(4E) No answer or answer not understandable.

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Classroom Evidence of Teachers' PCK of the Interplay of Physics and Mathematics

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Abstract The interrelations between Physics and Mathematics caught the attention of the physics education research community. Focusing mainly on students and teachers competency, the research in physics education (PER) found that learners, at different ages and levels, lack the ability to construct the mathematical models of physical processes or to describe the physical meaning of mathematical constructs. Mathematical knowledge was also found to reflect on the quality of explanations of physical phenomena. (Clement et al. 1981; Cohen et al. 1983; Rozier and Viennot in International Journal of Science Education 13:159–170, 1991; Rebmann and Viennot 1994; Bagno et al. in Physics Education 43(1):75–82, 2007; Redish and Smith in Journal of Engineering Education 97(3):295–307, 2008; Baumert et al. 2010; Zuccarini and Michelini 2014). The approach that underlines our study adopts the view that the context of physics teaching invites investigating the interplay between physics and mathematics. This "Phys-Math" interplay is regarded as a complex two ways track by which the knowledge and understanding of physics is constructed by learners. Our multi-national group examines this subject from various perspectives: history and philosophy of science as well as its instruction in different levels from high school to university (Eylon et al. 2010; Pospiech and Matthias 2011; Lehavi et al. 2013; Pospiech et al. 2014, 2015). The present study

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follows our previous research in which we addressed, through interviews, the "Phys-Math" PCK of expert high school physics teachers from Israel and Germany (Lehavi et al. 2013, 2015; Pospiech et al. 2015). Here we report on a study which follows this research by analysing data collected from classes. The data was collected by videotaping physics lessons at middle school level. The videotapes were analysed, looking specifically for incidents in which Phys-Math interplay is evident.

1 Introduction

Although Physics and Mathematics can be regarded as autonomous disciplines, Physics, since its modern evolution, is considered to be heavily interrelated with Mathematics. In addition to their historical and philosophical perspectives, the "Phys-Math" interrelations caught also the attention of the physics education research community. In the past, mathematics in physics education was mainly examined within the context of problem solving (Bagno et al. 2007; Redish and Smith 2008). Research has found that learners, at different ages and levels, lack the ability to construct the mathematical models of physical processes or to describe the physical meaning of mathematical constructs. Researchers reported on students' difficulties such as in constructing equations from situations described in words (Clement et al. 1981) or in describing the physical meaning of formulae (Bagno et al. 2007). Rozier and Viennot (1991) pointed at students' difficulties in addressing multivariable problems. Rebmann and Viennot (1994) discussed the difficulty of many university physics students in applying and interpreting algebraic sign conventions consistently. Some researchers pointed out that there is blending of conceptual and formal mathematical reasoning during the mathematical processing stage (Kuo et al. 2013; Hull et al. 2013). With regard to teachers, Karam and Krey (2015) addressed the understanding and explaining of equations in physics teacher education. They attempt to bring teachers to realize the role that equations play in the formulation of theories as providing explanations for physical phenomena rather than serving as calculating tools to solve problems or for describing in a concise manner experimental regularities.

Recently, it was suggested that the whole context of physics teaching invites interplay between physics and mathematics (Eylon et al. 2010) and that a distinction should be made between a technical approach, which involves an instrumental (tool-like) use of mathematics, and a structural one, focused on reasoning about the physical world mathematically (Karam 2014). This view considers the overlap between Mathematics and Physics to be a sub-area of physics education which is characterized by its own Pedagogical Content Knowledge (PCK) and deserves research of its own. This has been the goal of a bi-national research conducted in Israel and Germany that examines the views of expert high school physics teachers with regard to the "Phys-Math" interplay and the measures they take to implement it (Lehavi et al. 2013, 2015; Pospiech et al. 2015). The teachers reflected in interviews on the importance of the "Phys-Math" interplay and provided examples of how they practice it in their teaching. In order to characterize teachers' PCK of the Phys-Math interplay, we employed the PCK model suggested by Magnusson et al. (1999) which was adapted by Etkina (2010) to physics education.

According to Magnusson et al. teachers' PCK assists them in fostering the following goals:

a. Help students develop the 'science process' skills
b. Represent a particular body of knowledge
c. Transmit the facts of science
d. Facilitate the development of scientific knowledge by confronting students with contexts to explain that challenge their naïve concepts
e. Involve students in investigating solutions to problems
f. Represent science as inquiry
g. Constitute a community of learners whose members share responsibility for understanding the physical world, particularly with respect to using tools for science.

A central construct in the model is teachers' 'orientations toward science teaching' which impacts different facets of their knowledge and views. Figure 1 represents Etkina's representation of relationships between this construct and several interrelated facets of knowledge with regard to: scientific content, students, assessments and successful teaching strategies (Etkina 2010).

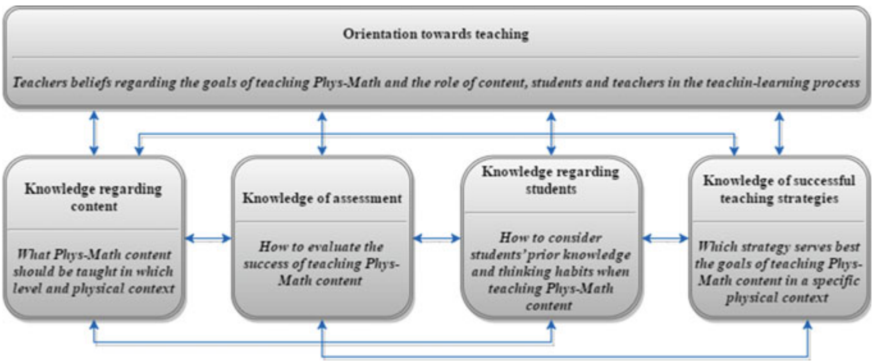

Fig. 1 Aspects of the Pedagogical Content Knowledge (PCK) framework from Magnusson et al. (1999) adapted by Etkina (2010)

2 The Bi-National Research on the "Phys-Math" PCK

2.1 Previous Findings

We limited our previous analysis of the teacher interviews in the bi-national research to the following components of Magnusson's framework:

a. The content of the Phys-Math interplay
b. Teachers' knowledge of successful teaching strategies.

Our findings revealed that teachers practice the use of Phys-Math interplay in order to foster different teaching goals and in doing so they employ different "patterns" that follow different "steps" between physics and mathematics and within each domain. Each of these patterns serves different teaching goals in the general PCK framework as can be seen in the following table (Lehavi et al. 2013, 2015) (Table 1).

The starting and ending point of all the found patterns is the physics domain, and they relate theory with experiments in different ways. The examples provided by the teachers cover different content areas of the physics curriculum. In addition, the teachers mentioned the role of Phys-Math content knowledge in deductive reasoning, in relating experiment and theory, in constructing students' broad view of physics and in problem solving. They described how they practice various teaching strategies that they employ within the Phys-Math interplay. This, together with the Phys-Math patterns, clearly fit into the PCK framework categories: orientation towards teaching, knowledge regarding content and the knowledge of successful teaching strategies.

Table 1 Phys-Math patterns, teaching goals and teaching practices (note close relations to goals a-f in the Magnusson PCK model)

Pattern	The teaching goal	The teaching practices
A. Exploration	To demonstrate how phys-math is used to explore the behavior of physical systems	Exploring within math ramifications for the physical system: borders (of validity, of approximation), extreme cases, etc.
B. Construction	To demonstrate how phys-math is used in constructing a model for physical systems	Constructing and developing (from experiments or from first principles) mathematical tools to describe and analyse physical phenomena
C. Broadening	To demonstrate how phys-math can be used in broadening the scope of a physical context	Adopting a bird's-eye view and employing general laws of physics, symmetries, similarities and analogies
D. Application	To demonstrate how phys-math provides aid in problem solving	Employing already known laws and mathematical representations in problem solving

Interestingly, our study revealed that the practice of employing different patterns of the Phys-Math interplay can distinguish master teachers from other expert teachers. The master teachers were very clear on rendering students *aware* of various aspects of the Phys-Math interplay and addressed the deep relations between physics and mathematics in philosophical and historical perspectives. They were highly aware of the various patterns of the interplay and the teaching methods for each pattern. Thus, our previous study supports the claim that teaching orientations play a critical role in distinguishing the quality of teaching (Abell 2007).

3 The Present Study: Phys-Math in Classrooms

In the present study we took a step beyond what is *described* by teachers as their interpretation of the Phys-Math interplay in the context of physics education, and investigated what is *actually* performed by them in the classroom. Based on actual scenarios of teaching we investigated how teachers' PCK with regard to the interplay between Physics and Mathematics may be manifested in their actual teaching.

The data was collected by videotaping physics lessons at grade 9 (the end of middle school level in Israel). The videos were scrutinized, looking for occasions in which a Phys-Math interplay was manifested. Our analysis was comprised of two steps: An independent analysis of each occasion by at least three researchers and a group discussion by the researchers. In this analysis the researchers were asked to relate to several aspects regarding the PCK on the Phys-Math interplay such as the above mentioned Phys-Math patterns, how a–f in the Magnusson et al. framework were manifested (or missing) in the scenario, as well as additional aspects that came up in the scenario.

We shall present here two examples and first interpretations based on the video evidence. One example is extracted from a post-lesson meeting of a teacher with a guide. The lesson and the meeting were both video-recorded. The second example is based on a video of a classroom discussion. Both examples are focused on the definition of speed.

Example 1: "Math may screen physics understanding" a post-lesson discussion (Teacher = T; Guide = G): The guide and a group of teachers are watching together the video from the teacher's lesson.

G: "… I am asking about the teaching strategy by which you define speed."
T: "First of all I will approach their [students] intuition, to see their understanding from everyday life what speed is. I want to change their view, … to explain them that speed is the change in distance versus time, for example the change in the position of an object versus time.
G: "I am interested in the method you employ in order to change their everyday intuition to the physical one."

T: “They will say that speed is how fast you move. This is from everyday experience.”
G: “But this is not what they said…”

(Both are looking at the classroom video).

G: “You asked ‘what is speed’ and the student replied: ‘x divided by t’. And then you said: ‘Right. It is the change in position versus time’…. What is the difference between what the student said and what you have said? What is the student’s difficulty which is reflected by his answer? How do you respond to this difficulty?”
T: “The question is: what is the physical logic…. You try to explain what speed is and they tell you that it is the path divided by time, right? [Change in] position divided by time.”
G: “They said x divided by t…”
T: “He actually means, ah… because he remembers from his math lessons that the distance equals speed times time. This is what he learnt during his preparation for his Math exams.”
G: “More than that, he said before that…”
T: “[That] x is an unknown. Right, right. Ok, I say, we have here the position and we have here time and we would like to define for him what speed is.”
G: “Did you try to differentiate here between the mathematical definition and the physical one?”
T: “Not explicitly. But the explanation, the physical connotation was to try to explain, how ah… it [the definition] is related to the physics.”
G: “I would like to focus here on your teaching strategy. If you want to explain, and the student has a difficulty, which, like you said before, is related to his math studies, can you assist him by making the differentiation between math and physics explicit? The question is how to deal with students’ difficulties?”
T: “You can go over the definition few times, give them more and more examples until you realize that they have got the reason behind it…. I then gave them an exercise about constant speed to check their understanding and they answered it very well. They were able to explain that if the object covered a distance of 10 m within 5 s, its speed was 2 m/s because it advanced 2 m every second. So they really got the logic here.”
G: “So, do you think that they understood the difference between the mathematical definition and the physical one?”
T: “I said that it is the change in position over time. In mathematics they learn that S equals vt.”
G: “We can see [in the video] that you wrote on the board that x is position and t is time but the student, after 10 min of explanations, asked: ‘what is x?’. So, what was so difficult for him?”
T: “How can I explain more what position is? What is the problem here?”
…
G: “Everything was written correctly on the board. So, where does the difficulty come from?”

T: "Because he didn't feel it by his own hands?"
G: "When will it happen?"
T: "When he will make an experiment"

The above discussion can be viewed through the following components of our adopted PCK model (see the above list):

a. Help students develop the 'science process' skills
b. Represent a particular body of knowledge
c. Facilitate the development of scientific knowledge by confronting students with contexts to explain that challenge their naïve concepts

In the discussion the teacher is fully aware that there is a difference between how motion is addressed in mathematics and in physics. He realizes that for students who hold the mathematical conceptualization, time, speed and distance are merely three quantities related by an equation. However, he finds it difficult to *develop a teaching strategy* (see Fig. 1) to make this difference clear for his students, moving them away from their mathematical conceptualization into the physical one. Finally, the teacher begins, through the guidance, to consider the idea that what really makes physics different from mathematics are the former's empirical bases.

Example 2: "A Phys-Math surprise" This example describes a scene from a teacher's classroom representing a different strategy to address the same difficulty.

(T = Teacher; S = student(s)), excerpt from a classroom discussion:

T: "We want to describe motion. I have here few toys, each group will have one. I want you to describe the motion of the toy.
S: "What, the energy that it has?
T: "No. What kind of motion; Time and position.
S: "Position - classroom (S2: Desk) [is a position]. Time is t"
T: [Referring to a drawing on the board] "We have two drawings, each with a certain reading of my stopwatch. I have two things: I measure the time and the change in position. This change in position is called a displacement. … What concepts do we need to describe motion?"
S: "Time and distance."
S: "Speed, time and distance."
T: "OK. So we said that we can calculate the speed."
S: "No. we just said distance and time…"
T: "It is sufficient to measure the distance and time and from these we can calculate the speed and in fact to describe motion. You have studied it in Mathematics. In physics it is a little bit different. The concepts that we will use are position, relative position and displacement. Now, how can I in general measure motion?"
S: "To measure motion?
T: "Yes."
S: "Distance?"
S: "Speed"
S: "Speed, time and distance."

T: "[If] my car goes from Jerusalem to Tel Aviv…"
S: "[you can measure the speed by] a speedometer"
T: "The speedometer measures the speed."
S: "This is what you wanted. Right?"
S: "It [the speedometer] measures speed and minutes."
S: "It measures everything."
T: "What do you mean?"
S: "Speed and distance. It measures speed and time and derives the distance!"
T: "So, if we want to measure the motion of one of our toy-cars, how would we do that? Would we place a speedometer on it and measure its speed?"
Students: "Yes! Yes!"

Apparently, this line of thought was not what the teacher expected:

T: "OK. How else could we do it?"
S: "With an Equation. Speed multiplied by time equals distance."
T: "We can use a formula and calculate."
S: "This is what the speedometer does."

This teacher begins from a "hands-on" experience, develops the required vocabulary and tries to employ it in describing motion. However, she is not well aware of the *knowledge regarding student* (Fig. 1) with regard to two aspects:

a. The mathematical conceptualization that students bring to the class. For them all the three quantities that appear in the distance-time-speed equation are equivalent—you just have to know two of them in order to derive the third. They do not pay attention to what are the measured quantities and what is the derived one.[1]
b. The fact that their everyday experience ("speed is measured by a speedometer") does not conflict with their mathematical conceptualization.

Therefore, the teacher was apparently not expecting a situation in which students' mathematical knowledge not only hindered their physical understanding but enhanced their misinterpretation of the measured versus derived quantities.

4 Discussion

We provided here only two classroom examples (out of many) in order to depict how teachers' PCK with regard to the interplay between Physics and Mathematics may affect their teaching. As mentioned in the two examples, the findings fit rather well Magnusson's et al. PCK model adapted by us previously with regard to two

[1]It is possible to measure the speed directly via the Doppler Effect. However, this was not the strategy adopted here by the teacher.

components: knowledge regarding students and the need to develop a teaching strategy.

The examples provided above address components a–f (see the list above). They demonstrate that within the context of physics teaching, the juxtaposition of physics and mathematics carries its unique students' pre-knowledge and misinterpretations. Furthermore, the Phys-Math interplay requires teachers to develop specific assessments in order to reveal students' difficulties and their origins and specific teaching strategies to assist students in overcoming their learning difficulties.

With regard to the patterns we have recognized in the teachers' description of their instruction, we may identify two such patterns in our two teachers' practice. The first teacher follows the "application pattern" and employs the already known (to the students) mathematical representations of motion. This teacher exhibits difficulties in changing the students' previous mathematical knowledge and provide them with physical insights. Apparently, the teacher is not fully aware of the importance of making the Phys-Math interplay explicit to the students.

The second teacher seems to practice the "construction pattern". Similar to the first teacher, she begins from a physical situation and then constructs the mathematical tools to describe and analyse physical phenomena. Importantly, both teachers seem to follow the patterns intuitively and show little awareness with regard to possible difficulties that students may have with regard to the Phys-Math content.

It would thus be advisable to regard the Phys-Math interplay as a sub-content of its own and develop special teachers training programs in order to address the special challenges posed by it. Consequently, our next step in the coming year is to invite experienced teachers to develop Phys-Math teaching strategies and try them in their own classes.

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Development of Research Based Teaching Materials: The Learning Output of a Course for Geometrical Optics for Lower Secondary Students

Claudia Haagen-Schützenhöfer

Abstract Learning physics is a difficult endeavour since our everyday experiences frequently result in naïve theories which do not or do only partly correspond to scientific concepts. If instruction does not take these well-known conceptions as a starting point for learning processes and neglects typical learning difficulties, it is likely to be non-effective. This holds true for all areas of physics, also for introductory optics. This article reports the development and evaluation of research based teaching materials. These teaching materials take domain specific learning problems known from research into account. In addition, they are based on an atypical content structure which was developed based on Design Based Research. The current version of the optics course was evaluated in year 8 physics classes. The comparison of Austrian students' achievement after conventional instruction in optics in year 8 (N = 16 classes) and students instructed with our optics course (N = 5 classes) will be reported.

1 Background and Aims

Physics Education Research of the last decades has investigated subject specific learning, students' conceptions and learning difficulties. The insights gained about domain specific learning have, however, hardly been used for effective rearrangements of instructional designs or instructional materials. "Basic research in education is viewed as irrelevant by practitioners" (Duit et al. 2012, p. 15) and thus hardly effects school teaching practice. On the other hand, our experience shows that teachers are longing for teaching materials ready to use in class.

The core intention of this project is to bridge the gap between research based evidences concerning learning optics and conventional school settings, which are not informed by these research findings. So the idea behind our optics project is to

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find an informal channel of implementing research results on domain specific learning into school practice by offering teachers research based teaching materials and evaluate their learning output compared to conventional instruction.

2 Theoretical Framework

This research project consists of three big parts:

(1) the development of an optic concept test which is able to measure students' concepts on a psychometrically sound basis (cf. Haagen-Schützenhöfer and Hopf 2012a, b, 2014a, b)
(2) the development of teaching materials based on the paradigm of Design Based Research (Ejersbo et al. 2008; The Design-Based Research Collective 2003; Haagen-Schützenhöfer 2015)
(3) the implementation and evaluation of the optics course in the field.

As a consequence, this project rests on a number of theoretical pillars. The constructivist approach towards learning can be seen as the connecting element. Conceptual change theories (Treagust and Duit 2008) and the framework of educational reconstruction (Kattmann and Duit 1998) are the key elements for the development of the teaching materials. Educational reconstruction serves at the same time as the underlying research programme of this project, connecting physical content, learners' perspectives and the quality of learning environments.

2.1 Conceptual Change and Students' Conceptions

Science education research of the last half century has demonstrated impressively that learning science goes far beyond a simple information transfer process, where a teacher provides information (input) and the students encode and store this input in order to exactly recall the same information (output) when asked for. On the contrary, students do not enter formal instruction as a "tabula rasa" (Posner et al. 1982), they have already developed deeply rooted pre-instructional conceptions, which originate mainly from everyday experiences and everyday language. These students' conceptions—as they are frequently called in literature—are however in the majority of cases not in balance with scientific concepts and thus interfere with learning processes (Guesne 1985).

In order to adapt to the conditions of our environment, learning is a vital process. In this sense learning occurs as a permanent informal process. Following the ideas of Piaget, learning can be seen as "a basic life process that helps an organism adapt to its environment, […] [so that] it is able to cope with the demands of the immediate situation" (Shaffer and Kipp 2013, p. 54). Thus learning, at least in its informal manifestation, occurs all the time. “In interacting with environment, with others, and with the artefacts of technology, people form internal, mental models of themselves and of the things with which they are interacting. These models provide predictive power for understanding the interaction” (Gentner and Stevens 2014, p. 7). As a consequence, learners have already acquired numerous conceptions about the natural world before they enter formal instruction. These naïve theories have proved to work well in uncountable everyday situations (survival!) and have thus become relatively stable. Taking all this into account, from a leaner’s perspective, there is usually no necessity to abandon these everyday ideas (Posner et al. 1982).

However, especially in science, these everyday ideas are frequently not in harmony with scientifically sound conceptions (Vosniadou and Brewer 1992). So from an educational perspective it is the task of formal instruction to *change* these everyday concepts into more scientific ones. However, research in cognitive sciences shows that a *conceptual change* does not work as mere exchange of one idea against another one. Neither does it help to just make learners aware of their everyday conceptions. From a constructivist point of view, it is necessary to reconstruct students’ ideas fundamentally in formal learning processes, which turns out to be a complex and difficult endeavour (Duit et al. 2008).

The findings from cognitive science and corresponding fields indicate that the output of formal instruction strongly depends on the choice of learning environments, which take students’ domain specific preconceptions and learning difficulties into account. Consequently “just telling” facts about a scientific topic in class will not automatically lead to conceptual change and understanding. It is rather necessary to design learning environments which support learners in actively reconstructing their knowledge based on constructivist learning theory (Reusser 2001).

A widely accepted approach to facilitate conceptual change was suggested by Posner et al. (1982, p. 214). Accordingly, several conditions prove to be supportive: “dissatisfaction with existing conceptions”, new conceptions “must be intelligible […] appear initially plausible” and finally they “should have the potential to be extended, to open new areas of inquiry” (fruitful).

Research on domain specific students’ conceptions has been one major endeavour of science education research and so far a large number of students’ conceptions have been found and collected. As a consequence, reliable catalogues of those students’ conceptions, which potentially influence learning negatively, exist for all big topics of physic already. The scope of this paper is too limited to report students’ conceptions on optics in detail. Research on students’ conceptions in optics as well as in other fields of physics up to 2009 is well documented in STCSE (Students’ and Teachers’ Conceptions and Science Education) and can be found in Duit (2009). However, one essential and very basic key-idea of teaching introductory optics will be mentioned here, since the introduction and continuous reference to the sender-receiver model of vision is one major and outstanding characteristic of our optics course.

The concept of vision turns out to be an essential building brick for an overall understanding in optics. As our previous research shows (Haagen-Schützenhöfer and Hopf 2012a), even after formal instruction in optics in year 8, students have severe difficulties in solving basic items on vision. Numerous findings underline that if students do not grasp the idea of vision thoroughly, they do hardly have the chance to succeed in gaining conceptual insight into other sub domains of optics (Andersson and Kärrqvist 1983). The main categories of student alternative conceptions related to vision were categorized by Guesne (1985) and confirmed by many other researchers (Selley 1996; de Hosson and Kaminski 2007; Wiesner 2007). For students it seems to be very difficult to establish an adequate relationship between the light source, the object illuminated and the observer. Even after formal instruction in optics, the majority of students either thinks that only the presence of light—conceptualized as static entity—makes the object visible ("light bath idea") or that light just needs to be beamed on an object ("illumination of an object"). In both cases the connection between the object, (re)emitting light and the visual system of the observer is neglected.

3 The Optics Course

A design of successful learning environments needs to merge the subject matter point of view on a certain topic with related student perspectives (including preconceptions and interests) (Duit et al. 2012; Posner et al. 1982). Practitioners frequently do not balance both sides for several reasons. The aim of this project on geometrical optics was to develop research based teaching materials which are ready to be used in authentic school settings and which promote a deeper conceptual understanding than conventional instruction (cf. Haagen-Schützenhöfer 2015).

This optics course was developed for the phase of the first formal instruction of optics at the secondary level, which is scheduled for year 8 in the Austrian curriculum. The content of our optics course was aligned to the Austrian curriculum and contains the following subtopics: propagation of light, vision & visibility (sender-receiver model of vision), white light & its components, colour phenomena, shadows, image formation by pinholes (luminous dot—image dot relation), image formation by mirrors, law of reflexion, law of refraction, image formation by lenses, optical devices, image formation in the human eye.

There exist already a number of interventions on subtopics of geometrical optics (Schön et al. 2003; Viennot and de Hosson 2012; Wiesner et al. 1995) that facilitate conceptual learning processes. Our optics course is built on findings by Wiesner (e.g. Wiesner 1995, 2007) and Jung (e.g. Jung 1981, 1982) and on the course by Wiesner et al. (1995, 1996) which was evaluated in a comparative study as highly efficient and superior to conventional instruction in optics in terms of learning output and conceptual understanding (Herdt 1990).

The unique features of the course by Wiesner et al. can be summarized as follows: A sender-receiver model of vision is introduced early and used throughout the course. Ray diagrams are introduced in the course at a late stage. At the beginning, propagating light is represented by cone shaped beams and the abstract model of rays is explicitly introduced later. Ray diagrams are always directly and explicitly related to the phenomenon they represent. And the characteristic path of light, starting from a light source, interacting with matter until finally arriving at an observer is made explicit (Wiesner 2007). Next to the course by Wiesner, Engelhardt and Herdt more recent empirical findings about learning introductory optics were taken into account (Colin et al. 2002; Martinez-Borreguero et al. 2013; Haagen-Schützenhöfer et al. 2013, 2014; Haagen-Schützenhöfer 2014; Viennot and de Hosson 2012).

The development of the optics course was mainly put into practice by designing student's text in course book style (Haagen-Schützenhöfer et al. 2013a). Firstly, a preliminary draft of the student's text was produced based on the teachers' book by Wiesner, Engelhardt and Herdt and using the model of educational reconstruction (Kattmann and Dui 1998). Chapter by chapter, this student text was improved in several Design Based Research cycles, where the interventions were tried out in micro-teaching school settings and evaluated with the help of teaching experiments. More details about the development process and teaching experiments on certain subchapters of the course can be found in Haagen-Schützenhöfer et al. (2013b), in Haagen-Schützenhöfer et al. (2014) and in Haagen-Schützenhöfer (2015).

4 Research Questions

As mentioned above, there is empirical evidence that the course of Wiesner et al. (1995, 1996) works in school settings better than conventional instruction in optics in terms of conceptual understanding (Herdt 1990). It is however left open, whether our course is still efficient, despite the changes made in the content structure (Haagen-Schützenhöfer 2015), the adjustment to the Austrian curriculum and the transformation of teachers' materials into student's text. In order to find out in how far the course in its present form is supportive in fostering students' conceptual learning, the current version of the student's text was tested in the field. The following research questions will be analysed:

> Research Question I: Is the developed student's text appropriate to teach basic key-ideas of introductory optics?

To answer this question the hypothesis is tested that those students working with our materials (intervention group) improved their conceptual understanding of key-ideas in geometrical optics.

> Research Question II: Does the developed student's text foster conceptual learning of basic key-ideas better than conventional instruction in geometrical optics?

The research of Herdt (1990) reports that students benefit from the optics course by Wiesner et al. in conceptual understanding of geometrical optics. Therefore our hypothesis contains a considerable benefit in conceptual understanding for students instructed with our course compared to conventionally instructed students.

> Research Question III: What are the differences in the post instructional achievement between the students instructed with our optics course and students with conventional instruction concerning the concept of vision?

If an overall better performance of the students instructed with our student's text can be found, further analysis is needed. One presupposition was that student benefit in our course from the consistent use of the sender-receiver model of vision. Based on the unique features or the course mentioned above we therefor draw the hypothesis that both groups differ even more concerning items on the concept of vision.

5 Research Design and Methods

This study was conducted in Austrian year 8 high school classes. In 5 classes (N = 125) our student's text was used for the instruction of introductory optics. The physics teachers (N = 3) of these classes were not explicitly introduced to the student's text, nor were they given any additional details about the theoretical background. A short informal meeting took place with each of the teachers individually before the intervention. There the teachers were also asked to fill in a log book after each lesson for reasons of documentation. Additionally, after the intervention their impressions were collected during a second short meeting.

Conceptual understanding of the students was measured with a concept test which was in accordance with the requirements of the Austrian curriculum related to geometrical optics. The concept test was designed as a multiple choice test and its items were based on common misconceptions discovered in former studies (cf. STCSE). Details concerning the test and its development can be found in Haagen-Schützenhöfer and Hopf (2012a, b, 2014a, b). Versions of the test with varying lengths were administered as pre- and post-test before and some time after the intervention in paper and pencil form. Both test versions contained next to other items, nineteen equal items, of which ten were two tiered.

In order to be able to contrast the post instructional knowledge base of our intervention group with the knowledge base of "average Austrian high school classes" after intervention in optics, a baseline for conventionally instructed year 8 students was needed. Therefore the optics concept test was administered in 16 classes of 10 Austrian schools. We invited teachers from different parts of Austria to take part in this test, which was administered in paper and pencil form. Among all the teachers, who were willing to take part with their classes, we selected those who had fulfilled the year 8 curriculum and who had taught optics in the summer term. These conditions helped to make sure that time lags between the end of the intervention and the post-test were comparable. The version of the concept test administered contained also the subscale of nineteen one-tiered items, which was used for the intervention group. The teachers (N = 13) who took part in the testing also filled in a short questionnaire containing mainly open questions about their optics lessons (how many lessons, which subtopics were taught, which schoolbooks and materials were used, which problems were caused by the student's text, etc.).

At this point, before reporting the results, the handling of missing data needs to be clarified. Single missing values were interpreted as not known. If a full questionnaire was missing (e.g. because of absence) or if only a part of the questionnaire was filled in (more than one item missing), the student was excluded from the analysis. These restrictions result in a total sample size of 93 students in the intervention group (49 female, 40 male, 4 not assignable) and 393 students in the baseline group (169 female, 196 male, 28 not assignable). Data was analysed with IBM SPSS 22. Cronbach's α was 0.57 in the pre- and 0.70 in the post test.

6 Results

First, the characteristics of the sample are described. The total number of students investigated was 93 in the intervention group and 396 in the baseline group. The students' mean age in the intervention group was M = 13.8 years (SD = 0.571) and M = 13.99 years (SD = 0.585) in the baseline group. The groups were also compared according to their last marks in physics. The Austrian system uses marks from 1 to 5, 1 stands for excellent and 5 for fail. The average mark in physics was M = 2.15 (SD = 0.988) in the intervention group and M = 2.23 (SD = 1.077) in the baseline group. A Mann-Whintey U-Test was performed which shows no significant difference (sig = 0.618) between the groups at a 0.05 significance level.

At first, the hypothesis was tested whether the intervention group could improve their conceptual understanding of key-ideas of geometrical optics (Research Question I). Results of the pre- post-gains of the intervention group are displayed in Fig. 1.

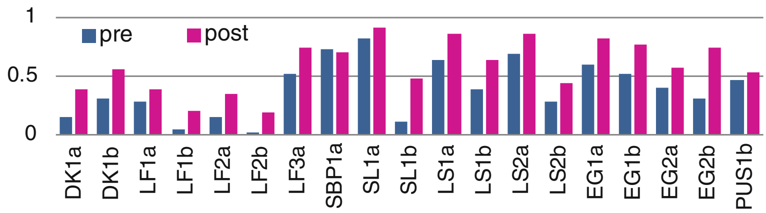

Fig. 1 Comparison of pre- and post-test solution frequencies on item level (intervention group)

In order to answer research question one, the pre- and post-tests of the students of the intervention group were compared. The analysis carried out represents the intra-individual gain in knowledge. Pre- and post-tests were rated as sum scores, with a maximum score of 19 points. The t-test on paired differences indicates a highly significant difference between the mean pre- and post-test scores of the intervention group ($t(92) = -11.855$, $p < 0.001$). To get an impression of the effect of the interventions, Cohen's d was calculated and shows a big effect ($d = 1.31$).

Secondly, we tried to find out whether the intervention group outperformed the baseline group in the post-tests (Research Question II). We ran a t-test on independent samples, comparing the means of the post instructional sum scores of the intervention- and the baseline group. The results of the performed Levene test report the equality of variances ($F = 0.329$, sig = 0.566). The t-test indicates that the students of the intervention group perform significantly better in the post optics concept test ($t\ (484) = 10.197$, $p < 0.001$). The overall effect size due to the treatment is big ($d = 1.18$).

Finally, an analysis on the level of individual test items was carried out. Figure 2 shows the mean solution frequencies for both groups. Depending on the items the performance gap between both groups seems to be different. One hypothesis was that the intervention group may have an advantage solving items based on the sender-receiver model of vision (Research Question III). A closer analysis on this hypothesis was carried out. Therefor, items which are based on the sender-receiver model of vision (DK1b, SL1b, EG1a, EG1b, EG2a, EG2b) were analysed in detail.

T-tests on independent samples, comparing the means of the post instructional sum scores display that 5 (DK1b, SL1b, EG1a, EG1b, EG2b) out of these 6 items show a highly significant difference between both groups (see Fig. 3). This difference is in favour for the intervention group, as a comparison of the solution frequencies confirms (see also Fig. 2).

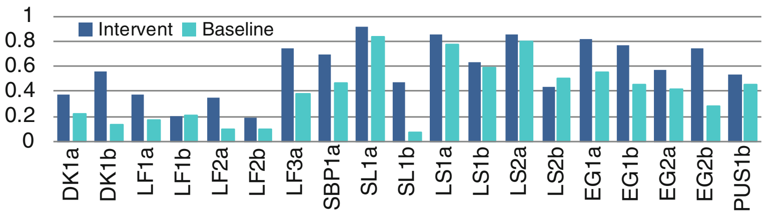

Fig. 2 Solution frequencies of intervention and baseline-group in the post-test on item level

Fig. 3 Comparison of group performance on item level: items based on the sender-receiver model of vision are highlighted

Independent Samples Test			
	t-test for Equality of Means		
	t	df	Sig. (2-tailed)
DK1a	3,247	484	,001
DK1b	9,543	484	,000
LF1a	4,309	484	,000
LF1b	-,147	484	,884
LF2a	6,604	484	,000
LF2b	2,378	484	,018
LF3a	6,537	484	,000
SBP1a	4,016	484	,000
SL1a	2,082	484	,038
SL1b	10,159	484	,000
LS1a	1,416	484	,158
LS1b	,734	484	,463
LS2a	1,008	484	,314
LS2b	-1,003	484	,316
EG1a	4,886	484	,000
EG1b	5,894	484	,000
EG2a	2,537	484	,011
EG2b	8,811	484	,000
PUS1b	1,240	484	,215

7 Conclusion

The reported study investigated the effectiveness of research based teaching materials, which were developed within a course for introductory optics for year 8. The design of this course, which followed the paradigm of Design Based Research, was based on earlier developments by Wiesner et al. (1995, 1996). The results indicate that the course in its present form, having undergone several changes and adaptions, is qualified for further use.

The analyses reveal that the students of the intervention group could improve their achievement significantly.

Concerning conceptual understanding, the results of the concept test show that the intervention group clearly outperforms the baseline group. This can be interpreted in the way that the developed student's texts are more effective in fostering conceptual understanding on basic key-ideas of optics than conventional instruction. At this point it is also important to stress, that one of the distinguishing features of this course, the continuous use of the sender-receiver model of vision, seems to be one quality factor, since the students of the intervention group performed significantly better on this key-idea. All in all, this may be a hint that we are coming closer to our goal of finding informal channels of bridging the gap between research findings and school reality.

It can be assumed that the unique content structure of the course, as well as the way the key-ideas were reconstructed, contribute to better conceptual understanding. This is remarkable, especially since the teachers implementing the student's text were not introduced to the underlying framework and theoretical considerations of the course. So it is likely that the implementation of research based ideas into the student's text was already enough to achieve good effects. However, it has to be kept in mind, that we do not have any hint concerning the level of pedagogical content knowledge of the three teachers involved. So a direct cause-effect relation between the student's text and the learning output cannot be drawn. One hypothesis which needs to be investigated is, however, that accompanying teacher training or a teacher's book may lead to even better learning outputs.

However, there are some limitations to this study: Conclusions from the obtained results are restricted by the small number of teachers in the intervention group. A detailed analysis on the level of two-tiered items will need to be made to gain deeper insight into conceptual relations. Since optics is usually taught at the end of the school year, it was not possible to administer follow-up tests, so retention could not be investigated.

In conclusion, it can be said that the results achieved within this sample reported here show a general positive influence of the student's text on conceptual understanding in introductory optics. However, further research is needed to find out if this success is long-term and which role the teacher and his or her anticipation of the theoretical considerations of the course play.

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Building the Basic Concepts of Quantum Mechanics with Math and Computer Science Students

Marisa Michelini, Francesca Monti, Lorenzo Santi and Giacomo Zuccarini

Abstract A teaching module of eight hours was carried out with four computer science Ph.D. students and five math students enrolled at the University of Verona (Italy) in order to calibrate an Inquiry-Based proposal on Quantum Mechanics for non-physics majors and to develop educational supporting tools. The path is situated in the context of linear polarization of photons, employing a formal approach based on the description of the quantum state as an abstract vector, both representing a needed background for students interested in Quantum Computing and Quantum Cryptography. A special focus is given to the superposition principle and its interpretation in a particle-like description, as well as to the different and new meaning of measurement. Single photon entanglement and the superposition of spatially separated states are also addressed. The proposal includes exploration through real experiments with macroscopic light beams, using Polaroid filters and birefringent crystals, and through ideal experiments on single photons, using a specifically developed Java applet. Seven worksheets were developed to support student concept building. Preliminary data analysis elicits two important conceptual hurdles: recognizing the active role of Polaroid filters with respect to the polarization of the photon; recognizing that a single particle can exist in a superposition of spatially separated states.

1 Introduction

Teaching Quantum Mechanics (QM) is becoming of increasing importance both for graduate and post-graduate non-physics majors, such as math and computer science students. This is true not only for those who are interested in the field of Modern

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Physics teaching at the high-school level (as required by the new Italian ministerial high-school program), but also for future researchers in the advanced fields of Quantum Computing (QC) and Quantum Cryptography (Quantum Key Distribution, QKD). Working both in QC and QKD fields, in fact, requires getting a functional understanding of basic aspects of QM. Quantum computers will in principle be capable of operating with quantum bits, i.e. quantum mechanical systems that can be in any possible superposition of two mutually exclusive physical properties. On the other hand, Quantum Key Distribution relies on random measurements of incompatible observables—namely the Horizontal/Vertical and the 45°/135° linear photon polarization—on a sequence of single photons sent from a sender to a receiver or on a sequence of two perfectly correlated photons. Quantum protocols are based either on single photon technologies (Bennett and Brassard 1984) or on two photons technologies and entanglement (Ekert 1991; Bennett 1992) and are able to guarantee the secure transmission of secret information because any interference with the process of sharing the key would destroy the perfect quantum correlations of the outcomes obtained by the sender and the receiver. Therefore, the professional formation of specializing students in these topics requires learning how to manage concepts and formal structures concerning the contexts of linear polarization of photons, building a functional understanding of mutual exclusive and incompatible properties, of the superposition principle, of photon entanglement, as well as of the new and different concept of measurement in quantum mechanics. The Udine research unit has developed an Inquiry-Based Learning proposal aimed at building the basic concepts of QM and related formal structures in the context of linear polarization (Ghirardi et al. 1995; Michelini et al. 2000; Michelini et al. 2004; Michelini and Stefanel 2010). Their approach focuses on the superposition principle and on its meaning and implications when passing from a macroscopic description of light to a particle-like description down to the single particle level, with the aim of introducing the need for a probabilistic interpretation. The proposal is situated in the two-dimensional space of linear photon polarization, avoiding technical difficulties related to the ordinary infinite-dimensional Hilbert space. It includes real experiments on light polarization using Polaroid filters and birefringent crystals and simulated experiments on single photons using a specifically developed Java software (JQM, Michelini et al. 2002).

In this work, we modify and develop the Udine approach in a pilot intervention for teaching QM to non–physics majors, with the aim of identifying critical points and most meaningful questions, and of optimizing the design of the worksheets. The educational path has been extended towards single-photon entanglement of modes and for the first time proposed to computer science Ph.D. students interested in QKD and QC. The present pilot formative intervention module of eight hours, developed through seven worksheets, was carried out with five math students and four computer science Ph.D. students enrolled at the University of Verona (Italy). Preliminary data analysis and results will be discussed with reference to the first worksheet, concerning the role of Polaroid filters, and to the last worksheet, concerning the role of birefringent crystals.

2 Context and Background

The Computer Science Department of the University of Verona has a long-term tradition in research fields related to QC and QKD. In 2015 a new 20 h course on "Physical Principles of Quantum Computing and Quantum Cryptography" was proposed for the first time to four Computer Science Ph.D. students. The original Udine approach was inserted in the course as an eight hours module which was also followed by five math students of the Master Degree in "Mathematics", in the framework of a Modern Physics course comprehensive of 18 h dedicated to QM and lectured by the same teacher.

Students had none (Computer Science students) or only limited (Math students) laboratory experience and knowledge of measurement theory and error analysis. All of the students had the same background about electromagnetism and electromagnetic waves and about the concept of photon, previously introduced through the photoelectric and Compton effects.

3 Educational Path and Worksheets

Seven worksheets were developed by the Udine research unit in order to meet specific demands of the sample of students on whom the educational intervention has been conducted. All of them have been used. The rationale of the educational path implemented in the worksheets is the following.

The path starts with a qualitative exploration of the interaction of light with Polaroid filters in order to address the concepts of preparation and analysis of polarized light, to identify the polarization direction (polarization property), and to recognize the active role of the filter. A quantitative study of the interaction of light with two Polaroids allows then to obtain the Malus law, by varying the angle between the polarization property prepared by the first filter and the permitted direction of the following one. The discussion of the Granger-Roger-Aspect experiment provides an empirical basis to the idea of a granular nature of light. This is used to support the hypothesis that photons represent the elementary components of light. Describing the property of light polarization in a photon model entails identifying polarization as a property of the individual photon, which represents the main requirement for the analysis of a sequence of single photon experiments interacting with one or two Polaroid filters. Performed by means of JQM applet (JQM, Michelini et al. 2002), these experiments are used to discuss preparation and analysis of the Malus law in the case of single photons. By focusing on the interaction between photons and Polaroid filters, students are led to identify mutual exclusivity and incompatibility between polarization properties. The outcome-properties of a photon-filter interaction are the basis for introducing quantum measurement and its essential features, i.e. its active character and its genuine statistical nature. A deep discussion concerning the comparison between the concept of state in the classical perspective and in the quantum one allows the introduction of the formal representation of a quantum state as an abstract vector of unitary length. The distinction between property and state is underlined both on the conceptual and on the formal level. Coming back to the macroscopic level, a phenomenological exploration by means of birefringent crystals paves the way to the discussion of the superposition principle, of the concept of trajectory and of single photon entanglement of modes. These aspects are explored in JQM by sending single photons and photon beams through one birefringent crystal and then through a couple of direct and reversed birefringent crystals. The transition probability is the bridge for ascribing physical meaning to the coefficients of each basis vector in a superposition, allowing a clear distinction between a mixed and a pure state. The value of the continuous change in perspective from macro and micro levels is completed by the single photon interpretation of the Malus law.

The structure of each worksheet is the following:

(A) the problem: the proposed "attack angle" to the selected conceptual node is offered in problematic way
(B) the situation: the problem is set in one or two experimental situations, each of them allowing to overcome a specific conceptual aspect
(C) the prediction: for each situation students predict the results of the proposed experiment, in connection with a well defined qualitative or quantitative aspect on real or ideal level
(D) the experiment: students perform the experiment, describing some selected aspects
(E) the comparison: students compare predictions and outcomes of the exploration in order to identify analogies and differences
(F) the conclusions: a short sentence is required to summarize the conclusions.

Each worksheet addresses a specific subject.

WS1 to WS3 aim at exploring and constructing concepts using Polaroid filters in real experiments with light and in simulated experiments with single linearly polarized photons (JQM): Malus law, incompatible and mutually exclusive properties referred to two polarization basis (Horizontal and Vertical), (45° and 135° degrees), quantum measurement.

WS4 aims at bridging the concepts to their formal representation: quantum state, measurement and probability.

WS5a and WS5b aim at bridging previously constructed concepts to the phenomenology of the interaction of photons with a single birefringent crystal in real experiments with light and in simulated experiments with single linearly polarized photons (JQM): distinction between quantum superposition and statistical mixture of states.

Finally, W6 aims at introducing the concept of the superposition of spatially separated states and single-photon entanglement with two (direct and reversed) birefringent crystals.

4 Preliminary Data Analysis and Results

In order to illustrate how the phenomenological approach is implemented at the macroscopic level and how student ideas are taken into account in facing the problem of the state of the photons interacting with birefringent crystals, we present the results of the analysis of some selected questions from worksheets WS1 and WS6.

4.1 WS1: Active Role of Polaroid Filters

WS1 addresses the problem of identifying the results of the process of interaction of light with Polaroid filters in terms of transmitted intensity of light and its polarization direction, therefore building an awareness of the active role of the filter. By raising the question of the distinction between the observed quantity (the intensity of transmitted light) and the property producing its reduction (polarization), this task paves the way to an analysis of light beams in terms of single photons and of the active nature of quantum measurement.
All of the 9 students answered to this worksheet.

4.1.1 Item C3

In WS1, item C3 asks to explain what determines the intensity and polarization of light transmitted through a couple of Polaroid filters crossed at a generic angle α (Malus law). Answers were analysed through the following research questions:
(RQ1) do students distinguish between polarization properties and intensity?
(RQ2) how do students understand the active role of Polaroid filters?

C3.1 Light polarization after the second Polaroid is determined:

(a) only by the permitted direction of the first one;
(b) only by the permitted direction of the second one;
(c) by the relative orientation of both allowed directions;
(d) something else (explain).

Here 6/9 students gave the correct answer (b). 3/9 gave answer (c), hence putting into evidence an ambiguity between the property of light polarization and light intensity as a property itself: students tend to favor light intensity because the polarization is detected through light intensity in the Malus law.

C3.2 Light intensity after the second Polaroid filter depends on (students were asked to complete the sentence):
Here all the students gave the correct answer: light intensity depends on the relative orientation of the two Polaroids.

Intensity emerges as a familiar concept that students easily handle: all of them answered that light intensity after the Polaroid filters depends on their relative orientation.

C3.3 Explain your answers and draw a sketch to illustrate them.

Here 8/9 students draw a sketch:

5/8 represented a couple of crossed Polaroids at a generic angle (Fig. 1).
3/8 consider also or only the case of a 90° angle (Fig. 2).
In the explanation the attention is focused:

For students who chose answer C3.1—c: on the light as a generic physical entity, on the angle and on the intensity or gray tone of the transmitted light

For students who chose answer C3.1—b: on the relation between α and the intensity of the transmitted light as related to its polarization.

Comment to WS1-C3. In tutorials, attention must be paid to the distinction between the permitted directions of Polaroid filters and the transmitted intensity as strongly correlated to the polarization properties after each Polaroid and after a sequence of Polaroid filters. This activity can be fruitfully used to introduce the

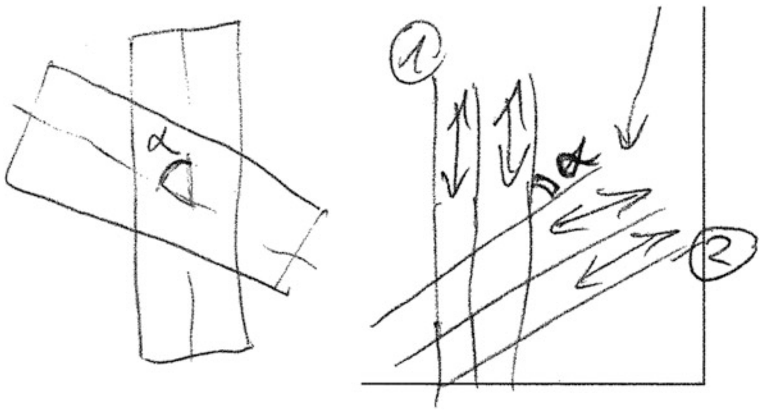

Fig. 1 Answer to item C3.3: example of student sketches showing Polaroid filters crossed at a generic angle

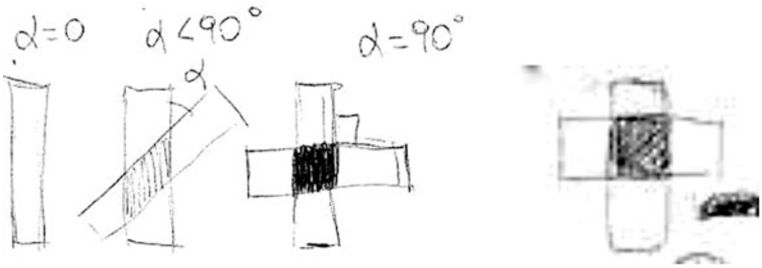

Fig. 2 Answer to item C3.3: two student sketches showing Polaroid filters crossed at a 90° angle

distinction between polarization state and consequences of the interaction (active role of the Polaroid as a selector of state).

4.2 WS6: Role of Birefringent Crystals

WS6 addresses the problem of identifying the effect on the photon of its passage through birefringent crystals in determining its polarization and trajectory at the exit of the crystal and during its propagation inside the crystal. Four students (2 math and 2 computer science) answered to this worksheet.

4.2.1 Item B

WS6, item B (Fig. 3) asks students to analyse the polarization properties of a single photon prepared in a 45° polarization state and detected at the exit of a couple of direct and reversed birefringent crystals that have been cut and positioned in such a way that the ordinary beam corresponds to the vertical polarization (V) and the extraordinary beam to the horizontal one (H).

B1. Experiment: send a beam of 100 photons.

B1.1 Which fraction of the incident photon beam is transmitted through the second crystal?

All the students recognize that 100 photons are detected.

B1.2 Which fraction of the incident photon beam is detected after the Polaroid?

All the students recognize that 100 photons are detected.

B1.3 Which is the polarization of the transmitted photons after the second crystal?

3/4 students gave the correct answer: 45°

1/4 says that the polarization after the second crystal is H or V, evidencing that he considers the beam as a statistical mixture.

B2. Reasoning: make a motivated hypothesis and give a graphical representation about the way the polarization of a single photon behaves from emission to detection.

B3. Reasoning: does a single photon follow a well-defined trajectory from emission to detection? Why? Which? Make a hypothesis and give a graphical representation.

As regards items B2 and B3:

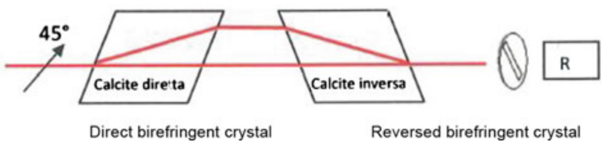

Fig. 3 Set-up of the situation proposed in item B: photons are prepared in a 45° polarization state and detected at the exit of a couple of direct and reversed birefringent crystals. The ordinary beam corresponds to the vertical polarization (V) and the extraordinary beam to the horizontal one (H)

1/4 says that the polarization is splitted following the Malus law; no graphic is sketched. The photon "chooses" a trajectory.

1/4 (Fig. 4) answers that the polarization is the H or V component of the electric field in the respective channel; in the graphical representation at the exit of the second crystal each photon has the H or V polarization and after the Polaroid the two polarization states are recombined and all photons are detected; the photon travels on the ordinary and extraordinary channel with a 50 % probability in each case; after the second crystal all photons return on the same channel and all pass through the Polaroid.

1/4 (Fig. 5) gives a similar answer but with reference to photons not to the electric field.

1/4 (Fig. 6) answers that the polarization changes because photons are splitted into two channels but at the exit "same channel" means "same initial polarization"; in the graphical representation some kind of a continuous change in the polarization state of the photons is sketched; each photon follows one of the two possible trajectories.

Comment to WS6-B. Students answer that photons follow a well-defined trajectory and have a defined polarization state. They look for an explanation of how these two polarization states are recombined after the second crystal or after the 45° Polaroid. This shows that the interpretation of spatially separated superposition states represents a deep hurdle to a consistent interpretation of quantum superposition.

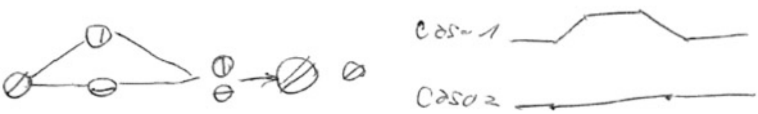

Fig. 4 Answer to item B2 and B3 by one of the students: sketches show that the photon polarization is the H or V component of the electric field in the respective channel and the corresponding photons trajectories. The Italian words "caso 1" and "caso 2" in the sketches mean "case 1" and "case 2", respectively

Fig. 5 Answer to item B2 and B3 by one of the students: sketches show that the photon polarization is H or V in the respective channel and the corresponding photons trajectories. The Italian words "DIRETTA" and "INVERSA" in the sketches mean "direct" and "inverse", respectively

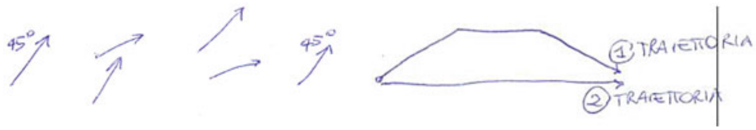

Fig. 6 A student's answer to item B2 and B3: sketches show a continuous change in the polarization state of the photons and the corresponding trajectories. The Italian word "TRAIETTORIA" in the sketches means "trajectory"

4.2.2 Item E

In WS6, item E asks to discuss the effect of the interaction of a birefringent crystal with a single-photon.

E1.1 Compare the photon polarization when photons enter the first crystal with the photon polarization when they are detected at the exit.

Here, all the students recognize that the photon polarization remains unchanged.

E1.2 Remove the 45° Polaroid filter at the exit of the two crystals and send linearly polarized photons at different angles (e.g. at 30° and at 60°) using JQM. Do photons at the exit have a different polarization state?

Here, all the students recognize that the photon polarization remains unchanged.

E2 In the propagation through the two crystals, do photons acquire the polarization state corresponding to that of each respective channel in the crystals?

Here 1/4 recognizes that photons do not acquire a defined polarization state, while 1/4 answers that they do and 1/4 answers that "it seems" they do.

E3 What can be said about the polarization state of the photon during its propagation inside the crystals?

Here one student didn't answer and all the others gave different answers: it acquires the polarization of the "chosen" channel; photons are polarized H or V independently of their initial polarization; once acquired, the polarization remains unchanged.

E4 Does the crystal make a polarization measurement on the photon?

Here one student wrote he doesn't understand the meaning of the word "measurement"; 1/4 answered that the crystal does a measurement because the polarization state changes; 2/4 answer that the crystal doesn't make a measurement on the photon.

E5 Give an explanation of the effects on the photon of its interaction with the birefringent crystal

Here 2/4 do not answer; 1/4 says that the crystal changes the photon polarization; 1/4 answers that it seems that the crystal polarizes the photon according to each channel, as though the crystal was made of two H and V Polaroid.

Comments to WS6-E. Students discriminate between what happens during the propagation and what happens at the exit of the crystal as regards the polarization state. The visualization of the two trajectories seems an obstacle to a consistent interpretation of the superposition principle. As a consequence, we will consider for future purposes using a different graphical representation, as sketched in Fig. 7.

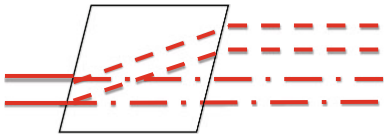

Fig. 7 Sketch of the photon beam paths inside a birefringent crystal

5 Conclusions

Preliminary data analysis allows highlighting two main conceptual issues and making some general comment.

Concerning the role of Polaroid filters, tested students interpret the relation between the property of photon polarization and the permitted direction of a Polaroid in terms of the outcome of an interaction but not in terms of an active role of the Polaroid. There is a difficulty in recognizing the active role of Polaroid filters with respect to the property of light polarization. As this is a pre-requisite to identify the active nature of quantum measurement in a photon model of light, a need emerge to modify the worksheet, in order to support students in developing an awareness of the distinction between the observed quantity (the intensity of transmitted light) and the property producing its reduction (polarization).

As regards the role of birefringent crystals, the behavior at the exit of a single crystal is interpreted in terms of interaction outcome but not in terms of the role of the crystal in determining an entangled superposition of two trajectories and of two polarization states. Students' tendency to assign a well-defined trajectory to a particle leads to the need of assigning a well-defined polarization state. The superposition principle was introduced in the space of polarization states, but recognizing that a single particle can exist in a superposition of spatially separated states remains a problematic issue for students.

Both for math students and for computer science one, the inquiry-based approach represented a totally new experience. In an informal discussion, most of them expressed a positive attitude towards the approach. Math students in particular showed interest not only in the scientific contents of the module, but also in the approach itself and in its possible applications, in the eventuality they become high school teachers.

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Preliminary Data Analysis of SSQ-HOPE Questionnaire on Factors Inspiring Secondary Students to Study Physics

Marisa Michelini, Gesche Pospiech and Alberto Stefanel

Abstract SSQ (Secondary School Student Questionnaire)-HOPE questionnaire is one of the actions of the EU HOPE-Project (Horizons in physics education), a cooperation project of 71 European partners. The HOPE-project is striving to find ways to inspire young people to study physics (Working Group 1—WG1). SSQ is part of it in concentrating on the transition school-university with a focus on the factors motivating secondary school students which are talented in physics to study physics. In order to reach the pre-defined target group the questionnaire was distributed in events with physics content mostly taking place at universities, research institutions or at similar occasions. In order to identify promising activities information on the type of event, its characteristics and the process of selection of students were collected. From the preliminary administrations the role of open questions emerged which are necessary to get a quite precise impression of the reasons inducing students to study physics and the role of the school in relation to outreach activities. A preliminary analysis of the data collected with a restricted sample of 139 students participating in the International IPPOG-Masterclasses in the universities of Udine and Dresden is presented here. From the data emerged that a positive decision to study physics seams highly correlated to existing deep interest and perceived traits of a physicist.

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1 Introduction

Several studies and international surveys analysed the generalized problem of diminished interest in scientific studies, both at the high school level (Lavonen et al. 2005; Trumper 2006; Lemonick 2006; Sjøberg and Schreiner 2010) and at university, as well as in pursuing careers in these fields (TIMS 2007; Sadler et al. 2012; AIP 2015; IOP 2015). Correlation between this lack of interest and the results of international surveys such as OECD-PISA (Basl 2011) have highlighted significant differences between males and females (Lavonen et al. 2005; Mitchell and Dianne 2006; Sadler et al. 2012). Furthermore they showed that students have a perception very partial if not distorted of scientific studies and of the profile of a physicist (Aschbacher et al. 2009; Bevins et al. 2005; Gray et al. 2008; Hong and Lin-Siegler 2011).

On the other hand, there is evidence that the school and connected activities may play an important role in activating motivation and interest in science in general (Schraw et al. 2001; Eurydice 2006; Martin et al. 2008; Swarat 2008; Basl 2011). For physics, the effectiveness of problem-solving activities (Erdemir 2009), of educational lab-based activities and in particular of the use of new technologies in lab (Hofstein and Lunetta 2004) for involvement and activation of learning as well as interest have been shown. The research on the teaching/learning of modern physics at school showed the strong interest of students for both fundamental theories, and specific areas such as elementary particles, astrophysics and superconductors (Ostermann and Moreira 2000; Lavonen et al. 2005; Michelini et al. 2014).

Although it is clear that the motivation and interest are decisive factors for the educational success as well as the choice of future careers, much work remains to be done to identify which factors, aspects and content may enhance this motivation and interest in several specific disciplinary areas and physics in particular. Furthermore it remains an open question what hints can be suggested to implement effective actions enabling effective and lasting interest and motivation in young students to study physics.

The identification of these inspiring factors and their role is one of the objectives of the European project HOPE (Horizons in physics education—http://hopenetwork.eu/content/horizons-physics-education). The HOPE-Project is a cooperation of 71 European partners striving to find ways to inspire young people to study physics (Working Group 1—WG1), to enhance physics education on university level (WG3), to smoothen the transition from university into the professional career (WG2), to improve and support physics teacher education and professional development (WG4).

Different inquiries and inventories are being carried out for these different scopes. In the present work we concentrate on the transition school-university with a focus on the factors motivating secondary school students, which are talented in physics, to study physics. It is well known that also students interested in physics do not study physics in each case. Therefore the goal is to gain insight into factors that act positively on the choice of physics as field of study and to shed light onto the conditions of this choice. Hence we identified as target group students in the last two years of school education before university. They should be highly interested in physics and be involved in the decision process about their field of study or even already have chosen it. To explore factors activating interest in young students the HOPE work group has developed a questionnaire which was administered by several partners of the HOPE-project.

In order to reach the pre-defined target group the questionnaire was distributed in events with physics content mostly taking place at universities, research institutions or at similar occasions. In order to identify promising activities information on the type of event, its characteristics and the process of selection of students were collected. In the following we discuss the process activated to set up the questionnaire and some preliminary results will be presented.

2 Theoretical Framework

Concerning interest our reference was the Krapp model of interest (1999, 2002). According to the person-object-theory of interest by Krapp: "An interest represents a (…) specific relationship between a person and an object" (Krapp 2002, p. 387), where object "can refer to concrete things, a topic, an abstract idea, or any other content of the cognitively represented life-space" (Krapp 2002, p. 387). "Value-related and feeling related valences" are relevant "for his or her sense of self" (Krapp 2002, p. 388). For that reason it is useful to explore interest along different dimensions: cognitive, emotional and value-related components of an interest relationship. According to Krapp different aspects of interest-related phenomena must be taken into account. Qualitative and quantitative data must be combined in order to extract the relationship between interest and the different factors for the choice of field of study: emotional, value-related, but also content–structure of the interest domain and in particular, concerning our work, relevant aspects of physics (Krapp 1999).

In our perspective an important dimension related to interest in physics study is the image that students have of a physicist and those traits they recognize in themselves. Students construct their identities and may loose their interest in pursuing a career in sciences during high school because of a perceived mismatch with the own personality. In this perspective we agreed that "many of the Lost Potentials perceived school as their only access to science and only window on the world of scientists." (Aschbacher et al. 2009). That extra curricular activities might be helpful is shown by the results of Aschbacher et al. (2009), that "working in a real laboratory helped break her stereotype that only certain kinds of people could become scientists".

3 Goals of Research and Design of Study

The intention is to characterize students and their needs just before their choice of subject for study at university, the inspiring factors and their motives. Therefore it is appropriate to choose selected students who are more than average interested in physics and show an inclination towards a career in science or engineering in general, and especially in physics. In order to recruit this group of students we applied several criteria for the selection. The students should be in the last two years before the final exam of school before going to university. This enhanced interest should be documented by additional activities concerning physics, e.g. participation in out-of-school physics events e.g. Masterclasses, Mastering of olympiade in physics, successful application and attendance of summer schools in physics, choice of advanced courses in school, participation of extra work groups in physics or similar.

From the answers we expect information about how the actual enrolment of this special group in physics degree courses can be enhanced by offering events, courses or advice adopted to their special needs. For identifying appropriate offers the following questions have to be answered:

3.1 Research Questions

- Does the group of students with positive attitude towards study of physics show a special pattern of interest?
- Which presumed traits of physicists do the students see in themselves?
- Which aspects of physics or doing physics have contributed to their choice?

4 Method and Instruments

In the context of the HOPE project, the working group 1 (WG1) was established to investigate the factors that inspire the study of physics. The main task is to conduct a survey of first-year students of university courses in physics. For that goal a questionnaire for university students was set-up (SAQ). In parallel it was considered important to collect analogous data from secondary school students to be compared with those of the questionnaire administered to university students. For this purpose a specific questionnaire was designed to be submitted to secondary school students (SSQ), including the SAQ items, to perform the comparison of data and specific items concerning the secondary school students. These specific items were formulated after a long revision process addressed by two preliminary pilot studies performed using two draft-versions of SSQ. The preliminary studies were conducted in Udine: the 1st pilot study involved 57 good students from the surroundings of Udine attending IPPOG Masterclasses in March 2014; the 2nd pilot study involved 29 students selected from the best school students in scientific subjects of all Italy attending an intensive Summer School on modern physics. These data, presented at the Hope Helsinki Forum in September 2014, gave important indication to set-up the final version of the SSQ questionnaire, distributed to the partners in January 2015.

The final version of SSQ questionnaire consists of four parts, distributed in two pages (Michelini et al. 2015):

(1) Evaluation in 5 levels Likert scale of the interest in physics in several dimensions according to the interest construct following Krapp (1999)
(2) Open questions concerning factors influencing the choice of a career as well content-related aspects as social aspects such as the image of a physicist
(3) Factors inspiring young people to study physics (5 level Likert scale items of SAQ)
(4) Information that students give anonymously, such as gender, age, type of school and intention of study.

Part 1 contained nine items on interest in physics, physics research and a career in physics. These were constructed on the basis of an existing questionnaire relying on the construct by Krapp (Gedigk 2014). These were answered on a 5 point Likert scale. Part 2 contained three open questions concerning the reasons why they wanted to study physics, which topics in physics they considered most interesting and about the perceived identity of physicists and their occurrence in themselves. These were evaluated according to categories that were inductively found with part of the material and discursively validated. The remaining part of the material was then coded according to a manual. Part 3 contained again 21 closed items on inspiring factors with a 5 point Likert scale. These were taken from a questionnaire developed in the framework of the HOPE-project (Jones 2015).

To ensure an homogeneous administration of the questionnaire and data collection, the following materials were sent to the partners of the SSQ community: (A) The questionnaire SSQ; (B)Template for SSQ sample description (half page); (C) Template for SSQ data collection event description (half page); (D) Prepared Excel sheet for data collection; (E) Guidelines for administering and preliminary data analysis, with examples and operative definition of qualitative categories.

The HOPE-SSQ community includes 19 partners of 14 countries (Fig. 1). Data was collected from more than 1300 students in more than 70 events of three different types: intensive course at University (i.e. Summers School); educational lab activities (i.e. Masterclasses); activities related to Physics Olympia at local or national level.

5 Results of Preliminary Studies

From the 1st preliminary study, it emerged that the external factors (i.e. TV documentaries, Books or Magazines; Museum Visit; Laboratory Visit; Visit from University Staff/Students to school; Internet) were equivalently scored by students (from 2.6 to 3.2 (maximum 5) and a standard deviation of 1.3). The importance of the physics teacher is the factor most quoted in this section (mean 3.8 ± 1,3). Advices from friends and family appeared to have very little influence (2.1 ± 1.1). The main internal factors are: wish to understand the world, the universe, how things work (4.2 ± 1.1) and advanced physics (3,8 ± 1.1). The least scored factor was the perspective to become a physics teacher (1.8 ± 0.9). No significant differences emerged in male and female groups. From the open item "The most important factor that triggered interest in physics", answered by 17 of the 37 answering, more interesting indications have emerged: Curiosity (5/17) as well as interest in specific topics (8/17) triggered mostly male; visits to laboratories (4/7) and stimuli of family and friends (3/7) were quoted only by females. The open questions gave a rich overview on important factors and made explicit differences in the sample (otherwise quite similar); male-female differences became more evident and showed need for more insight into the role of school activities.

Concerning the 2nd preliminary study, analysing the answers to the open question "What are the factors that most motivate you to study Physics" it emerged that the interest in many students was triggered by characteristic of physics as a discipline (12/29—"The very general nature of this research"; "The capability to rationalize and model the reality that surrounds me"). Moreover from the answers to the question "I like to study physics at school for the following reason" showed some characteristic aspects of physics teaching in their experience (11/21), as for instance: interaction with teacher; interaction by peers; possibility to make experiments. The desire to improve the job prospects have a greater importance for females than for males (3.7 vs. 2.8). Creative activities were significantly larger for males than for females (3.8 vs. 3.3). Finally, for talented students the visits in laboratories or science museum and information are more important to inspiring for physics than for other students, as well as the role and usefulness of physics classes and the important role that physics could play in the future job or field of study.

6 Preliminary Results from Main Study

In the first round of the main study we selected students participating in the International Master classes conducted by CERN. There were 72 participants from Udine, all more than 16 year old and 69 participants from Dresden from which 40 were 16 year and older (see Fig. 2). In the evaluation we included only those students.

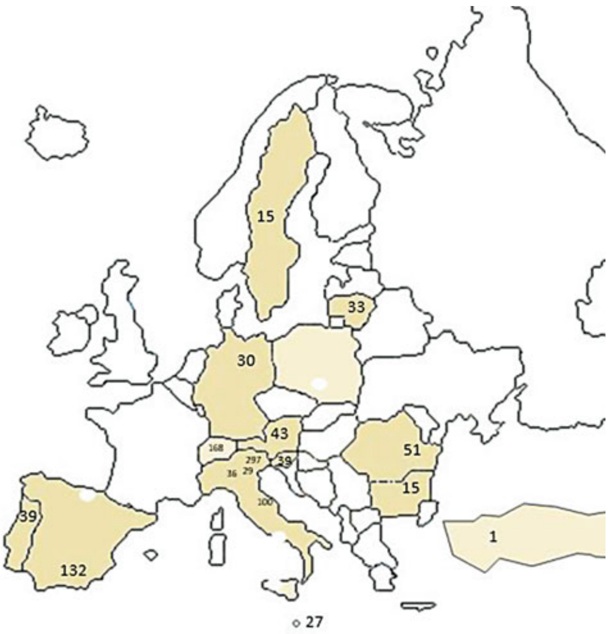

Fig. 1 Overview of the HOPE-SSQ community

6.1 The Relation Between Interest and Intention of Enrolment in a Degree Course

Here we describe the results on the specific patterns of interest in relation to the wish to study physics at university.

6.1.1 Description of Interest

From part 1 of the questionnaire (see previous section) we could extract three factors. The first factor described the subjectively perceived "Knowledge about physics research and the work of physicists" in the self-assessment (4 items, Cronbach alpha = 0.71). A sample item is "I have some insight into the goals of physics research." The second factor could be called "Deep interest in physics" with sample item "I like to be engaged in physics in my free time." (2 items, internal reliability = 0.81) and the third factor: "Attitude towards physics lessons at school" with e.g. "I learn useful things in physics lessons." (2 items, internal reliability = 0.81). The means of these factors are shown in Fig. 3.

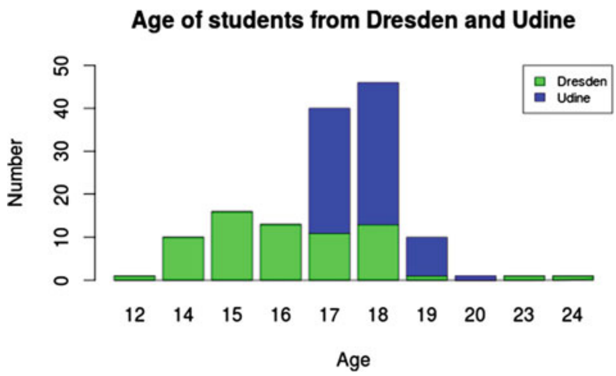

Fig. 2 Participants in the study. In the diagram all students participating in the event are shown. From these we selected only the students 16 year old or older. 72 from Udine (37f, 31m) and 40 from Dresden (10f, 30m)

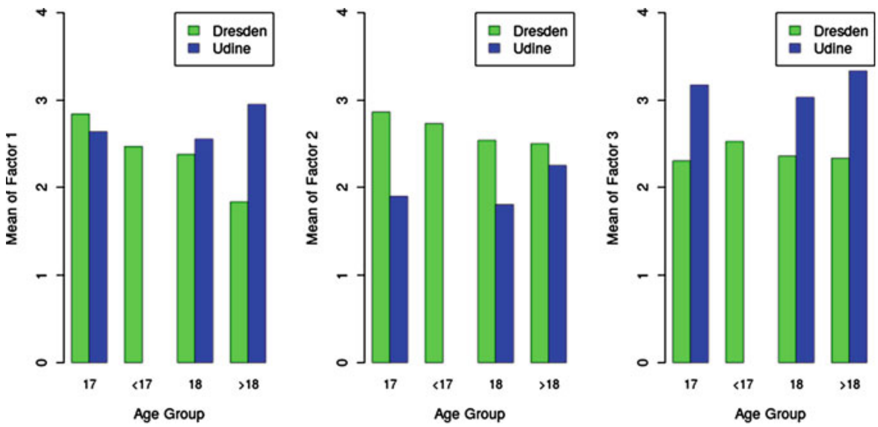

Fig. 3 Mean of the factors, separated according to the partners. The 5 point Likert scale was shifted towards the interval 0–4

6.1.2 Correlation of Interest with Intention to Study Physics

The research question aims at identifying special patterns or characteristics of those students who want to study physics or a related subject. There was a highly significant correlation of the factor "Deep Interest" with a positive decision towards physics ($p < 0.001$, Cramers V = 0.475) with a nearly large effect size. If the students show high interest but do not consider physics as a field of study they name other sciences or engineering subjects such as chemistry, engineering, computer science or medicine as preferred study. The factor "Knowledge on research and physicists" shows a weakly significant correlation to positive decision with a medium effect size. (p = 0.03, Cramers V = 0.22).

6.1.3 Qualitative Questions

The open questions should throw additional light on the structure of the interest of students intending to study physics. Especially we asked for the interest in the different topics of physics at school. These were systematized into 6 categories: Universe, Classical Physics, Modern Physics, Particle and Nuclear Physics, Application and others. There was no significant correlation with the intention to study physics. However, there was a trend that those students who want to study physics are more often interested in topics related to "Universe", whereas those students who do not want to study physics express more often interest in topics related to "Classical Physics", such as kinematics or electromagnetism.

Especially important for the decision about pursuing a career in science is the image of a physicist compared to the self concept. Therefore the question about the traits of physicists seems to be important. The answers were first categorized into 11 categories which then were condensed into 5 bigger categories: "*ability*" e.g. with statements such as "intelligent", "*curiosity*", also including "passion for science", "*inquiry*", expressed as e.g. "search for explanation of different processes", "not to be discouraged if an experiment fails the first time". Quite often also the aspects of mathematics was mentioned, which we called the "*mathematical mind*", often seen in statements like "logical thinking" or "precision". "*Other*" comprised perception of physicists such as creativity or other aspects of doing physics e.g. "big imagination" or "evaluation of statistics".

If we look for relations between the perceived traits of a physicist with the intention to study physics we find significant connections with a medium effect size ($p = 0.01$, Cramers $V = 0.235$). Especially we find that those students who do *not* want to study physics more often connect "ability" with a physicist. This might indicate that science is perceived as only suited for special persons. On the other hand those students who are *not yet decided* if they study physics more often connect "inquiry" with a physicist which stresses more the persistence or the desire to understand. Other correlations are not very pronounced.

If we ask for the reasons why students in their last two years of their school career choose physics on an advanced level we have identified seven categories that were mentioned: emotional aspects, personal interest, knowledge, scientific approach, insights, research, societal role, achievement. We wanted to know if students who want to study physics name some reasons more often. Here we find only weakly specific answers: Those students who *want* to study physics at university in a degree course more often name "emotional aspects" and "wish for knowledge" indicating that they have deep intrinsic motivation. Students who are *not yet decided* more often name "concrete scientific approach" or the "societal role" indication a type of interest more directed towards applications. Those students who decided *against* enrolment in a physics degree course indicate especially often "achievement" (i.e. good marks in science), but significantly less often the "concrete scientific approach", which means doing experiments or working in a laboratory.

6.2 Characterization of Positively Decided Students

In order to be able to develop attractive offers stabilizing the interest and the intention for enrolling in a physics degree course we asked for the reasons of such a choice. But only a small part of the participants in the study indicated their intention whether they wanted to study physics at university and gave a reason (17 participants out of 112).

Some of these see studying physics as a possibility of delaying the concrete choice of a profession with a big variety of possibilities (3/17). Some (4/17) have enjoyment as a driving motive, 8/17 utter the wish to understand the world and the universe, 1/17 names the importance for mankind. 4/17 are attracted by the logic and the possibility to calculate the physical processes. It is remarkable that 10/17 are interested in topics related to the universe and its origin; 1/8 seems to have already chosen a concrete subject (acoustics combined with electronics), which he pursues in his free time.

In addition we evaluated which traits of a physicist were perceived by this group with a throughout positive attitude. The most important appealing trait seemed to be "curiosity" mentioned by half of the students (9/17). The next important trait is the desire to know new things, to ask for the "why" and research them (7/17). Clearly weaker is the trait of "enjoyment" in the topic (4/17), "scientific work", "persistence" (2/17) or "logical thinking" (3/17).

6.2.1 Learning from Exceptions

It can be very instructive to analyse special cases, the exceptions from the general pattern: what can be constellations which are perhaps unexpected. Those cases broaden the experience and show the very different attitudes students could have towards doing physics as a profession.

There were a few students (three students from Udine) showing low interest but being positively towards studying physics at university. It was remarkable that they stated to have only little knowledge of physics research but showed high enjoyment of physics lessons. Therefore it seems that in these cases not extra-curricular or out-of-school experiences were decisive but probably the kind of lessons and the teacher. As traits of the physicists these few students mentioned "ability" and the "mathematical mind". The reason to choose physics at school was "research" and as interesting topic they named "Astrophysics" or "Mechanics". On the whole they seem to be very abstract thinking students, being easy with mathematics and liking rigorousness and precision.

But there was also the opposite: students with high interest in physics according to our questionnaire but with a negative attitude towards enrolling into a degree course in physics. This group was bigger with 10 students (4 from Dresden (3m, 1f) and 6 from Udine (1m and 5f)). The students from Dresden had already decided to study another scientific subject or medicine. As traits of a physicist they mentioned mostly "*curiosity*" (4/10) and "*mathematical mind*" (3/10) or seem to have as reason the "*societal role*" (3/10). The topics they were mostly interested in were "*Modern Physics*" (6/10) and "Classical Physics" (4/10).

7 Conclusion

The most obvious factor for studying physics is a deep interest in physics as it is expressed e.g. in doing physics in free time. In line with these statements the students are interested in fascinating topics like Astrophysics, dark matter and so on. They do not seem to be attracted by physics in everyday life, but by deeply-rooted motives. The pattern is completed by their perception of the curiosity and the urge for inquiry as the most prominent traits of a physicist. In addition a positive choice seems to be correlated with positive emotional attitude and the desire to know more deeply and understand better the world.

However, it is a bit disturbing that seemingly the older the students are the less decided they are to study physics at university. Therefore it seems most important to stabilize interest during the last years of school (see also Aschbacher et al. 2009, Gedigk and Pospiech 2015). Furthermore the conviction that a physicist has to excel and has to possess special innate gifts seems to deter students from study. This is connected to the impression that physics seems attractive mainly for mathematically thinking students. Therefore in order to attract more students to physics as a rewarding study in several respects it seems important to show the societal role and possibility of *learning* physics.

Nevertheless it has to be taken into account that studying physics needs genuine deep interest, resulting in the wish to do it in free time. All these aspects require to provide students with adequate opportunities for experiencing physics from different perspectives and to learn about many facets of doing physics as a researcher or as a user of physics.

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Part III
Classroom Ideas and Teaching-Learning Practice

Representational Issues in Teaching Ideas About Matter

Peter Hubber

Abstract This research study was designed around the notion that learning involves the recognition and development of students' representational resources. It describes classroom sequences in the topic of ideas about matter that focused on representations and their negotiation, and reports on the effectiveness of this perspective in guiding teaching, and in providing further insight into student learning. Classroom sequences, involving two experienced teachers (Year 8 classes) and an inexperienced teacher (Year 7 class), were videotaped using a combined focus on the teacher and groups of students. Video analysis software was used to code the variety of representations used by teachers and students, and sequences of representational negotiation. The study found several issues that impacted on the teaching of the topic that include the epistemological position of the teacher, impact on pedagogy with a representational focus, content coverage and assessment as a consequence of adopting a representational focus in introducing ideas about matter.

1 Introduction

There is now a growing consensus that learning science at school entails students learning the literacies of a specific discourse community, one that uses a range of subject-specific and general representational tools to construct and justify evidence-based claims about the natural world (Kress et al. 2001; Lemke 2004; Moje 2007). Researchers in classroom studies where students were guided to construct their own representations of scientific ideas (Carolan et al. 2008; Greeno and Hall 1997) have noted the importance of teacher and student negotiation of representational meaning and of students having opportunities to explore, elaborate, re-represent and coordinate representations to interpret science phenomena. There is

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growing evidence (Hubber et al. 2010; Hubber 2010; Tytler et al. 2013) that this can lead to increased student engagement and improved learning outcomes.

The students' conceptions literature within the topic of ideas about matter is quite extensive (Hadenfeldt et al. 2014; Kind 2004) which highlights the difficulties students have in understanding this science domain. The particle theory of matter is one of the most fundamental scientific theories and yet, according to Wiser and Smith (2008, p. 205), "current K-12 science teaching is typically not effective in helping students understand and accept it" because they often "fail to understand the central tenets of the theory, as well as its explanatory power." This paper will report on part of an Australian Research Council (ARC) funded Representations in Learning Science (RiLS) project that involved Year 7/8 teachers who adopted a directed-inquiry pedagogy, called representation construction, based on student generation and negotiation of 'particle' representations of properties of matter in their classes (12–13 year olds). It will address the research question, *what are the issues of an explicit representational focus on the teaching and learning of ideas about matter?*

The main principles of representation construction pedagogy, developed by the RiLS project (Tytler et al. 2013, p. 34), and enacted by the Year 7/8 teachers, are broadly described as:

1. ***Teaching sequences are based on sequences of representational challenges***: Students construct representations to actively explore and make claims about phenomena.
2. ***Representations are explicitly discussed***: The teacher plays multiple roles, scaffolding the discussion to critique and support student representation construction in a shared classroom process. Students build their meta-representational competency (diSessa 2004) through these discussions.
3. ***Meaningful learning involves representational/perceptual mapping***: Students experience strong perceptual/experiential contexts, encouraging constant two-way mapping/reasoning between observable features of objects, potential inferences, and representations.
4. ***Formative and summative assessment is ongoing***: Students and teachers are involved in a continuous, embedded process of assessing the adequacy, and their coordination, in explanatory accounts.

2 Methodology

A Case study methodology (Yin 2009) was employed with a mixed methods design. The teachers' practices, student-teacher interactions, and student activity and discussion were monitored using classroom video capture. Data collected included: (1) video recordings of most classroom sessions and of student interviews; (2) student workbooks; (4) pre- and post-tests; (5) transcripts of tape recordings of teacher and student interviews and (6) researchers' field notes. Most lessons in the teaching sequences were videotaped as many of the lessons had some part or parts that had a representational focus. The videotaped lessons were coded using 'Studiocode' software which has been designed for this type of analysis, to allow quick reference to representational events and instances of classroom negotiation of representations.

The research team worked collaboratively with two experienced Year 8 teachers, Lyn and Sally,[1] and one inexperienced Year 7 teacher, Therese, to develop a teaching sequence that involved the introduction of elements of the particle theory of matter. The state-based curriculum at the time of teaching the topic allowed teachers flexibility as to what year level, 7 or 8, the particle theory was introduced to students. Since then a nationally-based curriculum (ACARA 2014) states that the particle theory is taught at Year 8 level. Lyn and Sally taught at the same school whilst Therese taught at another school; Lyn and Sally each had a single Year 8 class whilst Therese taught three Year 7 classes. In addition, there was a time period of two years between the Year 8 and Year 7 teaching sequences. The sequence involved students being introduced to particle ideas to explain such phenomena as changes of state and various macroscopic properties of matter like the stretchiness of rubber or the compressibility of air. The sequence focused explicitly on student generation and negotiation of representations related to key concepts about the nature of matter and the particle model. The teaching sequence lasted 14 lessons (Year 8) and 10 lessons (Year 7) varying between 45 and 90 min of class time.

The features of the sequence were:

1. Pre-test of key ideas associated with the topics to be taught. The pre-test included true/false and multiple choice questions as well as short answer questions where students were to provide full explanations using text and/or drawings.
2. For the Year 7 sequence the students' notebooks were different to their normal A4 lined notebooks but larger sized project type notebooks which, when opened out, had one lined page on the left and an unlined page on the right. This encouraged the construction of multiple representations by the students.
3. Students were given representational challenges where they were to generate a representation with a particular purpose. For example,
    a. Draw a diagrammatic representation, using particle ideas, to explain the observation that when you pick up a piece of paper it holds its shape.
    b. Draw a representation that explains the ability of a rubber band to stretch without breaking.
4. There was explicit discussion of representations where students assessed the adequacy of their own representations in addition to the canonical forms.
5. Instances where representations where used in exploring properties of matter. For example,

[1]Pseudonyms are used for the teachers who participated in the study.

a. Animations showing the motion of particles in different states;
b. Role play of the dynamic systems involved in heating an object;
c. In most instances representations did not stand alone but were integrated with others. For example, gesture, everyday/science language and diagrams.

6. Inquiry-based investigations such as 'investigating the viscosity of three different liquids'. Student groups were to initially collect some data and represent it in a form of their choosing, to then analyse and interpret this data with the purpose of answering some questions. The students were to provide a written report of their investigation, which was used for summative assessment purposes, and also present their findings to the rest of the class in whatever form they chose. For example, oral presentation with PowerPoint slides.
7. A Predict Observe Explain (POE) activity whereby students predict compression of a syringe when full of air, liquid and solid.
8. Post-test that included the same set of multiple choice questions and true/false questions given in the pre-test and also included some of the short answer questions. In addition, further short answer questions were given.

3 Findings

Several issues arose in undertaking the teaching sequence with a representational focus implied by the pedagogical principles described above. These issues related to epistemology, pedagogy, content coverage and assessment.

3.1 Epistemology

In planning for each of the topics the research team collaborated with the teachers in identifying key concepts at the planning stage in order to guide the refinement of representational work. For example,

- All matter is composed of tiny indivisible particles too small to see even with the most powerful microscopes.
- The particles that make up the substances do not share the properties of the substance they make up.

In past years the Year 8 teachers, Sally and Lyn, had developed a two-week teaching sequence that extended a previous year's topic on changes of state and particle model with the introduction of the concepts of atom, molecule, element, compound, mixture and pure substance. The teachers were somewhat surprised at the prevalence of alternative conceptions elicited by the students in the topic pre-test, particularly in areas covered in teaching the students the previous year. This prompted them to rethink the way they were teaching particle ideas about matter. The pre-test responses by the students indicated that whilst the majority of students understood the terms ‘atom’ and ‘molecules’ they exhibited several alternative conceptions that included: *matter is not conserved in evaporation*; *the space between molecules is filled with air*; and, *molecules have the same properties of the bulk material they constitute*.

The teachers realised that they had been teaching the particle theory as a body of knowledge itself and only loosely using it to explain macroscopic behaviour of matter. They now thought that the teaching approach needs to have constant movement between macroscopic behaviour of substance and particle ideas through various forms of representation that explain the behaviour. There was also a view that there needed to be an emphasis on evaluating the adequacy of a particular representation to explain a particular behaviour. These views are reflected in the following comment by Lyn.

> **Lyn:** *So what we would have done before is teach the particle theory and then incidentally relate it to real life. But through teaching the year 8s we realised that the model has to sit within everyday experiences. But you know we’re not teaching the particle model as in, this is the model and see how it relates to real life. It’s more, this is real life and we have a model and does it actually explain real life, and does it explain this and that? And particularly, one of the areas I focus on, is how good the representation is?*

Lyn’s comment not only expresses a change in a pedagogical practice it also points to an epistemological change whereby the *model has to sit within everyday experiences* and is not separate to how one thinks about explanations of the properties of substances.

The Year 7 teacher, Therese, responded differently to Lyn and Sally in relation to her students’ pre-test results despite the results being very similar to the Year 8 pre-test results. That is, the students displayed a range of alternative conceptions. This is shown in the following comment where Therese referred to having knowledge of the students’ conceptions literature.

> **Researcher**:*Was there anything surprising for you in these results or were they what you might expected?*
>
> **Therese**: *To be honest, I think the pre-test results for any Year 7 class should be quite similar. Therefore, there was nothing surprising for me for my classes.*
>
> **Researcher**: *Why is that?*
>
> **Therese**: *For my [science teaching] degree most of my assignments dealt with alternative conceptions with any topic. For example, with light, that cats can see without any light but humans can’t.* [Therese later indicated that she was teaching her students about light].

Therese also had a more sophisticated epistemology than Lyn and Sally had initially in respect of the function played by the particle model.

> **Researcher**: *What do you see as the main purposes of introducing the particle model to Year 7?*
>
> **Therese**: *I see that the main purpose of introducing the particle model at Year 7 is that it gives the students the foundation of the true essence of science. We aren’t able to see everything in the world around us so we do experiments after experiments to try and make*

sense of it. The Particle Model enables the students to come up with their own particle ideas of what substances are made up of and how these ideas can explain the behaviour of different states.

3.2 Pedagogy

The teaching sequence for Year 7 and 8 began with the students exploring properties of different substances, for example, comparing the properties of a rubber band with those of a stick of chalk. Particle ideas were then introduced on the basis to explain a specific property of a substance. For example, after the students had been informed that scientists, whilst being unable to see inside matter, imagine it to be composed of particles the students were set the challenge to represent the state of the particles to explain the property of a piece of paper's ability to hold its shape (see Fig. 1). After students undertook this task three students were chosen to share their representation with the rest of the class. Each representation was evaluated by the class as to whether it served its purpose. Figure 2 provides another example of student generated representations in response to a representational challenge to use particle ideas to explain properties of matter that was given by the teacher. Figure 2 shows three different ways in which the students imagined two different substances. There were different types of particles, different types of bonds, and different arrangements of particles and bonding.

Generation and negotiation of student representations played a significant role in the Year 7 and Year 8 teaching sequences. This opened up more negotiated activities and discussions with students. A greater level of discussion than in previously taught topics is reflected in the following comments.

Therese: *There was more class discussion in this teaching sequence as there were a lot of open ended questions set out to the students. I wanted to hear the majority of the class' thoughts before moving on to a new stage in the sequence. They all felt a part of the group if they got to share what they thought*

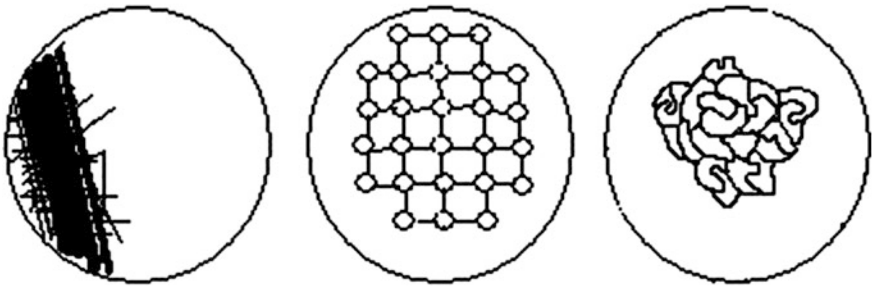

Fig. 1 Year 7 students' particle representations to explain how a piece of paper holds its shape

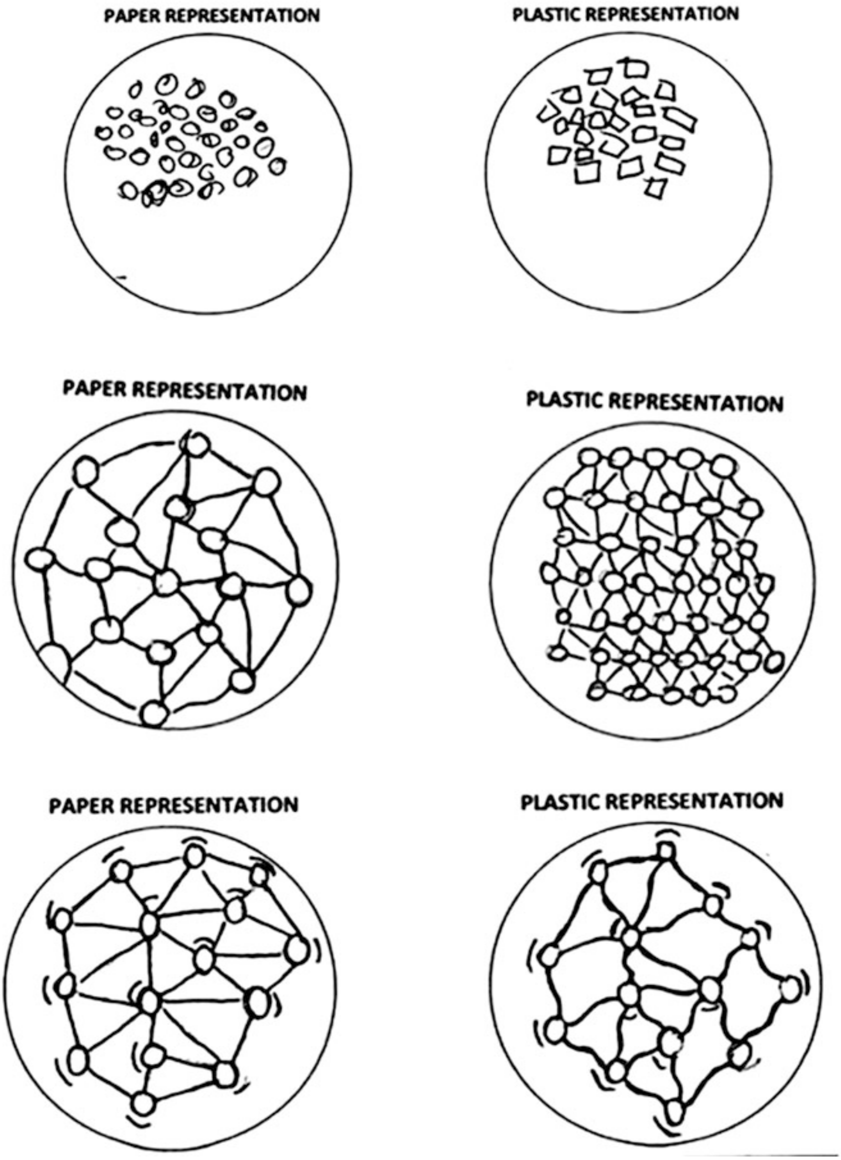

Fig. 2 Year 7 students' particle representations of different substances

Sally: *It's the most rewarding thing taking stuff in their everyday experiences into the science room…that type of conversation would not have occurred before, and that's the richness where you get the kids having science debates and conversations, rather than delivery of fact; it's a higher order level of thinking and that was really fantastic.*

The teachers had constant movement between macroscopic behaviour of substances and particle ideas through various forms of representation that explain the behaviour. Different particle representations, either generated by the teacher or the students, were discussed in terms of their adequacy in explaining properties of matter. Apart from the iconic pictorial representations of particles as spheres other forms, such as a picture of students on a bus, pop-corn being made or a section of a jigsaw puzzle were discussed in terms of their particular features to explain macroscopic behaviour of matter in addition to those features that did not explain the behaviour.

Apart from students critiquing each of the student generated representations they also critiqued the canonical forms. For example, the Year 7 students critiqued their own textbook representation that showed particle arrangements and movement in each of the three states of matter. The students picked up two limiting features of this representation which were the separation of the particle in the liquid state and lack of movement shown by the particles in the solid state. In other activities the students were challenged to generate their own representations, whether by role play or in diagrammatic form to explain a variety of specific macroscopic behaviour of matter. For example, 'candle wax goes 'gooey' when the candle is lit' or 'an elastic band breaks when overstretched'.

The greater level of use of representations was seen by Therese as coming from the students when she responded to the question, '*Did you use more representational forms than before*?'

Therese: *Yes, we normally just gave them the textbook representations. Now there is more getting them thinking them up themselves.*

This suggests that Therese had not in previous years undertaken a key feature of the representational pedagogical principles that suggest that student generation and negotiation of representations is important. Lyn felt that in past years her use of representations was narrow when compared to her current teaching sequence. She commented:

Lyn: *I always used representations but particularly stronger for instructions and then I would just use visual representations…and now I use many different forms.*

The teachers pointed to an enhanced student engagement with a focus on representations as it facilitated student learning.

Lyn: *Adam, who is very, very difficult, and has a lot of issues, and has been very disengaged and has been very confrontational, he can't help himself to get sucked into the conversations. It's so powerful.*

Sally added:

Sally: *That's the other thing; we don't manage a lot of behaviour, because the lessons are solid lessons.*

The three teachers saw representations as tools for learning when they commented:

Sally: *It's good to give them a representation, but it's more powerful when they re-represent it…it helps in their reasoning.*

Lyn: ... *it's a very powerful way of showing understanding and getting the kids to think. And the other thing too is, it allows kids to be creative in showing their understanding with different representations. And we can all see different ways of doing it.*

Researcher: *Do you think it is important for students to come up with their own representation?*

Therese: *They get engaged more, it's like a puzzle because they have to come up with a specific explanation like how can you explain why a piece of paper holds its shape.*

3.3 Content Coverage

In terms of content coverage it was the unanimous agreement of the teachers that undertaking a representation construction pedagogy means that less content is covered. This is not surprising given that they spent class-time in getting students to generate and negotiate their own representations and critiquing the canonical representations, which is something they did not undertake in the past.

Researcher: *In comparing what was done in the past with what you did this year. What do you see were the main differences?*

Therese: *I noticed this year that we were able to choose just a couple of topics that blended together well and use the time available to really connect with the students.*

We concentrated on some key ideas. If I ask some of my Year 8's now they wouldn't know but my Year 7's would.

Therese's comment of a *couple of topics blended together* was illustrated with the following exchange where she referred to the early teaching of temperature, the inclusion of bonding and reasons for such phenomena as evaporation and heat transfer.

Researcher: *You taught about temperature very early on. Why was that?*

Therese: *Temperature related to states of matter and is critical to the particle model as energy of particles relates to temperature. In the past we never really did bonding but we had the students thinking about bonding in this topic.*

Researcher: *Why is that?*

Therese: *Because the students needed bonding to explain the properties of matter that were given as challenges, it explains how a rubber band can stretch.*

Researcher: *Were there some things you didn't get to teach?*

Therese: *Yeah, reasons for evaporation and heat transfer. We started to do it at the end.*

3.4 Assessment

In terms of assessment the teachers saw benefit in the knowledge gained from the pre-tests in resolving alternative conceptions that arose and for the students to be made aware of their own thinking as an important part of the teaching sequence.

> **Lyn**: *Because we have more understanding of the misconceptions we can teach accordingly and we can single out misconceptions…we can tackle them straight away…the pre-test was used as a basis to begin discussions, it gave kids a good reference point.*

There were many instances during the teaching sequences whereby the students were given the opportunity to interpret and generate representations. This gave the teachers a good sense of student learning from a formative and summative perspective.

> **Lyn**:*…what you're seeing with representation is that you're seeing what's in their brain, not what they're regurgitating.*

> **Researcher**: *You often had students evaluating each other's representations.*

> **Therese**: *To open up different ideas. This gave insight into their thinking and how they interpreted my teaching so this gave constant feedback on their understandings.*

The pre and post-testing found substantive increases in the students' understanding of the topic that introduced the particle model. For example, normalised gain scores[2] (Hake 1998) of 0.74 (Year 8) and 0.55 (Year 7) were found for the true/false questions of the tests. In the short answer questions students were more willing to add to their text responses with drawings showing particle type explanations. The post-test had added questions that tested the students' meta-representational competence. For example, Fig. 3 shows a student's response to a question that asked the students to critique the value of using a section of jigsaw to represent properties of a solid. The students had not discussed jigsaws as a particle model in class.

The following excerpt from a post-topic student interview illustrates a sophisticated view held by many of the students as to the role of representations in understanding and communicating about aspects of the world.

> ***Researcher***: *You have two separate words, one is Understanding and the other one is Representations.* [The letters R & U were drawn on the page] *how do they connect?*

> ***Student***: *Through many representations you can come to an understanding* [Student drew arrows from R to U]. *So many representations help you get an understanding*

> ***R***: *So do you use representations to show your understanding?*

> ***S***: *Representations help you understand but then* [Student now drew arrows from U to R] *through your understanding you can give many representations. So it works both ways.*

[2]Normalised gain = [post-test score – pre-test score]/[maximum score – pre-test score].

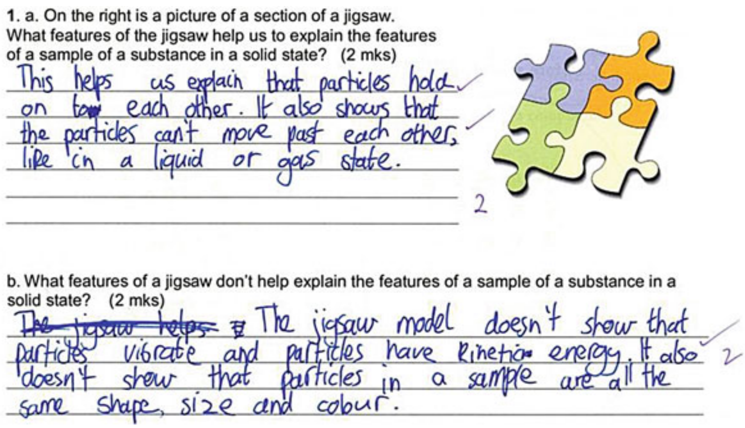

Fig. 3 Year 7 student response to post-test question

4 Discussion and Conclusion

The representation construction approach allowed the teachers to introduce the particle model of matter, not as another reality, but as way in which one can explain the macroscopic world through imagining the sub-microscopic world. Students were able to construct their own particle representations of the world to then negotiate and evaluate alongside the canonical forms. In doing so the students experienced the actions of scientists in the manner in which they construct explanations of the world.

A key implication of the study is the need to shift practice in teaching science from its current focus on the delivery of content that is conceived of as resolved knowledge structures, to the pedagogical practices of this representation approach based on a discursive, more active view of knowledge and learning. This will require changes in conceptions of the role of the teacher in the science classroom, and changes in how knowledge and learning are thought of in science.

To make this change, teachers need to:

- understand the role of representation in learning science, implying both a pedagogical and an epistemological shift;
- provide a representation rich environment and opportunities for students to negotiate, integrate, refine and translate across representations;
- make explicit to students the role of representation in learning science; and
- conceptualize learning in science in terms of students' induction into the representational conventions and practices of science and their capacity to coordinate these.

Given current concerns about the engagement of students in meaningful science learning, and the relatively limited success of pedagogical approaches based on cognitive views of learning, we would argue that this is an agenda that needs to be vigorously pursued both in research and policy.

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Dynamic Visualizations of Multi-body Physics Problems and Scientific Reasoning Ability: A Threshold to Understanding

James Christopher Moore and Josip Slisko

Abstract Visualization is a common and important step in expert-like problem solving across multiple disciplines. Within the context of physics education, significant intervention is often required to develop visualization skills with novice problem solvers. In particular, dynamic multi-body problems require mental models that incorporate multiple objects time-varying in space, which may require significant development of spatial and/or other cognitive abilities. We have investigated student abilities in applying a dynamic visualization to solve a simple multi-body problem and that ability's correlation with scientific reasoning (SR) cognitive ability as measured by Lawson's Classroom Test of Scientific Reasoning (LCTSR). A broad population of students (N = 212) attending a regional comprehensive university in the USA were classified into four SR categories based on Piaget's theory of cognitive development: (1) concrete operational, (2) early transitional, (3) late transitional, and (4) formal operational. A short problem was also administered that required students to construct a dynamic visualization to correctly answer. Specifically, the problem involved a situation where two trains leave opposite stations once per hour. The stations are 3 h apart. The task was to determine how many trains an observer on one of the trains would see during the 3-h trip between stations. Through analysis of expressed student reasoning, we have found that students answering with 3–4 trains typically have built a visualization based on at least one set of trains remaining stationary. Students answering 6–7 trains typically recognize the evolving nature of the problem and construct an appropriate dynamic visualization with both sets of trains in motion. Students struggle to deploy a successful dynamic visualization when classified below formal operational level. Formal operational reasoners within the population succeed

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almost universally in applying a successful dynamic visualization. This suggests an epistemological threshold may exist, whereby students struggle with constructing dynamic visualizations before reaching a high-formal level of reasoning ability. This has implications for instruction and textbook/classroom problem construction, especially considering that a significant majority of students enrolled in introductory physics courses within our population demonstrate late transitional and below SR levels.

1 Introduction

A review of popular introductory physics textbooks in the United States of America reveal that although visualization is often included as an important component of the problem solving process, little discussion is devoted to how students can learn to develop good visualization skills. Furthermore, very few textbook problems in motion incorporate multi-body dynamics, which can arguably be considered more authentic across contexts (Ramirez et al. 2014). Visualization is a common and important step in expert-like problem solving across multiple disciplines. Within the context of physics education, significant intervention is often required to develop visualization skills with novice problem solvers. In particular, dynamic multi-body problems require mental models that incorporate multiple objects time-varying in space, which may require significant development of spatial and/or other cognitive abilities.

Content knowledge gains and process skill development have been linked to several cognitive variables (Moore and Rubbo 2012; Carmel and Yezierski 2013; Tsitsipis et al. 2012). In particular, scientific reasoning (SR) cognitive ability has been shown to have an effect on content knowledge gains in physics, and has been linked to the development of process skills in experimental methods courses (Coletta and Phillips 2005; Moore and Rubbo 2012; Larkins et al. 2013). Ates and Cataloglu (2007) correlate formal reasoning level to conceptual understanding and problem-solving skills in introductory mechanics. As a process skill, problem visualization may be similarly associated with SR cognitive ability, which should be considered during the development of instructional materials designed for student growth in problem solving.

In the study described in this paper, we have investigated student abilities in applying a dynamic visualization to solve a simple multi-body problem and that ability's correlation with SR cognitive ability as measured by Lawson's Classroom Test of Scientific Reasoning (LCTSR). We present an observation experiment with the purpose of determining if such a link exists between cognitive ability and visualization.

2 Background

What exactly constitutes SR is both complex and debatable. Lawson suggests that scientific reasoning has a structure that is chiefly hypothetico-deductive in nature and consisting of interrelated aspects, such as proportional reasoning, control of variables, probability reasoning and correlation reasoning (Lawson 1982, 2005). Inductive and deductive process are involved, with some researchers intimately linking reasoning with the process of drawing inferences from initial premises (Holyoak and Morrison 2005).

Piaget's theory of cognitive development includes classification into two formal reasoning levels (concrete operational and formal operational) with a transitional stage between the two (Ginsburg and Opper 1979). Students classified as mostly concrete operational reasoners are characterized by their appropriate use of logic; however, they struggle with solving problems outside of a concrete context, demonstrating significant difficulty with abstract concepts and hypothetical tasks. Formal operational reasoners begin to think abstractly, reason logically, and draw conclusions from available information. Furthermore, unlike the concrete operational reasoner, they are able to apply appropriate logic to hypothetical situations in most contexts. In this way, formal operational reasoners can begin to think like a scientist, and specifically develop strong hypothetico-deductive reasoning. Transitional reasoners fall between the other two classifications where they find success with hypothetical tasks in some contexts. Lawson describes these levels as Level 0, Low Level 1, and High Level 1, respectively (Lawson et al. 2000). Lawson further describes a post-formal level of reasoning, which is beyond the scope of this study. In this paper, we will use a similar Piagetian classification scheme. Students are classified into four categories: (1) concrete operational, (2) early transitional, (3) late transitional, and (4) formal operational.

It has been shown that the LCTSR can be used as an assessment of formal reasoning level, and its validity has been established (Lawson 1978). We have used the 2000 revised, multiple-choice edition of the LCTSR, which assesses reasoning patterns such as proportional reasoning, control of variables, probability reasoning, correlation reasoning and hypothetico-deductive reasoning (Lawson et al. 2000). The LCTSR consists of 12 scenarios followed by two questions each assessing 6 different scientific reasoning patterns. Questions on the LCTSR are pairs with the exception of the last two questions, with scores out of a possible 13. To get a question marked correct, a student must correctly answer both within the pair correctly. One question in a pair elicits a response requiring effective use of the pattern, while the second question has the student describe the reasoning behind the response.

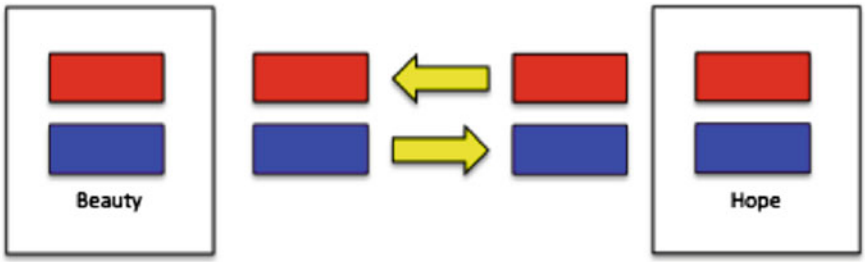

Fig. 1 Illustration of the train problem

2.1 The Two-Train Problem

Figure 1 shows an illustration for the two-trains problem used in this study. This short problem was administered to the student population at the same time as the LCTSR. It requires students to construct a dynamic visualization to arrive at a correct answer. Specifically, the problem involved a situation where two trains leave opposite stations named Beauty and Hope once per hour. The stations are 3 h apart. The task was to determine how many trains an observer on one of the trains would see during the 3-h trip between stations.

The text of the two-train problem as administered to students was as follows:

> Between two imaginary futuristic cities, named Beauty and Hope, a perfect non-stop train system operates. Every hour a train leaves Beauty for Hope and a train leaves Hope for Beauty. The travel between the two cities takes precisely 3 h. The question is: how many trains, coming from Hope, will a person count that is travelling from Beauty? The train seen in Beauty, when the travel begins, and the train seen in Hope, when the travel ends, are also counted.

Students were not provided with an illustration for this problem. Initially, student responses were collected as free response. After free-response data was collected from 75 students, the problem was assigned as a multiple-choice response at the end of the LCTSR for the remaining students in the population.

2.2 Student Population

The data set used in this study consists of students enrolled in one of four different courses: (1) a calculus-based physics course for science majors (PHYS 212, N = 57); (2) a first-year science process course for physics majors (PHYS 137, N = 36); (3) a physical science course for non-science majors (PHYS 103, N = 52); and (4) a conceptual astronomy course for non-science majors (ASTR 101, N = 67). These courses were taught at Coastal Carolina University (CCU) in Conway, SC USA. CCU is a comprehensive, regional institution with few graduate programs and a significantly larger undergraduate population. The courses used in this study were chosen in an effort to accumulate data from students demonstrating a wide range of SR abilities. Data were collected over two years (2013–2014).

3 Scientific Reasoning in the Population

Students in the physical science and conceptual astronomy courses scored significantly lower on the LCTSR compared to students enrolled in PHYS 137 and PHYS 212. Table 1 shows the average score on the LCTSR for students in the four courses. Students majoring in a Science, Technology, Engineering, or Mathematics (STEM) fields are heavily represented in the latter two courses, whereas the former two courses are populated with students from outside these areas (non-STEM). Table 2 shows the average score on the LCTSR for non-STEM and STEM students. STEM students score significantly higher than non-STEM students according to an unpaired *t*-test ($p < 0.001$). That students in STEM majors demonstrate stronger scientific reasoning ability is not surprising, since most students typically choose their major based on their strengths.

Figure 2 shows a histogram for the percentage of the population achieving specific scores on the LCTSR. A broad distribution of scores was achieved across all of the courses.

Using individual student scores on the LCTSR, we classified students into four formal reasoning categories: (1) concrete operational, (2) early transitional, (3) late transitional, and (4) formal operational. Students scoring below a 4 were classified as concrete operational (CO). Students scoring between 5 and 7 were classified as early transitional (ET). Students scoring between 8 and 10 were classified as late transitional (LT). A score above 10 resulted in a classification of formal operational (FO) (Moore 2012).

Figure 3 shows the distribution of non-STEM and STEM students in the population within Piagetian formal reasoning levels. All levels are represented

Table 1 Average score on the LCTSR ($\bar{s}$) for students in the population

	$\bar{s}$	N	Std. dev.
ASTR 101	4.9	67	2.3
PHYS 103	5.0	52	1.9
PHYS 137	6.7	36	2.1
PHYS 212	6.9	57	2.3

Table 2 Average score on the LCTSR ($\bar{s}$) for non-STEM and STEM students

	$\bar{s}$	N	Std. dev.	p
Non-STEM	4.9	119	2.1	<0.001
STEM	6.8	93	2.2	

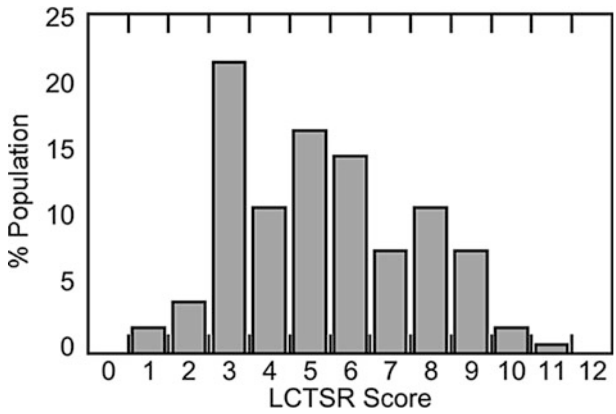

Fig. 2 Histograms showing percentages of the population achieving specific scores on the LCTSR

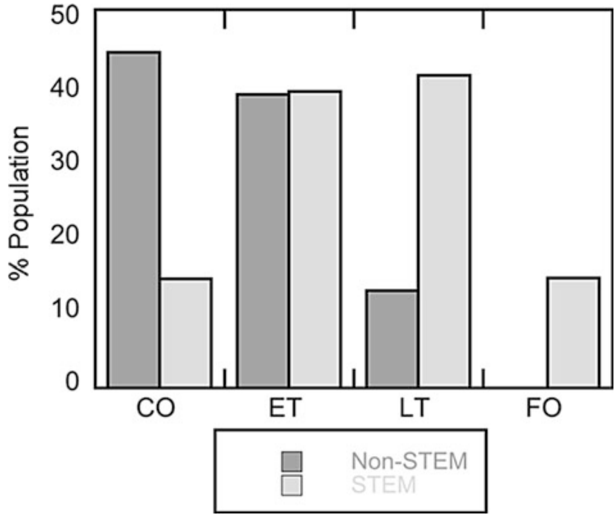

Fig. 3 Distribution of formal reasoning level for non-STEM (*dark gray*) and STEM (*light gray*) students participating in this study. Concrete Operational (CO), Early Transitional (ET), Late Transitional (LT), and Formal Operational (FO) reasoning levels are shown

approximately equally across the entire population, with the exception of formal operational reasoners. This is consistent with a previous study published by the authors of this paper, and previous studies of the general education population in biology courses (Moore and Rubbo 2012; Johnson and Lawson 1998).

4 Scientific Reasoning and Dynamic Visualizations

Figure 4a shows a student's response to the two-trains problem with reasoning based on a mental visualization that maintains the Beauty to Hope trains as static objects. Evaluation of the free response data shows that students concluding that between 3 and 4 trains will be seen during the trip almost universally demonstrate similar static-based reasoning.

Figure 4b shows a student's response to the two-trains problem with correct reasoning that recognizes the motion of both sets of trains. Evaluation of the free response data shows that students correctly answering the question (7 trains) universally demonstrate such a dynamic visualization of the problem. Some students (8 % of the free-response population) answered either 6 or 8, but did correctly demonstrate a dynamic visualization of the problem. These students made other errors in reasoning or calculation.

Based on the results from analysing the free-response data, we began administering the two-trains problem as a multiple-choice question added to the end of the LCTSR. Students answering 6, 7 or 8 trains on the multiple-choice version were counted as dynamic visualizers, whereas students answering below 6 were counted as static visualizers.

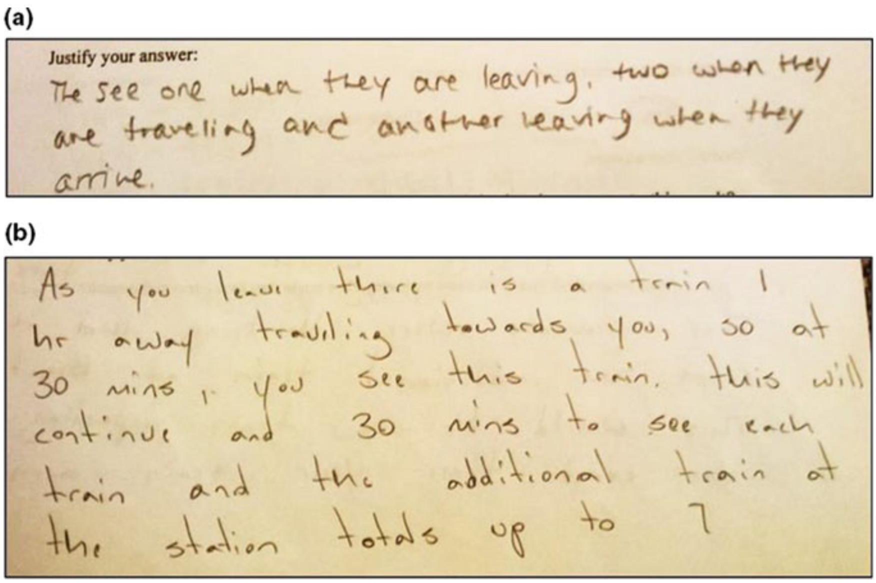

Fig. 4 Sample of student response to the two-train problem showing **a** a static visualization, and **b** a dynamic visualization

Table 3 Percent of the non-STEM and STEM populations demonstrating a dynamic mental model (% dynamic) in answering the two-train problem

	Dynamic (%)	N	Std. error (%)	*p*
Non-STEM	24	119	4	0.02
STEM	39	93	5	

The population size is *N*. STEM students are slightly more likely to utilize a dynamic mental model than non-STEM students ($p = 0.02$)

Table 4 Percent of students in various formal reasoning level classifications demonstrating a dynamic mental model (% dynamic) in answering the two-train problem

	Dynamic (%)	N	Std. error (%)
Concrete operational	15	66	4
Early transitional	35	107	5
Late transitional	35	69	6
Formal operational	86	14	10

The population size is *N*

Table 3 shows the percentage of non-STEM and STEM students within the population demonstrating a dynamic mental model (Dynamic %) in answering the two-trains problem. STEM students were significantly more likely to deploy a dynamic visualization than non-STEM students ($p < 0.05$).

Table 4 shows the percentage of students in various formal reasoning classifications demonstrating a dynamic visualization in answering the two-trains problem. Students classified at the formal operational level are significantly more likely to demonstrate a dynamic mental model in the solution to the train problem than students in lower levels ($p < 0.001$). In particular, students struggle to deploy a successful dynamic visualization when classified below the early transitional level, with very little increase with increasing level until the attainment of formal operational. Formal operational reasoners within the population succeed almost universally in applying a successful dynamic visualization, whereas students below this level do not.

This suggests an epistemological threshold may exist, whereby students struggle with constructing dynamic visualizations before reaching a high-formal level of reasoning ability. This thresholding has significant implications for instruction and textbook/classroom problem construction, especially considering that a significant majority of students enrolled in introductory physics courses within our population demonstrate late transitional and below SR levels.

5 Summary

In summary, we investigated student abilities in applying a dynamic visualization to solve a simple multi-body problem and that ability's correlation with SR cognitive ability. A broad population of student attending a regional comprehensive university in the USA were classified into four SR categories based on Piaget's theory of cognitive development. A short problem was administered that required students to construct a dynamic visualization to correctly answer. Students struggle to deploy a successful dynamic visualization when classified below formal operational level. Formal operational reasoners within the population succeed almost universally in applying a successful dynamic visualization. This suggests an epistemological threshold may exist, whereby students struggle with constructing dynamic visualizations before reaching a high-formal level of reasoning ability.

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Training Pre-service and In-service Secondary School Teachers: Analysis of Changes in Perceptions About Quantum Physics Concepts and NoS Views

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Abstract In this work we focus on the study of the changes in perceptions about Quantum Physics concepts and Nature of Science (NoS) Views of secondary school teachers attending three different typologies of professional development courses on Modern Physics. An open-ended questionnaire has been properly developed and administered in order to investigate Quantum Mechanics conceptual issues, NoS views and motivational aspects for all involved teachers. The same questionnaire has been submitted to the teachers both prior-to and after the courses. The analysis of teachers' pre-instruction answers highlights that the majority of them show several difficulties on both conceptual knowledge and epistemological issues regarding the basic properties of Quantum Physics systems. After instruction, the teachers answered to the questionnaire by showing a clear change of perspective on their view of Quantum Physics concepts. Moreover, our study demonstrates that differences in the educational background of the participating teachers, as well as the typology of professional development course attended, are important when comparing normalized gains. Even in NoS view and motivational aspects, teachers' answers, collected at the end of the professional development course attended, have shown interesting changes. An overall discussion is finally presented.

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1 Introduction

Quantum Physics (QP) has changed the way physicists examine the nature and the whole universe, by introducing indeterminism, probability and non-locality into the foundation of physics. QP is a technically difficult, complex and often counter-intuitive subject, making instruction quite challenging. In the last decades, physics educators proposed many teaching strategies to better address this issue. There are several important studies focused on the learning and teaching of key topics in QP at secondary school and senior/junior college levels (Kroemer 1994; Styer 1996; Petri and Niedderer 1998; Johnson et al. 1998; Ireson 2000; Singh 2001; Kalkanis et al. 2002; Taber 2004; Persano Adorno and Pizzolato 2015). Many researchers concluded that both teaching and learning QP concepts is difficult because it contains abstract ideas, requires strong mathematical tools, and deals with complicated operations.

Ireson (2000) suggested that teachers in colleges should be sensitive to the variety in the nature of their students' thinking regarding quantum phenomena and that textbook authors and course developers need to draw on the available research to plan a sequence of instruction which allows the student to develop a conceptual framework for a subject that is often counterintuitive to commonsense or mechanistic reasoning. In secondary school environments, most problems deal with the teaching strategies adopted for QP and conceptual difficulties (Kroemer 1994; Niedderer et al. 1997; Ireson 2000; Muller and Wiesner 2001; Olsen 2002; Didiş and Eryılmaz 2007; Didiş et al. 2010; Etkina 2010).

After a debate long more than twenty years, national directions from the Italian Ministry of Education promoted the inclusion of Modern Physics (MP) in Italian secondary schools. In Italy the introduction of MP is more complicated than in other countries because in many cases physics teachers at the upper-level secondary schools are not physicists, but mathematicians or engineers. Consequently, we deal with the very unusual situation in which a large number of potential teachers of QP never studied MP in their curriculum, such as for both mathematicians or engineers. Moreover, in many cases physicists, despite having received an educational background in MP at the time of their university studies, have never taught it before. In order to fill this gap and to obtain an effective teaching of QP, several training activities have been organized and carried out by some Italian Universities and upper-level secondary schools in recent years, and others are still in progress (Pospiech 2000; Michelini et al. 2000; Michelini et al. 2004a, b; Francaviglia et al. 2012).

The objective of the current study is to investigate significant conceptual problems and the most common difficulties experienced by physics teachers during their teaching of QP in upper secondary school. An open-ended questionnaire has been properly developed and used to investigate QP conceptual issues, NoS views and motivational aspects of all involved teachers. In particular, we investigate the difficulties of teachers both prior-to and after attending one of the three different typologies of professional development courses on QP about concepts related to quantum measurements and time development. Our study is based upon the analysis of the answers to the questionnaire and upon the analysis of structured interviews obtained at the end of the courses. The items of these interviews were designed with the purpose to achieve information about the teacher affective development and motivation to learn and teach MP, on the course weaknesses and strengths, with a focus on the interest-enjoyment and perceived competence dimensions. A preliminary analysis of teachers' pre-instruction answers has highlighted that the majority of them hold several difficulties on both conceptual knowledge and epistemological conceptions regarding the basic properties of QP systems. Unexpectedly, in the pre-instruction phase many teachers showed the same difficulties despite of the different educational background and years of teaching experience. For high-school teachers, as for undergraduate students, the concepts related to stationary states, eigenstates, and time dependence of expectation values were found to be particularly difficult to manage (Singh 2001). Teachers' post-instruction answers to the questionnaire evidence a clear change of perspective on their view of QP concepts. Moreover, we unveiled several differences on teachers' responses depending on the typology of training course attended, as well as on their educational backgrounds. Also teachers' answers about their NoS view and motivational aspects have shown interesting changes after the refresher courses.

This current study addresses both teachers' difficulties and perspectives on inclusion of MP in upper-secondary level classes, which is something that has not been much investigated, with a focus on the teaching/learning of QP. In the paper, we briefly introduce the three different typologies of professional development courses. Then, we describe the details on the questionnaire design and the answers' evaluation process. Finally, we report and discuss the results. Concluding remarks about the efficacy of the investigated training courses are reported at the end of the paper.

2 The Three Typologies of Professional Development Courses

The first investigated typology of professional development is a refresher course for in-service teachers, organized by the University of Palermo, Italy, in collaboration with a local lyceum, for a total amount of 60 h, equally distributed in two years. A sample of 38 physics teachers (13 physicists, 20 mathematicians and 5 engineers), coming from several high-schools of Palermo province and having an average of ten years of teaching experience, decided, on a voluntary base, to take part to this training experience. During the first year (November 2013–March 2014), they mainly attended theoretical lectures and some demonstrative experiments on MP at the Department of Physics and Chemistry, University of Palermo. During the second year (January 2015–May 2015), a stimulating deepening, based on peer-to-peer discussions on QM and relativity concepts, has been provided them.

The second typology is a shorter training path (40 h in three months) for in-service teachers, organized by the Regional Office for Secondary Education, jointly with a team of researchers at the Department of Physics and Chemistry, University of Palermo, within the PLS Project. This training course introduced the teachers to MP theoretical contents and basic laboratory experiments by following an inquiry-based approach. A number of 14 in-service teachers (2 physicists, 4 mathematicians and 8 engineers) from regional upper secondary schools attended this course (March 2015–May 2015). The in-service teachers who participated to this course had an average of 10 years of experience in teaching Physics at high school.

The last typology is a course of Didactical Laboratories on MP for pre-service teachers, organized by the University of Palermo within the context of an active apprenticeship teacher training (TFA courses). It focused on methodologies for teaching MP in high schools and on the realizations of inquiry-based laboratory experiments. A number of 11 candidate teachers (4 physicists, 5 mathematicians and 2 engineers) attended this course of 24 h distributed along three months (February 2015–April 2015).

3 The Questionnaire Genesis and the Answer Evaluation

In order to design the questions to be included into the open-ended questionnaire, two faculty members at the University of Palermo were consulted, each of whom had taught quantum mechanics to physics or engineering undergraduates. Each faculty member was asked about what he or she considered to be the fundamental concepts in Quantum Mechanics, NoS views and motivational aspects, that high-school physics teachers should hold. Initially, 20 questions were selected among those used in validated questionnaires to diagnose difficulties on undergraduate or teacher QP conceptions (Mashhadi and Woolnough 1999; Singh 2001; Bao and Redish 2002; Michelini 2010). The questionnaire, in its initial form, was administrated to students enrolled in the "Introduction to Quantum Mechanics" course at the Engineering Faculty of the University of Palermo. After an extensive discussion in the class, followed by individual interviews to student volunteers, the seven more problematic questions were chosen to be included in this phase of our work. In this preliminary form, the questionnaire includes two motivational questions, two questions on NoS views and three questions on conceptual issues of QP. The test is designed to be administered in 1 h.

Below we report the questions of the open-ended questionnaire presented to the teachers.

Motivational questions

Question 1: Do you think that modern physics should be also taught in high-schools? Please, motivate your answer.
Question 2: What aspects do you believe are essential in a quantum physics teaching/learning path?

Table 1 Answering index in the Likert-like 5-value scale adopted in this study, corresponding to the teacher's answer typology

Answering Index (AI)	Answer typology
0	I do not know; I prefer do not answer
0.25	Incorrect answer
0.5	Partially correct answer
0.75	Correct, but incomplete answer
1	Correct and exhaustive answer

Nature of Science views

Question 1: Discuss the concept of probability in the context of both classical and quantum physics.
Question 2: Discuss the uncertainty and its implications on the limits of scientific knowledge.

Conceptual understanding

Question 1: Discuss implications of the Bohr's correspondence principle.
Question 2: Discuss the wave-particle duality and the principle of complementarity.
Question 3: The measure: how the meaning and the role of measurement change in quantum physics with respect to classical physics?

In order to evaluate the teacher answers we adopted a Likert-like 5-value scale, defining an Answering Index (AI), as shown in Table 1.

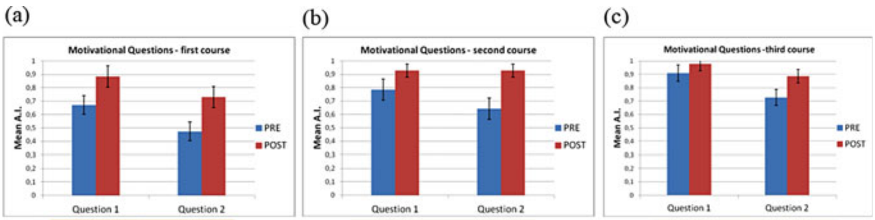
4 Result Analysis

After the initial phase of data collection, the authors analysed the data separately, ranking the teachers' answers by using the AI as defined in Table 1. This choice guaranteed the performance of independent analyses at the first stage, and only secondly a cross correlation among the different researchers' findings has been carried out. A good interrater reliability of the analysis was found, with a global percentage of accordance of about 95 % between the analysis table of the researchers. The discordances were negotiated in order to get to a unique classification of the teacher answers.

4.1 Analysis of the Answers to the Questionnaire

Motivational questions

The first question aims to assess the teachers' motivation to really introduce modern physics at high schools. The second question investigates the teachers' knowledge of the relevant aspects to be included in a QP teaching/learning path.



(a)

	PRE	POST
Question 1	0.67	0.88
Question 2	0.47	0.73

(b)

	PRE	POST
Question 1	0.79	0.93
Question 2	0.64	0.93

(c)

	PRE	POST
Question 1	0.91	0.98
Question 2	0.73	0.89

Fig. 1 Pre- and post-instruction mean answering indexes concerning the two motivational questions by secondary school teacher attending the: **a** first course; **b** second course; **c** third course, respectively

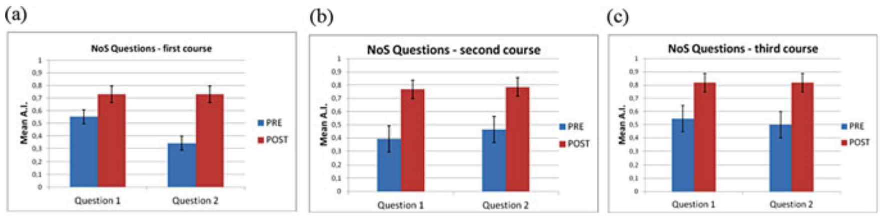
In panels (a), (b), (c) of Fig. 1 we show a mean AI, averaged over the number of teachers, concerning the two motivational questions for the three typologies of training course, respectively. In particular, blue histograms refers to the pre-instruction mean AI and red ones to the results obtained at the end of the training course. The length of the error bars represent two standard deviations. Initially, all our in-service teachers [panels (a) and (b) of Fig. 1] are greatly motivated ($0.67 \leq$ mean AI ≤ 0.79), but our results highlight several difficulties for the teachers to correctly identify the relevant aspects to manage in a learning path on QP ($0.47 \leq$ mean AI ≤ 0.64). For the same teachers, a relevant increase in the mean AI is found in both answers after the instruction. The analysis of the results reported in panel (c) of Fig. 1 shows that our pre-service teachers are strongly motivated and enough able to identify the relevant aspects to be included in a teaching/learning path on quantum mechanics. After the instruction both answers show a good improvement.

Nature of Science views

In this case, the first question aims to assess the teachers' epistemological view of the probability concept in both classical and quantum physics. The second question investigates the teachers' comprehension of the uncertainty concept and its implications on the limits of scientific knowledge.

In panels (a), (b), (c) of Fig. 2 we show the mean Answering Indexes concerning the NoS views for the three training courses; the blue colour refers to the pre-instruction results and red colour to the post-instruction findings.

The pre-instruction mean AI obtained by the in-service teachers attending the first and the second typology of professional development course [panels (a) and (b)] are very low for both the questions ($0.39 \leq$ mean AI ≤ 0.55 for the probability concept and $0.34 \leq$ mean AI ≤ 0.46 for the uncertainty principle, respectively). This happened probably because a large number of teachers preferred to do not answer, affecting the pre-instruction results. After the training we have found a relevant increase in both the answers.



(a)

	PRE	POST
Question 1	0.55	0.73
Question 2	0.34	0.73

(b)

	PRE	POST
Question 1	0.39	0.77
Question 2	0.46	0.79

(c)

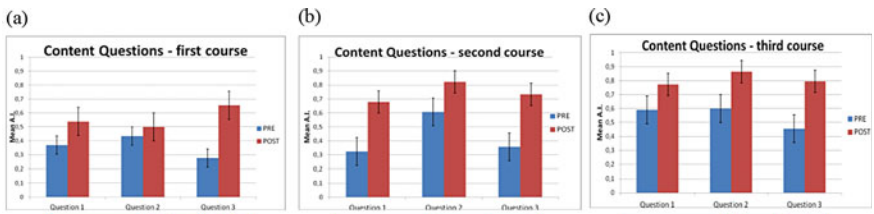
	PRE	POST
Question 1	0.55	0.82
Question 2	0.50	0.82

Fig. 2 Pre- and post-instruction mean answering indices concerning the two questions on nature of science views by secondary school teacher attending the: **a** first course; **b** second course; **c** third course, respectively

The pre-instruction mean AIs for the answers provided by the pre-service teachers [panel (c) of Fig. 2] also evidence the presence of not negligible problems in their NoS views, especially for what concerns the uncertainty principle and its implications on the limits of scientific knowledge (mean AI = 0.50). After the instruction we have found a great change in the mean AI for both the answers, up to 0.82.

Conceptual understanding

The answers of in-service teachers attending the first kind of refresher course [see panel (a) of Fig. 3] give evidence of the presence of several conceptual misunderstanding for all the issues investigated in the three questions (0.28 $\leq$ mean AI $\leq$ 0.43) and especially on the meaning and the role of *measure* in QP (Question 3). Unexpectedly, after the instruction we have found a moderate improvement for the first two questions and a considerable increase of the mean AI concerning question three.



(a)

	PRE	POST
Question 1	0.37	0.54
Question 2	0.43	0.50
Question 3	0,28	0.65

(b)

	PRE	POST
Question 1	0.32	0.68
Question 2	0.61	0.82
Question 3	0,36	0.73

(c)

	PRE	POST
Question 1	0.59	0.77
Question 2	0.60	0.86
Question 3	0,45	0.80

Fig. 3 Pre- and post-instruction mean answering indices concerning the conceptual understanding by secondary school teacher attending the: **a** first course; **b** second course; **c** third course, respectively

The pre-instruction mean AIs evidence a weak awareness of the QP relevant concepts also for the teachers attending the second typology of training course [panel (b) of Fig. 3], with a small exception for the knowledge of the wave-particle duality and the principle of complementarity (Question 2: pre-instruction mean AI = 0.61). After the instruction we have found a relevant improvement of the mean AI concerning all the conceptual issues.

The pre-instruction answers provided by the pre-service teachers [panel (c) of Fig. 3] evidence the presence of some misconceptions especially on the meaning and the role of measure in quantum physics. After the instruction our candidate teachers have reached a good awareness in all the three conceptual issues.

4.2 Strengths and Weaknesses of the Three Investigated Typologies of Training Courses

During the design phase, the strengths of the first training course were (i) the presence of a considerable number of theoretical lectures on QP concepts, (ii) the inclusion of peer-to-peer discussions and (iii) the request of a moderate workload for teachers (two meetings in a month). But, despite of the large number of theoretical sessions, only a small improvement in the post-instruction NoS views and in the conceptual understanding has been found. The analysis of teachers' answers to post-instruction interviews evidenced that the teachers have perceived this kind of refresher course as too long in time. Probably, this can be responsible of the fact that less than half of the teachers initially involved, only 15 (3 physicists, 10 mathematicians and 2 engineers) completed this course. Furthermore, during the interviews the teachers have highlighted other weaknesses related to the presence of (i) only *ex cathedra* demonstrative experiments without teacher involvement; (ii) the lack of design and testing in class of learning paths on QP.

The analysis of the answers to the interviews to the teachers attending the second kind of training gives evidence of the following course strengths: (i) the request to the teachers to carry out basic laboratory experiments by following an inquiry-based approach; (ii) the request of design and testing in class the proposed learning paths on QP; (iii) the sharing of the results of the experimentations in the classrooms with the analysis of the student feedback, via peer-to-peer discussions. However, also some weaknesses emerged: the teachers have complained for having too little time for both the deepening of QP concepts and the experimentation in class of the designed learning paths.

The third training course was more focused on contents and methodologies for teaching Modern Physics in high schools and required to the candidate teachers (i) to realize basic laboratory experiments by following an inquiry-based approach; (ii) to design multidisciplinary learning paths on MP. However, our pre-service teachers have claimed for the lack of opportunities to test in class the designed learning paths.

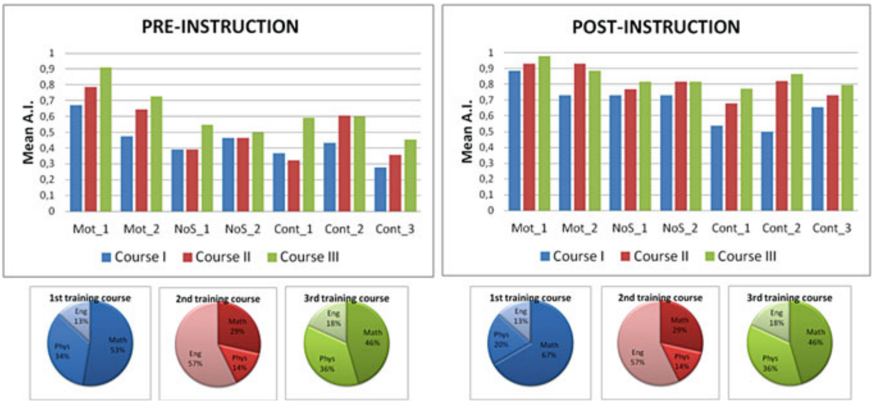


Fig. 4 Pre- and post-instruction comparison of the mean AIs with respect to the different typologies of professional development course attended. Pie charts show the different composition of the three groups of teachers in terms of educational background

4.3 Analysis of Results with Respect to the Different Training Course Typologies

In order to address the question concerning the efficacy of the three different typologies of training course, we show in Fig. 4 the pre and post-instruction comparison of the mean AIs, respectively. Each panel is accompanied by three pie charts showing the different composition of the three groups of teachers in terms of academic education.

The pre-instruction plot shows that, despite of the different composition of the three groups in terms of background education, the AIs related to the NoS views are very similar for all the in-service teachers and only slightly higher in the case of candidate teachers. Similar results are obtained for what concerns the background conceptual knowledge on QP. Furthermore our pre-service teachers are very motivated to teach QP in the high-schools.

Post-instruction histogram evidences that the most significant increments on the mean-AI are obtained for the second and third typology of courses, both based on a larger use of inquiry-based laboratory experiments.

4.4 Analysis of Results with Respect to the Different Teacher Educational Background

In Fig. 5 we summarize our findings concerning the analysis of the questionnaire answers, as a function of the different teacher educational background. Blue colour refers to the physicists, red one to the mathematicians and green to the engineers.

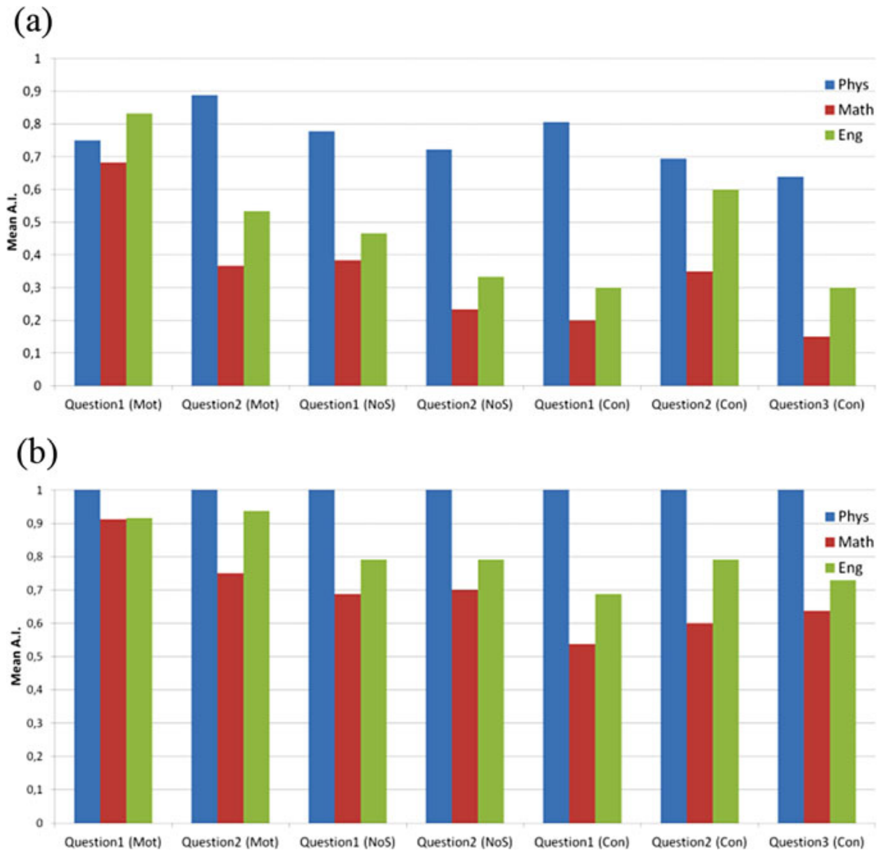


Fig. 5 **a** Pre- and **b** post-instruction comparison of the mean AIs with respect to the different background of academic education

The pre-instruction plot [panel (a)] highlights that physicists obtained the best rank in all the questions (the mean AI is always greater than 0.6), while both engineers and mathematicians evidence significant difficulties both in their NoS views and conceptual understanding. As a matter of fact, engineers seem to be more motivated than physicists and mathematicians to teach MP at high school, but actually only physicists have a clear idea of the relevant aspects to be included in a QP teaching/learning path. Post-instruction data [panel (b)] show that physicists achieve always the highest score, but also mathematicians and engineers show a significant improvement. In particular, we can see that engineers scored a little bit higher than mathematicians, probably because of their higher practical skills with respect to the more theoretical mathematicians.

5 Conclusions and Future Prospects

Our study examined the comprehension of key concepts in quantum mechanics from in-service and pre-service secondary school physics teachers, focusing on the changes in perceptions about QP concepts and NoS views, after they attended a professional development course on MP. We analysed the outcomes from teachers' answers to an open-ended questionnaire for three different typologies of professional development course.

On the basis of our results, an effective training course for high-school physics teachers should (1) focus on both contents and methodologies for teaching MP; (2) be strongly motivating and challenging; (3) include peer-to-peer discussions; (4) stimulate the teacher cleverness and elicit them to get back into play by designing and carrying out highly engaging inquiry-based learning paths on MP in their classrooms; (5) promote the sharing and dissemination of practice results collected from inquiry-based experimentations with the students.

Furthermore, our results have revealed several differences in the teachers' answers to the questionnaire, depending on their different educational background. These findings suggest that an effective teacher instruction on MP should include differentiated training paths, adapting to the diverse needs of the participating teachers. In particular we believe that physicists would need a short refresh of contents and methodologies for teaching MP in high schools and, above all, to be further stimulated to design and carry out highly motivating inquiry-based learning environments. On the other hand, mathematicians and engineers would need an adequate theoretical instruction on MP first, in order to reinforce their knowledge background, and then introduced to the design process and the practice of inquiry-based teaching/learning on MP.

This paper is one of the few focusing on the quantum mechanics conceptions held by in-service and pre-service physics teachers. Even considering that the problem of MP instruction of teachers having math or engineering educational background is not today widespread in many European countries, this situation may change very soon due to the shortage of physics teachers recently reported at the EPS Workshop during the GIREP conference. In this respect, the preliminary results discussed in this paper may be helpful in designing new curricula, more oriented towards an improvement of both fundamental knowledge and inquiry-based methods of instruction for next-generation teachers of modern physics.

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Teachers' Beliefs About Subject Specific Competences and Inquiry Based Learning

Claudia Haagen-Schützenhöfer, Gerhard Rath and Veronika Rechberger

Abstract The Austrian Ministry of Education has set up several measures as reaction to the low results in international student assessment studies like TIMSS or PISA: On the level of systematic monitoring, one strategy was to implement educational subject specific standards to change the focus of the educational system from input to output orientation. Subject specific standards and standardization has become one main issue in Austrian education in the last decade. There are several reasons why teachers encounter the issue of standards with resentments. One is that teachers were not provided with sufficient supportive measures in time, like teacher training courses or teaching materials, for a paradigmatic change in their teaching culture. Due to this shortfall, a number of beliefs and misconceptions about competence oriented teaching have spread. There seems to be a high tendency among teachers to interpret competence orientation only in terms of implementing open learning strategies which do not require guidance by the teachers at all. In the field of science teaching this idea of open, unguided learning manifests in the increase of Inquiry Based Learning (IBL), which of course can only be one way of promoting competence orientation. However, our work with teachers suggests that IBL is frequently just perceived as doing experimental work without any interference by the teacher. This situation served as the starting point for a research project which investigates teachers' beliefs about competence orientation and IBL. As sample we chose teachers who applied for a continuous professional development programme (CMSE) focusing on the promotion of students' subject specific competences. Our results show that even this preselected sample, which is about to take the challenge of competence orientation, struggles with competence orientation and the introduction of IBL.

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1 Introduction: Motivation and Starting Point

At first sight it may be astonishing for the reader to find a study which combines research on subject specific competences with research on Inquiry Based Learning (IBL). In order to make this design of our research project plausible, it is necessary to describe two developments characterizing the national Austrian educational situation as prerequisite: the implementation of national educational standards and the continuous professional development programme CMSE.

1.1 Standardization in Science in Austrian Secondary Schools

The implementation of performance standards and consequently the development of subject specific competence models in the Austrian educational system was a consequence of "moderate" national results in international comparative studies like PISA or TIMSS. Thus educational, subject specific standards were launched with the medium-term aim to improve the quality of teaching and learning by shifting instructional practices from input- to output orientation.

A competence model for science year 8 and later year 12 was developed (Haagen and Hopf 2012; Weiglhofer 2008), based on the construct of scientific literacy as used in the PISA 2006 framework (Bybee et al. 2009) and based on already existing competence models of other countries. In-service teacher trainings as well as the adoption of schoolbooks and the availability of adequate teaching materials could not keep pace with the rush of the implementation plan of the educational authorities. This shortage or delay in supportive measures seems to contribute to teachers' reserved attitudes. Standardization is frequently perceived as top down initiative dictated by educational authorities to control teachers and their work. In addition to this, most teachers feel that they do not get enough support for changing their paradigm of teaching (cf. Altrichter and Kanape-Willingshofer 2012).

Especially science teachers seem to have developed the strategy of introducing scenarios of open, unguided learning into their lessons as the main measure of putting competence orientation into practice. Simultaneously, the hype connected to IBL has reached Austria during the last years and especially in science teaching, many teachers follow this trend using it often synonymously with competence orientation. Having a closer look at this development, it turns out, however, that several instructional strategies which may not be informed by what we find as IBL in literature are labelled as inquiry based (cf. Minner et al. 2010).

In our pre- and in-service trainings for science teachers we also get the impression that a number of myths about competence oriented teaching and subject specific competences are circulating. In order to improve pre- and in-service teacher-trainings that trigger a conceptual change in teachers' beliefs about and attitudes towards subject specific competences and IBL, it is necessary to find out about teachers' beliefs and misconceptions in more detail. So an explorative study on teachers' beliefs on subject specific competences and IBL was planned. High school teachers taking part in a continuous professional development programme focusing on subject specific competences in science subjects and mathematics (CMSE) were selected as sample.

1.2 Competences in Mathematics and Science Education: A Continuous Development Programme

CMSE is one of five thematic programmes within the IMST framework (Innovations in Mathematics, Science and Technology Teaching) which was another initiative launched after the PISA shock by the ministry of education in 2010. CMSE aims at the improvement of students' subject specific competences in mathematics and science subjects. The core idea is to simultaneously intervene at the teacher and at the student level by providing a support system of teacher trainers and science education researchers, which helps the participants to address the concept of subject specific competences in their teaching (Langer et al. 2014).

CMSE participants represent a selected sample. At this point it is important to mention that in Austria, in-service teacher training is not compulsory, so only one third of the teachers attend trainings on a regular basis, a second third now and then and the final third does never turn up in training courses. We assume that our sample belongs to the more active, innovative and informed group among teachers, since they had to apply for their participation in the CMSE programme themselves. They had to submit a proposal in which they outlined a school project that aims at implementing a teaching innovation related to subject specific competences. Their submissions were reviewed by external educational experts and by CMSE staff. Only 20 projects are accepted for the programme per year, the number of applications is typically around 45.

Our guiding research questions can be summarized as:

- RQ 1: Which ideas do in-service teachers of the CMSE 2014 cohort have about subject specific competences when they enter CMSE?
- RQ 2: Which ideas do in-service teacher of the CMSE 2014 cohort have about IBL when they enter CMSE?
- RQ 3: Are there any significant differences between the 2010 cohort (first year of CMSE) and the 2014 cohort in terms of knowledge about subject specific competences when entering CMSE?
- RQ 4: How do the ideas of the 2014 cohort change during the CMSE program?

This paper focuses on research questions RQ 1 to RQ 3.

2 Theoretical Framework

The theoretical frame of this explorative study rests on three pillars: the concept of competences, models of IBL and research results on IBL as well as on pedagogical content knowledge (PCK).

2.1 Competences: Definitions and Competence Models

Competence orientation and standardization has been a worldwide trend for the last two decades. Consequently, there is not one single definition for "competence or competences" but numerous. In this project we used these competence definitions which have been used as the basis for the Austrian competence model Science 8 and 12 (e.g. National Research Council 1996; Bybee 2002; KMK 2004; CMEC 1997). Two of those definitions are given in the following. Weinert (2001) defines competences as "[…] cognitive abilities and skills possessed by or able to be learned by individuals that enable them to solve particular problems, as well as the motivational, volitional and social readiness and capacity to utilise the solutions successfully and responsibly in variable situations."

Another root is the concept of Scientific Literacy as used for PISA (OECD 2004): "The emphasis of the PISA 2003 assessment of science is on the application of science knowledge and skills in real-life situations, as opposed to testing particular curricula components. Scientific literacy is defined as the capacity to use scientific knowledge, to identify questions and to draw evidence-based conclusions in order to understand and help make decisions about the natural world and the changes made to it through human activity."

The Austrian competence model for Science year 8 (see Fig. 1), which is the same for Biology, Chemistry and Physics, was developed according to these definitions. Like many other competence models it consists of three dimensions (axes): content, complexity and competence domains. The competence domains are subdivided in three facets, which reflect the core ideas of scientific literacy:

- **Knowledge** meaning "Scientific knowledge and use of that knowledge […] to acquire new knowledge [and] to explain scientific phenomenon".
- **Science Methods** as "understanding of the characteristic features of science as a form of human knowledge and enquiry" as well as the ability "to identify [scientific] questions" and answer them with the help of inquiry.
- **Judgement** describing "[the] willingness to engage in science-related issues, and with the ideas of science, as a constructive, concerned, and reflective citizen to draw evidence-based conclusions about science-related issues (OECD, 2006)" (quoted from: Bybee et al. 2009).

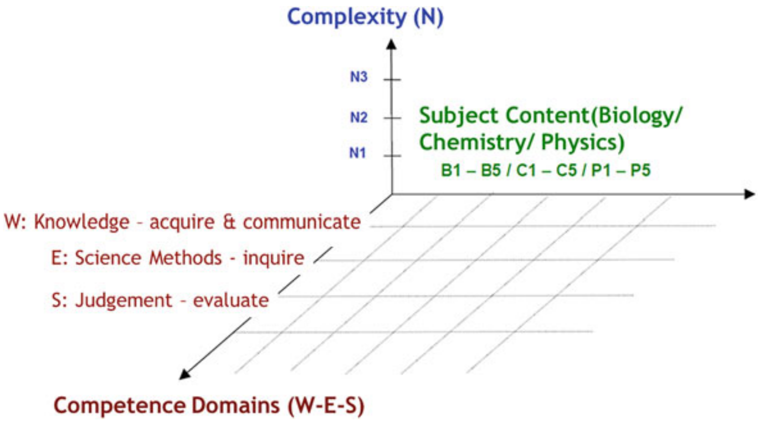


Fig. 1 Austrian competence model for science, year 8

More details concerning the Austrian competence model can be found in Haagen and Hopf (2012) and Weiglhofer (2008).

For this study we mainly focused on the dimension "Competence Domains" as the chosen content varied in the different school projects.

2.2 *Inquiry Based Learning (IBL): Models and Research Results*

Inquiry Bases Learning has become a big trend in Austrian Science Education during the last years. Finding one definition for IBL or extracting essential features of IBL from definitions is a difficult endeavour. As elaborated in Minner et al. (2010) it is not only difficult to give a definition of IBL, at the same time it is not possible to separate the concept of IBL from other methods. For our project we focused on a bundle of essential features extracted from definitions of IBL as used in NRC 2000 und NRC 1996 (National Research Council 1996; National Research Council (NRC) 2000).

Characteristic for scenarios of IBL is that students are:

"engaged by scientifically oriented questions.
[…] give priority to evidence, which allows them to develop and evaluate explanations that address scientifically oriented questions.
[…] formulate explanations from evidence to address scientifically oriented questions.
[…] evaluate their explanations in light of alternative explanations, particularly those reflecting scientific understanding.
[…] communicate and justify their proposed explanations" (Cited from: Pathway 2013).

	Source of the question	Data collection methods	Interpretation of results
Level 0: verification	Given by teacher	Given by teacher	Given by teacher
Level 1: structured	Given by teacher	Given by teacher	*Open to student*
Level 2: guided	Given by teacher	*Open to student*	*Open to student*
Level 3: open	*Open to student*	*Open to student*	*Open to student*

Fig. 2 Levels of inquiry based learning (Blanchard et al. 2010)

In order to pay tribute to the numerous varieties of IBL found in school settings, we base our research on the model of Blanchard et al. (2010) who define different levels of IBL based on the distribution of responsibility between teachers and students during three phases of the IBL-process (Fig. 2).

As far as the effectiveness of IBL is concerned, empirical evidences are heterogeneous, one reason for this may be that a wide range of activities are labelled as IBL. One common point of many studies seems to be that the level of guidance, especially when starting with IBL, is crucial for the effectiveness concerning students' learning and retention (Hattie 2013; Kirschner, Sweller and Clark 2006; Minner et al. 2010). As reasons Kirschner et al. (2006) mention "expert–novice differences, and cognitive load".

2.3 Pedagogical Content Knowledge (PCK)—Professionalization of Teachers

CMSE is designed to intervene on the level of students as well as on the level of teachers. The idea is to support the development of certain PCK facets during the CSME programme. Defining PCK is a task as demanding as defining IBL.

Pedagogical content knowledge as understood by Shulman (1987) "identifies the distinctive bodies of knowledge for teaching". Shulman's (1987) description of pedagogical content knowledge as "special amalgam of content and pedagogy that is uniquely the province of teachers their own special form of professional understanding" is frequently referred to by other researchers in this field and can therefore be seen as a general description.

The PCK model of Magnusson et al. (1999) gives an overview of several facets which make up the construct of PCK. We chose this model as it contains those PCK facets which are addressed in CMSE. In Fig. 3, the facets which are relevant for this continuous professional development programme are highlighted and the context in which these facets are addressed is added: In the domain "knowledge of science curricula", the CMSE programme focuses on this part of the Austrian curricula

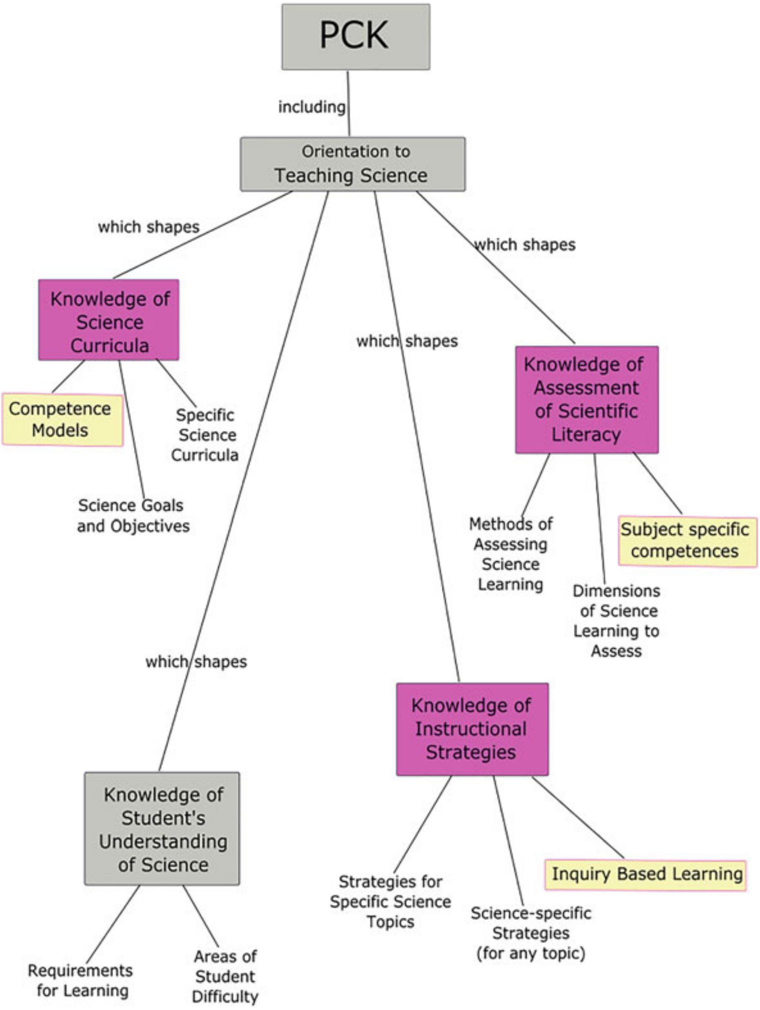


Fig. 3 PCK facets addressed in CMSE based on the PCK model of Magnusson et al. (1999)

referring to subject specific competence models and national standards. IBL in science teaching is the "instructional strategy" which is in the centre of professionalization. Finally, another goal of CMSE is to increase teachers' "knowledge of assessment of scientific literacy".

3 Research Design and Research Methods

The sample of our study consists of teachers who were selected for the CMSE programme in 2010—this was the first CMSE cohort—and 2014—the current CMSE cohort. The participants of CMSE teach science and mathematics at different types of schools and at different age levels from primary to upper secondary (students aged 6–19 years).

The 2010 cohort consists of 24 teachers ($N_{2010} = 24$) of whom 71 % are female and 29 % male. 41 % of the participants were primary teachers, 41 % taught in lower secondary and 18 % in upper secondary.

In the 2014 cohort there are also 24 teachers ($N_{2014} = 24$), of whom 79 % are female and 21 % are male. Compared to the 2010 cohort, the proportion of primary teachers has increased to 58 %, whereas the number of participants from lower secondary has decreased to 21 %. The proportion of upper secondary teachers remained at level of 21 %. For the 2014 cohort, a number of additional demographic data is available. The majority of the teachers (70 %) in the 2014 cohort have more than 10 years of teaching experience and only 12.5 % have less than 5 years of teaching experience when entering CMSE. Another interesting fact is that nearly 40 % of the 2014 participants had already been in the CMSE programme with another innovative school project focusing on subject specific students' competences. Another 38 % of the 2014 sample can be categorized as "IMST experts", which means that they have either been in one of the other four IMST topical programmes or in other CPD measures within the IMST framework. Only 25 % of the 2014 cohort did not have previous experience with CPD programmes within the IMST framework.

The research design of this study is mainly a pre-post design which uses two different data sources: written documents produced in the course of the project by the teachers and answers gained by questionnaires (see Fig. 4). The research design can be categorised as pre- post-design, since data of each type was collected before the actual implementation of the school projects as well as after finishing the projects: As written documents we analysed the project proposals which were produced by the teachers for their application at CMSE and the final project reports.

As already mentioned, teachers have to apply for CMSE by handing in a project proposal. The application form for CMSE contains sections concerning the participants' innovative projects and, among other issues, focuses also on their intended goals related to students' subject specific competences. At the end of the project year a final project report is compulsory to finish the CMSE programme. This report develops during the project year and serves also as tool for structuring and reflecting the participants' professionalization process. The structure given in the template of the final report corresponds partly to the structure of the application form. So it is possible to extract teachers' beliefs and goals as far as students' subject specific competences are concerned from one document produced before the start of the project—the project proposal—and one which records the final development stage at the end of the project—the final project report.

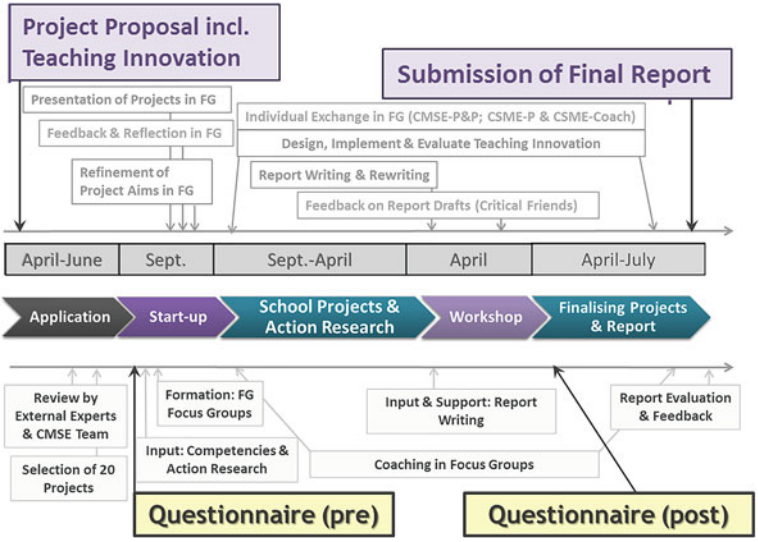


Fig. 4 Research design and data collection

Questionnaires were used as a second data source. Those PCK facets addressed during CMSE (see Fig. 3) were operationalized in a questionnaire which was administered at the start-up meeting and in similar form at the end of the project year. The questionnaire contained open questions and as well as multiple choice questions.

For data analysis, qualitative and quantitative methods were used: Statistical frequency analysis was used for the demographic data as well as for the multiple choice questions. Qualitative content analysis (Mayring 2014) was used for the open questions of the questionnaires as well as for the documents (project proposals and final reports). Categories were built deductively based on models of subject specific competences and IBL taken from research literature (see section "Theoretical Framework" in this paper). The structuring process guided by deductive categories did however not work for the full data material, so it was necessary to extend the categories inductively. Finally a comparative analysis of the results from the 2010 and 2014 cohort was carried out.

4 Selected Results

In a first step, the results gained from the analysis of the project proposals are discussed. In the 2014 CMSE proposals a large number of different competences and competence domains, which shall be addressed in the course of the school projects, are mentioned. The number of competence facets which shall be addressed

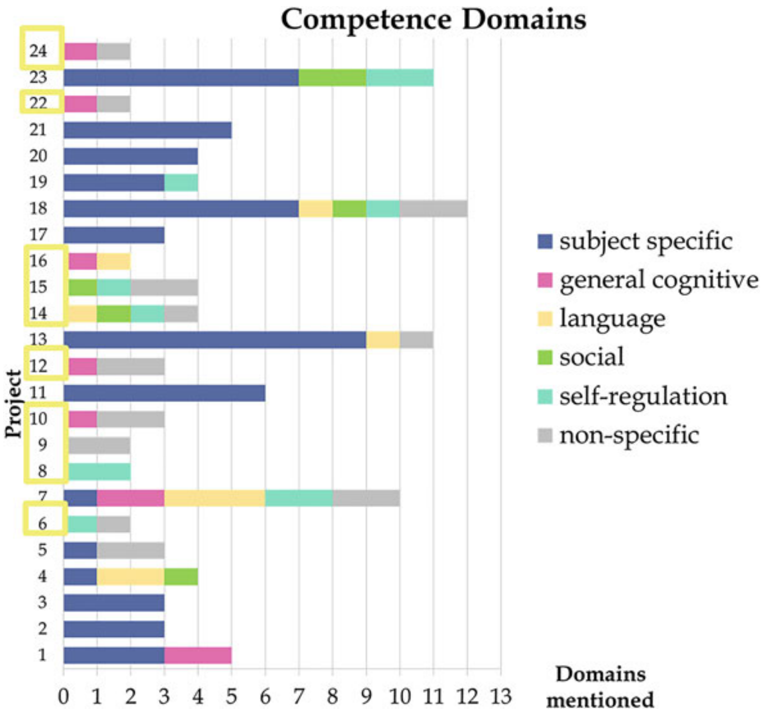


Fig. 5 The number of competence domains mentioned in the CMSE 2014 proposals

on the level of students range from 2 to 12 per project (see Fig. 5). 62.5 % of the project proposals contain at least one facet of subject specific competences (see Fig. 6). An interesting category, which can give insight into teachers' interpretation of competence orientation, is "non-specific". This category consists of those units of analysis which do not specify a certain competence but rather mention common places or are too vague to be assigned to any other competence domain.

When the 2014 project proposals are split into two groups, those with and those without subject specific competences on the level of students, we get a significantly different distribution concerning the category "non-specific". While 40 % of the proposals containing subject specific competences also mention "non-specific" competences, 77 % of the proposals without subject specific competences do so.

Figure 6 compares the results concerning subject specific competences of the 2014 and the 2010 cohort. Here we can see that in 2010 only one third of the proposals focused on subject specific competences, compared to 62 % in 2014. A detailed analysis of the different competence domains supports this finding (see Fig. 7). While the average number of competence domains mentioned in the project proposals in total remains constant, a significant shift can be seen in the 2014 cohort from "non-specific" competences to "subject specific" competences.

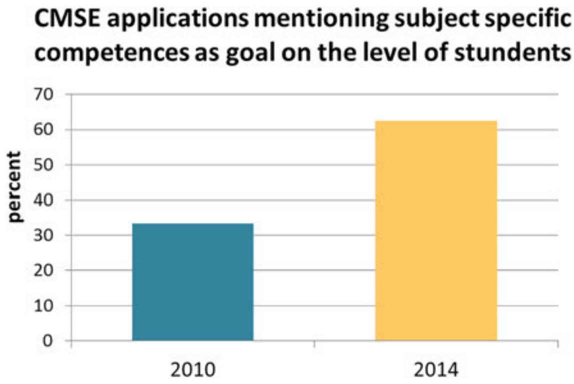


Fig. 6 The role of subject specific competences on the level of students in CMSE applications: comparison of the 2010 and 2014 cohort

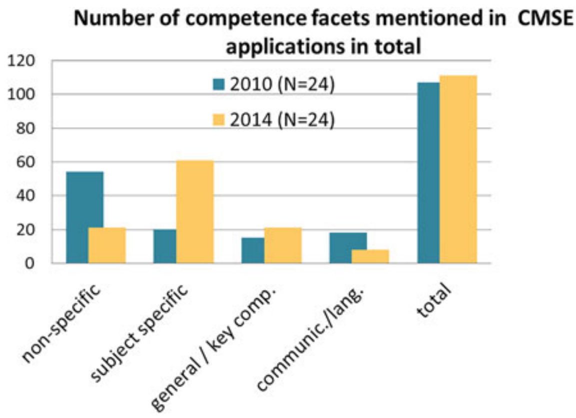


Fig. 7 Competence facets mentioned in CMSE applications on the level of students: comparison 2010 and 2014

In a second step, the findings of the pre-questionnaires, administered at the start-up workshop 2014, are discussed. About half of the teachers (48 %) stated to be and 28 % stated not to be familiar with a subject-specific competence model relevant for their projects. When they were asked to outline the competence model they had used as basis for their projects, we get a different picture (see Fig. 8). Only 21 % of our sample could sketch a subject specific competence model, 29 % described something very general which did not fit any subject specific competence model and 38 % preferred not to answer this question at all.

The IBL part of the questionnaire was only administered to teachers who indicated to use IBL in their projects (N = 19). One item of the pre-questionnaire referred to benefits of IBL for students. The maximum number of benefits mentioned per project was three. The most prominent factor was student activity, but rather in terms of trial an error than cognitive activation. Nearly half of the participants related IBL to "better memorizing content". This significantly corresponds to the idea that IBL addresses several sensory channels at the same time. Figure 9 shows the aspects of IBL identified as limiting for learning progressions.

Fig. 8 Participants' description of a subject specific competence model

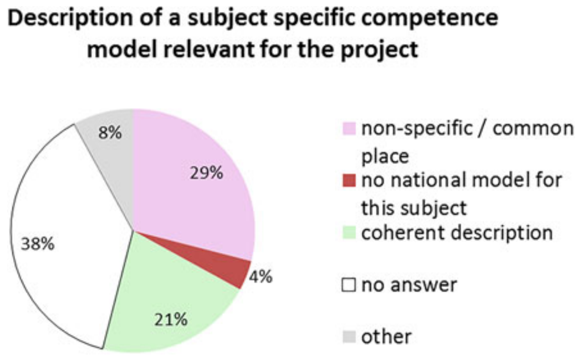
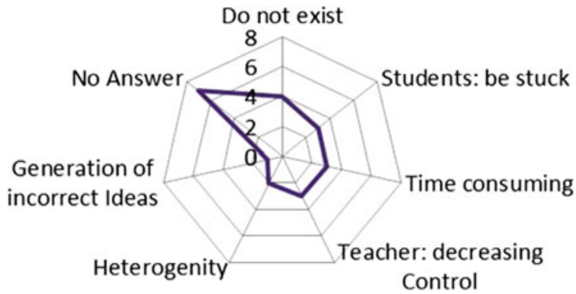


Fig. 9 Limiting factors of IBL for learning progressions



While 37 % of the participants did not answer this question, 21 % could not think of any possible disadvantages of this method, the rest could identify on average 2 disadvantages. These disadvantages mainly belong to classroom management like "decreasing control over the class" or "time consuming". Only three of the participants stated that students could get struck in such unguided learning processes and one indicated the possibility of generating incorrect conceptions during an unguided process (see Fig. 9).

5 Interpretation and Conclusion

In general, the results show that the ideas about content specific competences are very vague when entering CMSE. Our teachers' written documents do hardly reveal any distinction between subject specific competences and general competences in the sense of soft skills. Similar observations can be reported on IBL. The fact that the deductively generated categories did not fit the data produced by the CMSE teachers shows already a discrepancy between normative definitions of competences, competence models as well as descriptions of IBL as an instructional strategy and teachers' beliefs. This supports the initial assumption that competence orientation and IBL are used as labels in everyday school life without a systematic relation to the corresponding normative concepts.

What is surprising is that not all the projects proposals contain subject specific competences. This is especially surprising as these projects were selected by external experts for a CPD programme focusing on subject specific competences. This is a first hint that teachers—at least of our sample—still are not used to planning instruction based of subject specific competences. The heterogeneity within the sample can be seen form the fact that those proposals containing subject specific competences were by far more specific and concrete while project proposals which did not mention subject specific competences used in general "non-specific" descriptions more often and were vague in the outline of their intervention.

The finding that the 2014 cohort contains a seemingly low ratio of project proposals which really identify subject specific competences as the main driving force for their interventions is relativized by the 2010 results. At least for the applicants to the CMSE program it seems that competence orientation has gained a more important status and/or our applicants got more sophisticated in handling the vocab related to competence orientation.

Although teachers of the 2014 cohort are better informed about competence orientation than their colleagues of the 2010 cohort, only a minority of them is able to describe competence models of their subjects. This implies that there is still a big gap between the intentions of the ministry and what actual reaches school reality. The discrepancy between teachers' self-perception and their actual knowledge related to competence models hints at the lacking awareness that competence orientation needs a paradigmatic change in teaching culture.

The results concerning IBL also show a very shallow handling of this method. The teachers of our already preselected sample can name at maximum three advantages of this method in terms of learning and competence acquisition, which is compared with the list given in the theoretical part of this paper a small number. What is even more worrying is that they mentioned frequently aspects which are hardly addressed in IBL scenarios as various studies show. Similarly, the participants lack critical awareness of limiting factors of IBL concerning learning progressions. These results support our hypothesis that IBL is used as label for many different activities which are not congruent with the ideas of IBL as reported in literature.

Summing up, we can conclude that our sample's beliefs concerning subject specific competences and IBL are not in balance with normative concepts. Our sample's level of professionalization concerning these issues is low when they enter CMSE. Since this sample was selected by a review process, it indicates that they represent a positively selected sample and that many of their colleagues may even have less developed PCK concerning competence orientation and IBL, even though these issues have been dominating our educational system for several years.

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Hydrogels in the Classroom

Jerneja Pavlin and Mojca Čepič

Abstract Hydrogels are commonly used and novel smart materials. They are superabsorbent polymers with interesting properties. Hydrogels can also motivate students for playing and learning science because they reflect the trends in current research. Literature review yielded no results about students' conceptions of hydrogels. Therefore we decided to explore students' knowledge about hydrogels, acquired through informal learning process. The paper first presents the description of hydrogels, list of experiments with hydrogels and describes the prior research about hydrogels in some detail. The results of the study, which included 104 1st year pre-service primary school teachers from Faculty of Education, University of Ljubljana, are then presented. On February 2015 students filled in a paper-pencil questionnaire about hydrogels (QH) with 26 items. Results show that informal knowledge about hydrogels is limited, since students on average achieved 8 % of possible points on the QH. Results have further influenced the design of a pilot teaching module about hydrogels.

1 Introduction

Studying science is not popular between young people. One of the possible reasons might be that school science subjects lack topics, common to students' daily life. However, students' motivation and attitude towards science have an important role at decision-making for further studies. It is generally accepted that motivation and attitude towards science are developed in early education. If the content is related to students' daily life, it increases their motivation for learning science. Therefore the

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choice of science content in context plays an important part in early science education (Bulte et al. 2004; Dolinšek et al. 2006; Khazan 2012; Williams et al. 2003).

Hydrogels are widely spread materials with interesting properties. Students generally encounter products like hydrogel lenses, patches, pads, dermal sprays, decorative gel pearls etc., which all contain hydrogels. Furthermore, students spend plenty of time on the world wide web searching for information. If we write keyword “hydrogel*” into Google search engine we get more than 7,680,000 hits (30.10.2015) and more than 734,000 hits are given for the “know* hydrogel*” keywords. Number of search results reflect general interest in getting acquainted with hydrogels. School lessons should correctly present information about new discoveries in science found on the internet. School curriculum for science courses is flexible and allows implementation of hydrogels. Since this topic is new, however, the teachers often decide not to present it to students, even if they show interested in it (Repnik 2012; Pavlin et al. 2013).

Mathelitsch (2013) reports that competences play an important role in science education. He describes 3-dimensional competence model that includes *content*, *level* and *skill*. *Content* refers to a dimension reflected more or less by the syllabus of the science course. In physics, it might be related to mechanics, electromagnetism, thermodynamics, optics and matter. *Level* refers to three levels of understanding: 1st level is reproduction (knowing facts, procedures and concepts), 2nd level is understanding of concepts and application of knowledge and 3rd level is transfer (the independent ability to connect scientific concept with real situations). *Skill* refers to knowledge organization, gaining cognition and conclusions. On the other hand, experimental competence refers only to problems with an authentic hands-on interaction, involving scientific questions as well as engineering tasks. Experimental competence has various categories: *conducted observation*, *measurement with a given scale*, *scientific investigation*, *experimental comparison*, or *constructive problem solving* (Metzger et al. 2013).

Taking these into account, the paper will first briefly present hydrogels and experiments showing their basic properties and than discuss the pre-service primary school teachers’ conceptions about hydrogels in some detail.

2 Hydrogels

Hydrogels are smart materials because they change their shape (or some other property) in response to changes in the environment. These properties make hydrogels functional in biomedical applications, as for example, in soft contact lenses, disposable diapers, drug delivery, wound dressing, desloughing and debriding of necrotic and fibrotic tissue, for providing absorption, in hemo-compatible surfaces of medical devices, and scaffolds in tissue engineering. They are also produced naturally by the human body; like cartilage, mucin, blood clots, and vitreous humour of the eye. Scientists also try to discover how to grow replacement body parts in hydrogels (Paleos 2012; Wong 2007). Application of hydrogels are wide, from food, cosmetic, pharmaceutical, biotechnology, agriculture and colour production. All of this demonstrates that hydrogels are an important part of our lives (Gerlach and Arndt 2009).

Hydrogels and their properties are topic of current scientific researches of modern materials. They are part of soft matter, a group of materials called gels. The most important property of gels is that they are solid or semi-solid materials having 3D framework and small molecules of liquid. A well known gel is gelatine, often used for cooking (Gerlach and Arndt 2009).

Hydrogels have properties of both liquids and solids and are extremely interesting materials with web structure of polymer chains arranged in 3D (Fig. 1). Space between polymer macromolecules is filled by water molecules. The ability of water absorption, polymers dissolving in water and formation of hydrogels all make them useful for storage and transportation of active ingredients. Polyelectrolyte gels were developed as superabsorbent materials for diapers and controlling the humidity. These gels absorb more than 99 % of water (Gerlach and Arndt 2009; Kurečič 2011).

An important property of hydrogels is the absorption of water and water solutions. Polymers used in hydrogels are hydrophilic. Often used polymers are polyethylene oxide, polyvinyl alcohol, polyvinylpyrrolidone and polyhydroxylethylmethacrylate. Properties of hydrogels such are temperature sensitivity, pH sensitivity, behaviour in salt solutions, in E-field, etc. depend on the contained polymer (Kurečič 2011; Okay 2009; Yoshihito and Kanji 2001).

Hydrogels can absorb up to 500 times their own weight of water. This number is called the swelling ratio. It presents the ratio between the mass of absorbed hydration media (usually water) and the mass of dry hydrogel. Water can be bound or free. The strong interactions between molecules of water and hydrophilic parts of polymer are crucial for the hydration when water is bound. Due to the capillarity effect, the process of water absorption continues. Such water is free and is not bound (Kurečič 2011; Yoshihito and Kanji 2001).

Carboxylic acids are often used in hydrogels. The acid groups stick of the main chain of the polymer. The equation in Fig. 2 presents how polymer changes when water is added. This reaction is reversible. Added water causes equilibrium to shift to the right. If water is removed, equilibrium shifts to the left. The product of this

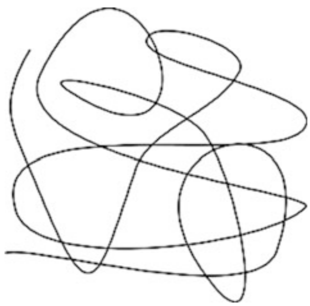

Fig. 1 A polymer chain coiled up in solution (Wong 2007)

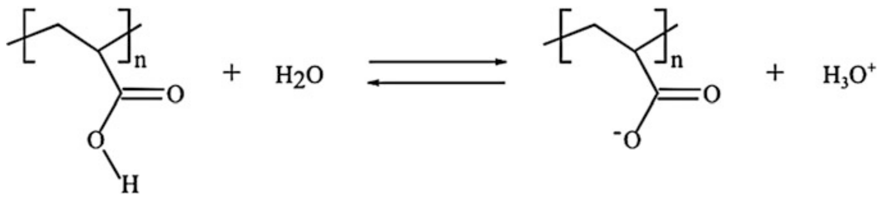

Fig. 2 Chemical equation describing equilibrium reaction between polymer of carboxylic acid and water

reaction is also oxonium ion, acid. If more acid is added, equilibrium turns to the left; if acid is removed, equilibrium turns to the right. The polymer on the left hand side in Fig. 2 is the collapsed form and the one on the right has a greater volume. Furthermore, there is a significant change in its properties, if pH changes (Advancing the chemical science 2015; Wong 2007).

3 Activities with Hydrogels

Since hydrogels are novel smart materials, they are also interesting from the educational point of view. There are several papers describing activities related to hydrogels. Wong (2007) in her paper describes hydrogels, their structure and bonding, use in diapers and plant water storage, as well as medical benefits when hydrogels are used in soft contact lenses and being biocompatible. Furthermore she briefly deals with the question why hydrogels are smart materials and discusses their use in growing new body parts. She suggests experiments with some of the domestic products that contain hydrogels, for example hair gel and plant water storage crystals.

Teaching material for students attending National youth science day (2008) deals with the question whether hydrogels can help the environment. The teaching material describes protection of groundwater as an important priority, because groundwater is a source for drinking and irrigation. Conservation of water means using water wisely and hydrogels can be useful in this regard. Teaching material suggest an experiment with hydrogels of a disposable diaper, trying to discover the amount of absorbed water in comparison with other materials (like cotton balls, paper towels, sponges) and the effect of other ingredients, as for example, salt.

Teaching material also includes concrete experimental tasks for students about hydrogels and how they work (Advancing the Chemical Sciences 2015). Teaching material contains tasks about the absorption of water in hydrogels and the effect of different environments (salty, acidic, sweet). Tasks also involve the use of hydrogels in diapers and in firefighting.

Drexel University (2008) presents the teaching material Bouncing Hydrogels! for students of 6th grade level. Material describes the procedure for synthesis of some hydrogels. Students mould them into shapes of their choice. Afterwards they compare the properties of two hydrogel "bouncy balls" that were exposed to different amount of freezing and thawing cycles to see how those affect the mechanical properties.

Student guide Hydrogels—Smart Materials (2015) presents 7 experimental investigations: (1) Making a hydrogel; (2) Which hydrogel is best at absorbing water? (3) Does the temperature of the water effect the volume of water absorbed by hydrogels? (4) Does the mass of hydrogel effect the volume of water absorbed? (5) The effect of salt concentration on the volume of water absorbed by hydrogels; (6) Which disposable nappy brand works best? and (7) Can hydrogels be used to fighting fires?

4 Experiments with Hydrogels Pearls

On the basis of literature review, we developed ideas for experiments showing interesting properties of hydrogels (Pavlin 2014). Hands-on experiments are suitable to enhance primary and secondary school students' interest and motivation in science learning. They can be carried out during chemistry and physics courses in the upper-secondary schools because several scientific concepts can be explained by a context of hydrogels. Experiments cover the following contents of the curricula: equilibrium reactions, polymerization, pressure, light (reflective and refractive law, lenses), physics and environment (issues related to modern discoveries), the structure and properties of polymers and chemical reactions (Syllabus Chemistry 2011; Syllabus Physics 2011). These present *content* on the three-dimensional competence model. Due to novelty of the subject and complexity of explanation for some experiments, the level of understanding of concepts that might be achieve after performing experiments is 1st and 2nd level. Simple hands-on experiments with hydrogels enable students to develop experimental competences as well: from measuring of diameter with Vernier callipers to planning and carrying scientific investigation (Example of the posed research questions: How does force influence deformation of hydrogel pearl?).

Hydrogel pearls have spherical shape and are therefore very useful for school experiments. Students can study the most important property of hydrogel—absorption of water (Fig. 3). Hydrogels can hold up to 500 times its own weight in water. If we are even more demanding students can study time dependence of the mass or volume of hydrogel pearls and observe the growth under the microscope. They can also calculate the swelling ratio. It is around 180 for the hydrogel pearls from Fig. 3.

Students might also play with hydrogel pearls of different sizes and discover their densities comparing it to densities of other known liquids. It is also evident that bigger hydrogel pearl has smaller density, very close to the density of water. Students can also learn that all transparent objects (like transparent hydrogel pearls) cannot be seen in the transparent liquids. While directing the laser pointer beam to

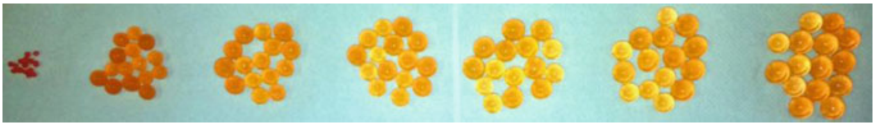

Fig. 3 Hydrogel pearls growth, dry pearls (on the *left*) were immersed to water, afterwards photos of pearls were taken every full hour

Fig. 4 Hydrogel pearls after 6 h in warm water (*left*) and cold water (*right*)

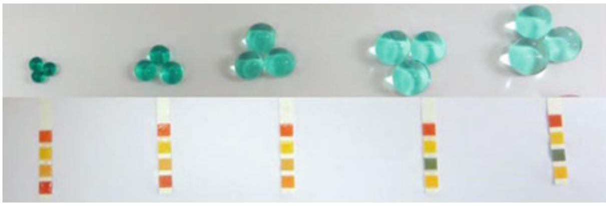

Fig. 5 Hydrogel pearls after 6 h in vinegar solutions, pH grows from the *left* to the *right* hand side

Fig. 6 Hydrogel pearls after 6 h in solution of salt, the concentration of salt decreases from the *left* to the *right* hand side

the hydrogel pearl, students experience that materials change the properties of light. Some of the hydrogel pearls also contain fluorescent dyes. Fluorescence is easily demonstrated by using a green or blue laser and the fluorescent hydrogel pearl. One can also use the hydrogel pearl as a magnifying glass. Furthermore, students can study the effects of the environment: temperature (Fig. 4), pH (Fig. 5), concentration of salt (Fig. 6) and pressure (Fig. 7), in order to show why hydrogels are smart materials.

Fig. 7 Pressing on the hydrogel pearl being put on the scale

5 Students' Conceptions About Hydrogels

Hydrogel pearls allow for interesting school experiments. Literature does not offer information about students' conception of hydrogels, which would help us to adapt the experiments and explanations. Because our aim is to introduce hydrogels into teaching of science subjects, we decided to evaluate students' conceptions about hydrogels. Even though hydrogels are not included as a subject in formal education, we expected that students gained some knowledge about them through non-formal learning. The following research questions were designed:

- Do pre-service primary school teachers on average achieve at least 25 % of points on the QH?
- Do students who self-assessed their knowledge as eligible achieve better results on the QH than students who self-assessed their knowledge as negligible?
- Do highly-motivated students achieve significantly better results on the QH?

6 Methods

6.1 Participants

104 pre-service primary school teachers attending first year university study programme (9 % male and 91 % female), participated in the study. On the average, pre-service teachers were 20.6 years old (*SD* = 3.4). Students did not attend science courses at the faculty until the beginning of the research. Students on average achieved 20.0 points out of 34 (on average 59 %, *SD* = 6.6 points) on the final exams at the end of the secondary school. The data proposes that pre-service primary school teachers included in the study show an average achievements at the final exams since average in school year 2013–14 was 19.7 points. The participants represented a predominantly rural population.

6.2 Instrument

A 26-item paper-pencil questionnaire about hydrogels was applied in February 2015 at the beginning of the spring semester, before attending science courses at the faculty. The QH was designed for this study. It had 3 parts: (1) general information (age, gender, finished secondary school, secondary school achievements in science subjects, score at the secondary school final exam, residence stratum); (2) motivation for learning science subjects and (3) questions about hydrogels (5 general questions, 10 items about hydrogels). Students had 20 min to fill in the QH.

6.3 Data Collection

The study was non-experimental and descriptive study. Hydrogels were not presented to them in advance. The QH was administered to the sample under normal examination conditions. Descriptive statistics were used for illustrating the QH characteristics. For clarifying the relation between the self-assessed knowledge and student achievements on the QH the independent-sample *t*-test was used. The one-way between-groups analysis of variance (ANOVA) was conducted to explore the differences in the QH scores regarding the motivation of students.

7 Results and Discussion

The analysis shows that 20 % of students already heard of hydrogels. 11 % of students self-assessed their knowledge about hydrogels as eligible. 16 % of students think that they use hydrogels in daily life, 15 % of them are sure that they have never used them, while 69 % do not know. Results of the QH are thus the following: students on average achieved 0.8 points out of 10 ($SD = 1.3$). We expected that students would remark that hydrogels are used in gardening and that they absorb large amount of water, but they did not. The most successful student achieved 6 points and the 2nd most successful one 5 points on the QH.

From the analysis of the students' answers the following can be concluded:

- 15 % of students knew that absorption of water is an important property of hydrogels.
- 11 % of students listed at least one known product containing hydrogels, the most common answer was decorative aqua pearls and disposable diapers.
- 11 % of students knew that hydrogels do not absorb all of the liquid.
- 9 % of students knew that hydrogels can be seen in oil.
- 6 % of students knew that hydrogels might contain water also at higher pressure.
- 6 % of students knew that hydrogel pearls can be used as a magnifying glass.

- Knowledge that some of the hydrogels fluorescence was demonstrated by 5 % of students.
- 5 % of students knew that hydrogels have smaller volume in acidic media.
- 1 % of students knew that hydrogels have the same refractive index as water.

11 % of students self-assessed their knowledge as eligible, 89 % of them as negligible. Students who self-assessed their knowledge as eligible on average achieved 2.3 points out of 10 ($SD = 1.6$), while others achieved 0.5 point ($SD = 1.2$). The *t*-test was used for testing a statistically significant difference in the QH scores between student who self-assessed their knowledge about hydrogels as eligible and those who self-assessed it as negligible. The result of the *t*-test shows that the assumption of homogeneity of variance was justified (Levene F-test: $F = 3.951$; $p = 0.05$), the difference between the mean values is statistically significant ($t = 4.467$; $p = 0.000$).

21 % of students wrote they are not motivated for science learning, 47 % of them self-assessed their interest in science as medium and 32 % as high. Students who have low motivation for science learning on average achieved 0.1 points out of 10 ($SD = 0.3$), middle motivated 0.8 ($SD = 1.4$) and highly motivated students achieved 1.0 ($SD = 1.5$). Analysis of variance was used to test if the difference in the average achievement is statistically significant. The Levene F-test shows that the assumption of homogeneity of variance is not justified ($F = 13.598$; $p = 0.000$), therefore Welch's approximation was used. Welch's approximation shows that the difference between the arithmetical means is statistically significant ($F = 11.654$; $p = 0.000$), thus there are statistically significant differences in knowledge about hydrogels between students who are highly motivated and those who have low motivation (the difference of arithmetic means is 0.9; $p = 0.027$). The statistically significant differences do not appear among students who are medium and highly motivated (the difference of arithmetic means is 0.2; $p = 0.825$) and among students who have a low and medium motivation (the difference of arithmetic means is 0.8; $p = 0.061$).

Answers to the research questions are:

- Students' conceptions about hydrogels after secondary school are weak. They achieved 8 % of points on the QH.
- Students who self-assessed their knowledge as eligible achieved statistically significant higher scores on the QH.
- Highly-motivated students achieved statistically significant higher scores than low-motivated students on the QH.

There exist similarities between this study and the study about conceptions of liquid crystals. Hydrogels and liquid crystals are both smart materials, topics of current scientific research and are applicatively dealt with daily. Since hydrogels and liquid crystals are not part of the curriculum, students are not aware of them and their knowledge about them after the secondary school is negligible. However, it might be concluded that the teaching modules about modern materials have to start with basics on qualitative level and carrying simple experiments, with which the students get concrete experiences (Pavlin et al. 2013).

8 Conclusions

The paper describes hydrogels, ideas for experiments with hydrogels, briefly indicates the development of competences while learning about hydrogels and describes pre-service primary school teachers' conceptions about hydrogels in details. The presented literature review shows a tendency to search for information about hydrogels and implement them into science courses because hydrogels are commonly and widely used as well as topic of current scientific research. Hydrogels are not taught in primary and secondary schools in Slovenia but our aim is to include them into teaching of science subjects on both levels, starting with secondary schools. Based on the literature the ideas for experiments taking into account competences development are presented. The possibility of the implementation is confirmed by review of the syllabuses for Chemistry and Physics for upper-secondary school in Slovenia because the contents of experiments cover the aims. Since we use hydrogels in everyday life, we were interested in just how much students already know about them and therefore gain necessary information for designing the teaching module about hydrogels. It is shown by study of the informally obtained knowledge about hydrogels prior to the university education that students' conceptions about them are negligible because only 15 % of students knew that absorption of water is an important property of hydrogels and 11 % of them listed at least one known product containing hydrogels. A statistically different average number of points is obtained in the QH between the students who self-assessed their knowledge as eligible and negligible, as well as between highly-motivated and low-motivated. Literature review and presented experiments show, however, that hydrogels are very interesting interdisciplinary and rich learning topic worth struggling to include into teaching of science subjects, starting primarily with basics, as seen from the results of the study.

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Teacher's Design of Practical Work

Wouter Spaan and Ed van den Berg

Abstract Much research has been done on the effectiveness of practical work in the classroom. Studies conclude that the way most teachers apply practical work is not the most effective approach. Some studies ascribe this at least in part to the very design of the practical work. This research project aims to answer the question 'What design principles do teachers use when designing practical work?' The research method comprised of structured interviews with 15 active teachers and teacher educators in the Netherlands about the design process of a particular piece of practical work. Interviews were guided by the Practical Activity Analysis Inventory (Millar 2009). Results show remarkable consistency amongst the ways in which teachers design practical work for students in some aspects and clear differences in others. Most teachers indicate that learning activities associated with the domain of ideas play a more significant role in their design than activities exclusively associated with the domain of observables (Abrahams and Millar 2008). Likewise most teachers take great care to provide an appropriate degree of scaffolding, but they differ considerably in their view how much and which scaffolding should be provided. Clear differences arise when considering learning objectives. Few teachers rigorously use learning objectives throughout the design of the activity. In most design processes they only play a marginal role. This holds even more for inquiry objectives. Sometimes these are not even recognized by the designer, even though inquiry activities were—unconsciously—included in the activity created. The results of this study can be useful to identify why so much practical work is ineffective. It seems that the problem does not lie in the primary design-objectives of the practical work, at least when considering experienced teachers. They take great care to enable

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the student to get to the domain of ideas, although they may lack a solid understanding of what is necessary to get their students there in terms of scaffolding. This study did not look at classroom-implementation, so it may be that the teacher puts less emphasis on the scientific ideas when doing the activity in class. Further research will look into this and identify reasons for possible discrepancies between design-principles and execution in class.

1 Introduction

Both recent (Abrahams and Millar 2008; Abrahams and Reiss 2012) and old (Germann et al. 1996; Tamir and Lunetta 1981) research has shown that there are serious problems with the effectiveness of laboratory activities for learning concepts and inquiry practices (Next Generation Science Standards, NGSS, 2012). One of the reasons appears to be inconsistencies between teacher intended learning objectives, the operationalization in laboratory instructions or worksheets, and actual implementation. For example, Tamir and Lunetta (1981) using their Laboratory Activity Inventory (LAI) found that even professional curriculum developers of curricula supported by the National Science Foundation in the USA such as The Harvard Project Physics and the Physical Science Study Committee (PSSC) and well known Biology and Chemistry textbooks for high school produced laboratory activities which were much less inquiry oriented than intended. In fact they concluded (p. 482) that:

Seldom, *if ever*, *are students asked to*:

a. *formulate a question to be investigated*;
b. *formulate an hypothesis to be tested*;
c. *predict experimental results*;
d. *work according to their own design*;
e. *formulate new questions based on the investigation; and*
f. *apply an experimental technique based on the investigation just performed*.

Many years later (Germann et al. 1996) used a similar analysis scheme to analyse activities in Biology textbooks and came to the same conclusions. In the UK Millar (2009) developed the Practical Activities Analysis Inventory (PAAI). Whereas the LAI of Tamir and Lunetta focused on analysis of inquiry practices in written instructions for laboratory activities, Millar's PAAI could be used to analyse both conceptual and inquiry aspects and focused on classroom implementation as well. Studies of Abrahams and Millar (2008) and Abrahams and Reiss (2012) again pointed at major inconsistencies between curriculum goals, design, and implementation of laboratory activities. Therefore this study takes a more in-depth look at how teachers design or select laboratory activities.

This study is based on the theoretical framework presented by Abrahams and Millar (2008), in which they develop two dimensions for evaluating practical work.

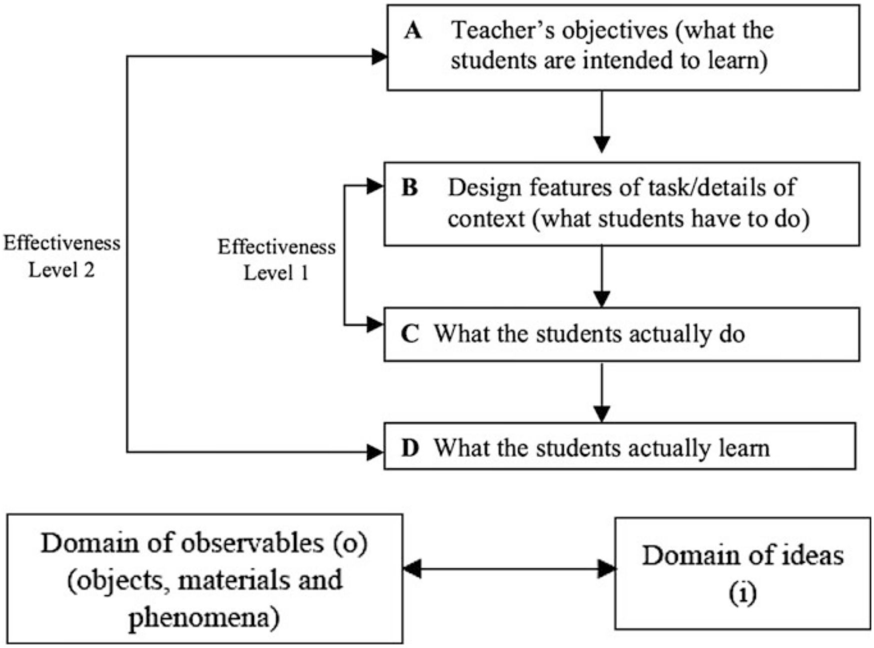

Fig. 1 Two dimensions to evaluate practical work: effectiveness on two levels and activities in two domains [figures taken from Abrahams and Millar (2008)]

The first is about the level of effectiveness, the second about the aim of the activities undertaken by the students. Figure 1 summarizes these two dimensions.

Effectiveness can be defined on two levels. Level 1 is about the actual activities students perform in the classroom. If these activities are as the teacher had intended, the task is effective on level 1. Level 2 is about the actual learning objectives the teacher had in mind. A task is only effective at level 2 if the students master these learning objectives.

The other dimension is about the type of activities undertaken by the students. These can be about the real physical work (like measuring some quantity) or about more abstract ideas, which use observations from the real world (like evaluating evidence gathered).

Millar (2009) used this framework to develop his Practical Activities Analysis Inventory (PAAI), which we used in our study. The inventory has been developed as an observational instrument to assess different aspects of a practical activity. In this study the following categories from the inventory were used:

- Learning objectives divided into three broad categories (develop knowledge and understanding of the natural world, learn to use laboratory equipment or a standard procedure, develop understanding of scientific approach);
- Openness (focussing on which part(s) of the inquiry are left to the students as choices);

- Structure of the activity (collect and explain versus research question and hypothesis and then collect data and compare);
- What students have to do with objects and materials (list of activities e.g. make an object or measure a quantity);
- What students have to do with ideas (list of activities e.g. design a measurement or observation procedure, explore how an outcome variable changes with time or decide if a given explanation applies to the particular situation observed);
- Learning demand (scale of 1–5).

2 Method

We conducted guided interviews with 15 participants: 6 teacher educators, 5 experienced teachers (each more than 8 years teaching experience) and 4 novice teacher (in their first or second year of teaching). All participants teach physics or chemistry.

All interviews followed the same procedure. Firstly participants were asked about their views of practical work in general in terms of goals, experience, kinds of practical work and received training. Secondly we focussed on the design process of a particular piece of practical work chosen by the participant. The first questions in this part of the interview were about the motivation for doing this piece of practical work, the source of the idea, the design process of the lesson and the choices made during this process. After that we used a slightly modified version of the Practical Activities Analysis Inventory to centre on these choices and investigate what student activities the teacher had in mind when developing this practical work. In this part the participant could choose amongst small cards with statements from the PAAI. He was asked to chose the item most applicable during the design process, explain his choice and emphasize how this choice influenced the design of the practical work. In some cases the participant was asked to choose all applicable statements. After filling in the PAAI in this way the participants were asked to order all the applicable items on significance during the design process. The third and final part of the interview consisted of questions about the learning demand of the work, both for the entire practical task and for its parts.

The minor modifications made to the PAAI were done to obtain an instrument more in accord with the Dutch curriculum, especially when considering the learning objectives. The main division of objectives was not changed.

The interviews were audio-recorded and summarized from the recordings. The statements about practical work in general were transcribed. The second part of the interviews about the particular piece of practical work was scored in the categories shown in Table 1. The possible scores are based on the answers given. We used an iterative process in which the definitions of the classifications were refined along the way.

Table 2 Categories used for scoring the design process of the practical work

Category	Possible classifications
Learning objectives	As in PAAI (main division: understanding of natural world, applying laboratory procedures, inquiry goals)
Point in time at which objectives are established	At the start, during the design process, after the design process or unclear
Reason(s)	Existing practical work, agreement in team, newly found practical, to solve a conceptual problem found earlier, fitting for the learning goals, grading, need for some practical work in this subject (more than one possible classification)
Changes made (if applicable)	Added activities or instructions, removed activities or instructions, changed activities or instructions, more student input
Cooperation	Yes with other teacher(s), yes with lab instructor, no
Learning trajectory	Yes with clear trajectory, yes but only conscious choice of skills without clear trajectory, no but awareness about earlier learned skills, no
Concerns	Various
Opennes/closure	According to PAAI (question given yes or no and amount of instructions about procedure given)
Domain of observables	According to PAAI
Domain of ideas	According to PAAI
Learning demand	Scale 1–5

3 Results

In this section we will present the general statements about practical work. After that we will discuss the design process of the practical work, along the categories mentioned in Table 1.

3.1 *General Objectives*

Teachers mention a wide range of objectives for performing practical work, including but not limited to:

- Learning laboratory skills;
- Learning inquiry skills;
- Developing an inquiry based attitude (e.g. curiosity);
- Strengthening and deepening conceptual understanding;
- Getting familiar with a (new) concept;
- Motivating students (explicitly mentioned only by experienced teachers and teacher educators);
- Introducing a new topic or theme;

- Verification of learned relationships or laws (explicitly mentioned only by novice teachers);
- Grading;
- For its own sake, it is part of science.

Other than the two cases mentioned above, there appears to be no correlation between the level of experience of the teacher and the general objectives of practical work. Only in a few cases the interviewees refer to these general objectives when discussing the design of the practical work.

3.2 Learning Objectives

The majority of the practical work we analysed has learning objectives about developing knowledge or understanding of the natural world. A minority also offers inquiry objectives, mostly limited to a few specific inquiry skills. A few teachers mentioned that their practical work always has some kind of inquiry goal associated with it. These teachers mostly do not explicitly emphasize these inquiry tasks when designing practical work. In one case the (novice) teacher did not intend to include any inquiry skills, but he presented the work to the students in such a way that they were required to design a large part of the experiment. Furthermore his students were required to get his approval on their design before proceeding. Only after the interview, when mentioned by the researcher, did this teacher recognize that he had presented a task with important inquiry skills.

Only one activity intended the students to learn how to use a piece of laboratory equipment. In this case a teacher educator was looking for an attitude change towards practical work in electronics. In order for that to happen he had his students gain a lot of experience with building electrical circuits and using the associated equipment including real circuits and computer simulations.

Approximately two-thirds of the teachers had a more or less clear learning objective in mind at the beginning of the design process. In the other cases the learning objectives formed on the way during the design of the practical work. In two cases the teacher could not remember the role of the desired learning objective in the design process.

3.3 Reasons for Practical Work

The reasons for doing and designing a particular piece of practical work vary greatly and there is a considerable amount of overlap. Usually there is more than one clear reason. The reason most mentioned is related to an existing piece of practical work; both the equipment and instructions/worksheets were easily available. Sometimes this is related to another reason: an agreement between the subject-teachers to perform a particular piece of practical work. In approximately one third of the cases the teacher has identified some problem (often conceptual) for which he seeks a solution in the practical work. Also about one third has the desired learning objective as a starting point and some do not have any clear motivation except that ‘we needed practical work within this subject area’.

3.4 Changes Made

None of the participants used the practical work unmodified, although this is biased as the teachers were asked to provide practical work they developed or altered. One third created the practical work from scratch without example. As far as they are concerned it is original work. All of the others changed something in an existing activity. The reasons they give for the changes vary greatly (see below under the heading concerns).

As an example let’s look at one particular activity aimed at familiarizing the students with the concept of density. The original practical work consisted of recipe-like instructions with which the students should eventually determine the density of four different materials, all cuboids. The novice teacher at hand changed this activity into one around the question ‘Which material is this?’ The new activity required the students to find the density of one material and had the students device their own method. As a reason for the change he mentioned his belief that both the context and the choices provided would enhance his students’ motivation. Besides this he consciously chose to include inquiry skills in his practical work, a few per activity. So, at the end of the activity, somewhat depending on the level of his students, he asked them how certain they could be about their answer considering their experimental design and the results they got. This illustrates the way in which some teachers consciously alter an existing experiment.

3.5 Cooperation

Out of the fifteen participants, nine cooperated with at least one colleague during the design of the practical work. Amongst these nine are all teacher students. The cooperation varied in extent: in two cases one could call this a joint design of the activity, in three cases a colleague only commented on the draft-version of the manual. The other cases are between these two extremes.

3.6 Learning Trajectory

We differentiate between learning trajectories aimed at laboratory skills (e.g. using a multimeter) and those aimed at inquiry skills (e.g. formulating a research question, interpreting results). Two practical activities are clearly part of a learning trajectory (a sequence of activities/lessons with closely related objectives), one of which as a final test. Both lab skills and inquiry skills are part of these trajectories. Seven activities were designed without any trace of a learning trajectory or conscious use of skills (lab nor inquiry) which students had learned before. Three other interviewees had chosen the new inquiry skills the students had to learn or practise in this practical work bearing in mind the skills (inquiry and lab) the students had already learned. These new skills were chosen more or less at random. They made no prior arrangement or sequence of all the skills the students eventually have to master. The remaining three activities did not address any new skills, but during the design process the teacher did take into account which skills (both lab and inquiry) the students had already learned.

3.7 Concerns

Teachers demonstrated a great variety of conscious concerns when designing practical activities. There is no clear categorization, although a few themes were mentioned more than once:

- Motivating the students through a proper design of the activity and the manual. The way teachers actually implement this concern varies: some write clear recipe-like instructions without choices, some offer choices deliberately, one teacher uses the design of something (a simple 'robot') as backbone for his activity, one teacher implements the activity as part of a didactic game, one teacher builds a series of activities that are challenging but not too challenging.
- The amount and degree of scaffolding. See below under 'Openness'.
- Some teachers used the activity explicitly as preparation for a test, which can be a practical or theoretical exam. In this case they used the test criteria as guidelines during the design of the activity.
- The use of simple materials, like cardboard or soft drinks.
- Time available. Mostly this leads to part of the activity being designed less open than the teacher had intended if time was of no concern.

Various other concerns were mentioned only once. The following list gives examples and is not exhaustive:

- A practical activity should last one period, not more, not less. For this particular teacher the adequate use of the materials and lab technician is best achieved this way.
- The students should get acquainted with a practical activity because of its significance in the development of physics.
- A lab activity should use cheap and environmentally friendly materials.
- A lab activity should concern everyday experiences, for example when designing an activity about density, the teacher refers to everyday objects that float or sink in water.

3.8 Openness

All teachers, except one, are concerned with the openness of the practical activity they design. In five cases the leading concern is the chosen learning objective(s). For these teachers this almost exclusively determines the degree of openness they opt for. Two teachers explicitly mention classroom management as a reason for giving the students few or no choices. Two teachers give their students choices in order to motivate them. They reason that giving choices in itself is motivating. On the other hand two teachers use the opposite reasoning: if students know exactly what to do, they will get motivated and hence they design activities with very few choices. Two other teachers create activities that are as open as possible. The constraints can be given by time, safety, learning objectives and challenges posed by the apparatus. The one exception simply did not consider the openness of his activity as he always uses the same structure, which in essence is a mixture of recipe-like guidelines and questions intended to engage the students in active thinking.

For most interviewees, the openness of the activity is the most important issue when designing a practical activity. This also follows from the fact that most changes made to existing practical work have to do with the amount and degree of scaffolding. Most participants clearly indicate that they struggle with this part of the design, which is also evident from the different choices they make, although they sometimes try to achieve the same goal (e.g. the mentioned openness-motivation relationship). This point is also stressed because four teachers realized during the interview that they had not succeeded in obtaining the desired openness.

3.9 Domain of Observables and Domain of Ideas

When asked which activities played an active role in the design process, all participants chose activities from both domains. Approximately two-thirds regard the activities in the domain of observables as a necessary activity in order to get the students involved with the domain of ideas. When asked to order the chosen activities and chosen concerns on the basis of their importance during the design process, all teachers except one, rated at least one activity from the domain of ideas higher than all activities from the domain of observables. The one exception is the teacher whose main objective was to get his students acquainted with an historical experiment (determination of the specific charge of the electron).

3.10 Learning Demand

Slightly less than half of the participants had a clear learning demand in mind at the start of the design process or developed a solid idea about the desired learning demand before the end of this process. For the other half the learning demand is of no conscious concern. They answered the question about the role of the learning demand during the design process with something like: 'if I take a look at the finished practical work, I think it is not too hard.' Three participants mentioned the desired learning demand in conjunction with the openness of the activity, indicating that a more open activity creates a larger learning demand.

4 Conclusion and Discussion

From the results a few interesting conclusions can be drawn. First the role of the learning objectives is somewhat limited. One third of the teacher does not even start from clear learning objectives. Approximately half of those who do start with clear objectives in mind, do not refer to them when making important choices, like the openness of the activity. It seems that teachers know they have to work from learning objectives, but they forget to implement them rigorously.

If we limit ourselves to inquiry objectives we note that only very few participants create activities that address them explicitly. Sometimes clear opportunities to give attention to them in a developed activity are not even recognized, therefore we conclude there is insufficient specification and prioritizing of inquiry skills. If these skills are to be addressed properly, teacher education should put more emphasis on the pedagogy of teaching inquiry skills and raise awareness amongst (student) teachers to grab opportunities that allow a teacher to give attention to these skills. Current curricula developments, with more and more emphasis on scientific abilities only make this issue more urgent.

Looking at the broader picture of aims and goals for doing practical activities, conclusions from previous work done by Kerr [as cited in Millar (2010)] is confirmed: teachers have a wide variety of goals, aims and reasons for doing practical work. In most cases these general objectives do not play a significant role when designing a particular piece of practical work. It seems that personal beliefs are important. There is almost no reference to literature.

Third, the amount of scaffolding is an important concern and most teachers lack knowledge and skills how to perform adequate scaffolding. They simply use their personal beliefs and (valuable) experiences when determining the openness of their activity. This study has only looked at the scaffolding intended during the design process. It is unknown how the teachers actually performed the activity or how they guided and helped their students during the activity itself. This can have a large influence on the amount of scaffolding eventually provided. For now we can conclude that teachers need more rigorous guidelines on how to scaffold more consciously and effectively. Etkina et al. (2009) can give valuable insights in this respect.

Lastly teachers are very concerned with the effectiveness of their activity. They try to get their students to think about the phenomenon at hand through activities in the domain of ideas, which in itself is a valid strategy. This gives an interesting insight to the findings of Abrahams and Millar (2008), where they conclude most teachers do not or barely address the domain of ideas. At least for the teachers in this study, the intention to do so is quite clear.

One of the differences between this study and the study of Abrahams and Millar (2008) is that the latter researched the actual classroom performance. In this concluding section it has become clear that the actual execution of the activity in the classroom is important in order to draw more definite conclusions about the effectiveness of any design process. As a follow-up study we will incorporate the classroom performance alongside the interviews about the design of the activity. This also provides a way of increasing the number of participants, as the sample was rather small in this study.

The study at hand does provide valuable insights about the focus-points of future studies into the way teachers design practical activities. The main focus in this type of studies and in our own follow-up should be: role of learning objectives, scaffolding, and effectiveness in terms of domain of observables versus domain of ideas. The framework provided by Abrahams and Millar (2008) and Millar (2009) has proven to be valuable when researching into the design of practical work.

In short the ineffectiveness of practical work identified by other researchers may in part be attributable to inadequate use of clear learning objectives during the design process. Besides this scaffolding is an important concern. The design process is adequate in the sense that teachers try to plan and emphasize activities from the domain of ideas in favour of activities from the domain of observables. Discrepancies between the activities planned during the design and the actual classroom performance may be more of an issue. Ongoing research will look into this aspect, the comparison between the design process and the classroom execution. This will lead to implications for teacher education.

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Electronic Properties of Graphene: A Learning Path for Undergraduate Students

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Abstract The purpose of this work is to present a learning path aimed at deepening student understanding of the fundamental concepts underlying the electronic properties of new materials, graphene in particular. To achieve this task, we propose a five-week long workshop where students may be introduced to fundamental concepts of advanced physics, rarely used in learning paths, such as the symmetry properties of the crystal lattice, the group theory, the features of the free electron wave functions and energy levels, the relativistic Dirac equation. Particular emphasis is given to the manner of introducing these concepts, since an essential knowledge of solid state physics, quantum physics and relativity is first necessary. We here present and discuss these concepts as preliminary steps towards a learning sequence that may guide physics/engineering undergraduates to reach a deeper understanding of the physics underlying the complex world of graphene and its properties. The conceptual framework might support both instructors and students toward further scientific investigations.

1 Introduction

The graphene is a single layer (2D) of graphite. It has been synthesized by Geim and Novoselov in 2004 (Novoselov et al. 2004). Since then, there has been a massive explosion of interest in the study of its properties (Geim and Novoselov 2007; Neto et al. 2009; Malard et al. 2009; Kogan and Nazarov 2012). The achievements can open doors towards new frontiers in electronics, as well as in manufacturing applications.

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Indeed, thanks to its remarkable unusual electrical and optical properties, the scientific and technological applications of this material seem to be unlimited (Wilson 2006). The circumstance that the electron mobility is much greater than in semiconductors promotes its use in bipolar transistors and integrated circuits. Moreover, graphene exhibits some exceptional characteristics that allow us to verify various exotic processes, which, although known theoretically, have not been observed previously, such as the Klein paradox (Katsnelson et al. 2006; Robinson 2012).

A deeper understanding of the peculiarities characterizing the electron behavior in graphene is essential in undergraduate education of electronic engineering and physics students, as well as in semiconductor science. Since the current scientific literature on the quantum peculiarities of graphene is beyond the scope of usual undergraduate courses and outside the experience of most non-specialist physicists, an effort is here devoted to fill up this shortcoming.

Traditional courses introducing quantum mechanics in solid state physics and materials science provide the students with a theoretical background on the band structure, which gives origin to the energy gaps, to the concept of effective mass and to the conductivity peculiarities of semiconductors (Dalven 1976; Persano Adorno et al. 2015). However, these courses do not furnish to the students a sufficient mastery, since the concepts are presented as separate pieces of knowledge or a fruitless mathematical formalism is adopted. The students, consequently, have difficulties to visualize the physics beyond equations. Most undergraduate courses still focus on an axiomatic approach whose relevance to the real world is obscure and where little attention is paid to what or how students actually learn (Persano Adorno and Pizzolato 2015). Finally, students difficulties may also arise from epistemological stances that limit an effective understanding of the concepts being presented to them.

Students achieve an effective instruction and hold a stable theoretical knowledge when they become able to view it as an instrument for further discoveries. An effective and efficient science instruction, should have a general character engaging the students toward a full comprehension of the fundamental concepts and training them to connect transversal facts that at a first look may appear to be not related (Pizzolato et al. 2014). Graphene is suitable to achieve this task.

The present work suggests a learning path intended for Physics/Engineering senior level Quantum Physics Course or for Ph.D. students; a basic knowledge of classical physics, quantum physics and relativistic behavior is required. The learning environment is based on the comprehension and utilization of important concepts of Solid State Physics, as symmetry properties of the crystal lattice (Bouckaert et al. 1936) and group theory for the calculation of the degenerate energy states (Slater 1963; Nussbaum 1966). In fact crystal structures are periodic and operators such as rotations and reflections, transport crystal sites into equivalent sites. In the presence of such operators, the allowable wave functions acquire symmetry properties that greatly help in calculating the energy eigenvalues (Huang et al. 2014). This learning path may be twofold useful for physics/engineering students: first, because they may develop a solid theoretical awareness by becoming able to view this knowledge as an instrument for further inquiries on the structure of new materials and, second, by understanding the reasoning sequence beneath this investigation, they may surmount eventual epistemological problems and achieve a mastery to treat the fundamental physics concepts introduced in this study.

2 The Learning Path Schedule

The learning path is structured into a five-week integrative workshop for a maximum of about 20 students having already attended regular lectures of Solid State Physics or Semiconductor Physics (before the beginning of the examination sessions). We estimate three hours of lectures per week plus two hours of tutorials (for a total amount of 25 h). Furthermore, each week we assign to the class an essay to be due before the next lecture.

For sake of space, we summarize below the arguments to be treated in the lectures and in the tutorials. In particular, in the first week we recall the notions of crystal structure, focusing on the symmetry properties of graphene; in the second week we introduce notions of group theory, a powerful theoretical tool to determine eigenfunctions, energy levels and degeneracies for electrons with particular emphasis to graphene. The third week is dedicated to the calculation of the energy levels in the context of the free electron model with especial attention to the K-point in the Brillouin zone. The effects of the crystal potential are, then, qualitatively taken into account and the actual electron distribution is illustrated in the fourth week. In this context, one of the unusual phenomena exhibited by graphene is the relativistic behaviour of the electrons as Dirac fermions with effective massless properties as a consequence of the linear dispersion in a limited region of the Brillouin zone close to the K point. In the fifth week, basic concepts leading to the relativistic Dirac equation are introduced in order to understand this behaviour and to explain consequential properties as the Klein paradox and chirality.

3 First Week: Crystal Structure and Electronic Configuration of Graphene

A pioneering work about the electronic structure of graphene was carried out by Wallace (1947). The crystal structure of graphene consists of a xy planar honeycomb lattice of carbon atoms.

It consists of two equivalent carbon sub-lattices A and B (red and blue colours, respectively) (Fig. 1a), the primitive cell, contains two nonequivalent atoms. Both the real lattice and the reciprocal lattice are hexagonal, as shown in panels (a) and (b) of Fig. 2. In graphene monolayer, the real lattice is two-dimensional. The primitive vectors in the real and in the reciprocal space are, respectively (Slonczewski and Weiss 1958; Slater 1963; Nussbaum 1966):

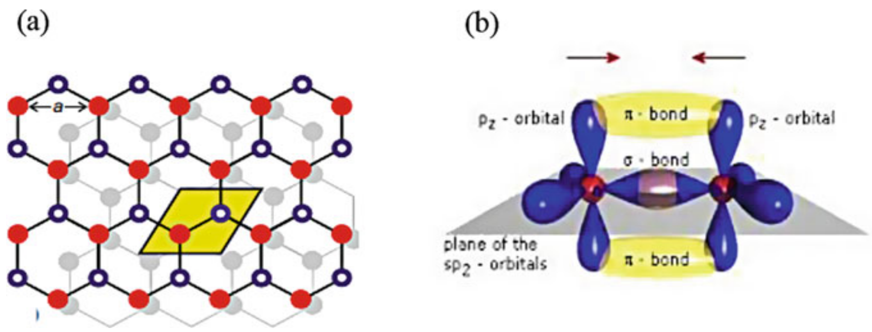

Fig. 1 **a** Graphene's stucture; the shaded parallelogram is a primitive cell (Matulis and Peeters 2009). **b** Graphene crystal bonds

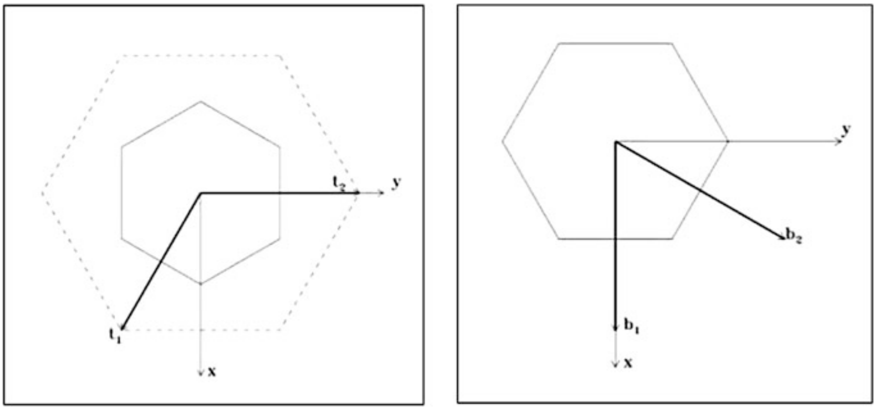

Fig. 2 **a** Graphene's real lattice. **b** graphene's reciprocal lattice (courtesy of Prof. K. Leo, www.orgword.de)

$$\mathbf{t}_1 = (a/2)(3^{1/2}\mathbf{i} - \mathbf{j}) \qquad \mathbf{t}_2 = a\,\mathbf{j},$$
$$\mathbf{b}_1 = 2/(3^{1/2}a)\mathbf{i} \qquad \mathbf{b}_2 = 1/(3^{1/2}a)(\mathbf{i} + 3^{1/2}\mathbf{j})$$

where a is the carbon-carbon distance.

It turns out that the sides of the real lattice are distant $1/3^{1/2}a$ from its center (Wallace 1947). Consequently the magnitude of a reciprocal lattice vector is (2π) $2/3^{1/2}a$.

It must be taken into account that the reciprocal lattice primitive vectors $\mathbf{b}_1$ and $\mathbf{b}_2$ are not orthogonal. The components of a generic vector $\mathbf{K}$, denoted K_1 and K_2 are defined along to these directions. It is possible to carry out the computation using this notation (Slater 1963), but it could be unfamiliar to the reader, consequently, we prefer to use orthogonal Cartesian components. The relationships between the components mentioned above and the Cartesian components, identified by the subscripts x and y are:

$$K_x = (2K_1 + K_2)/3^{1/2}a \quad K_y = K_2$$

In graphene, a carbon atom is bounded to other three atoms, although it has the capability to bond to a fourth atom. In follows that the electronic configuration consists of in-plane σ bonds formed by the 2s, $2p_x$ and $2p_y$ orbitals hybridized in sp_2 bonds that give rigidity to the structure, but do not contribute to the conductivity. The $2p_z$ orbitals bind covalently (π-bond) with neighboring atoms leading to the formation of the half-filled p band that contributes to the conductivity (Fig. 1b).

The consequence of this electronic configuration are various. We here recall the most important and give below a brief account of some of them: (i) the electron mobility is higher than any known material, this can be exploited in the realization of high-frequency electronic devices faster than those currently used; (ii) the absence of band-gap gives to graphene electron transport properties which conventional materials do not possess; (iii) the Dirac fermion behavior; as a consequence, the electrons that act as if they have no mass, much like photons, can travel relatively long distances without scatterings; (iv) high mechanical strength and excellent thermal conductivity, which make graphene suitable for the building of nanoelectromechanical devices; (v) since graphene is composed of carbon, it is intrinsically biocompatible and is suitable for biological applications.

4 Second Week: Basic Concepts of Group Theory

The symmetry of a body determines the ensemble of the transformations that leave it unaltered. Any possible symmetry transformation can be represented as a combination of one or more of the three fundamental types of transformations: translation, rotation through a definite angle about some axis and reflection with respect to some plane. A rotation through an angle 2π/n about an axis of symmetry is denoted by C_n. A reflection plane is denoted by σ. Translations are not of interest here.

The set of all symmetry transformations constitutes the symmetry group. In the calculation of the energies and degenerations, the symmetry operations that leave at least one point unchanged constitute the point group. In quantum-mechanical applications the symmetry operations can be viewed as coordinate transformations that leave the Hamiltonian invariant. The group theory is a powerful theoretical tool to determine the features of the wave function and to evaluate eventual degeneracies of eigenvalues.

From a formal point of view, we define representation of a group a set of mathematical operators, matrices for example, each corresponding to single operation that combine among themselves according to the rules valid for the operations of the group. It is customary to choose square matrices of the lowest order. These correspond to the simplest representations that are denoted irreducible representations and indicated by the symbol Γ. We shall refer to them in this work. The character (χ) of a matrix, is the sum of its diagonal elements. It is possible to choose a set of functions (ψ_Γ), denoted bases, for the various irreducible representations.

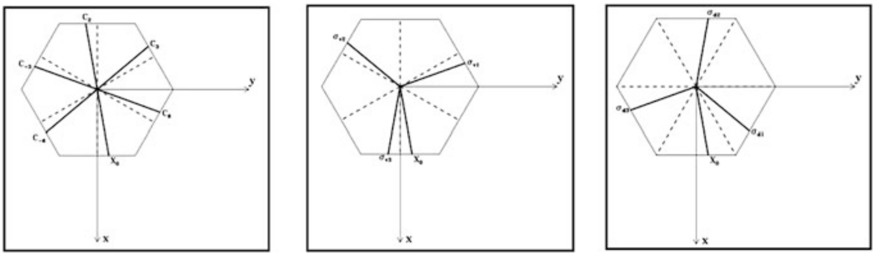

Fig. 3 Diagrams illustrating points to which the point marked X_0 is transformed by the rotation and reflection operations of the group

A basis for a certain representation remains unchanged or is multiplied by a constant when the projection operator,[1] corresponding to that representation is applied to it. If the function is not a basis for that representation, the result will be zero. To simplify the calculations and the reading of the expressions and results, bases of the lowest order are usually chosen.

The symmetry operations proper of the structure of graphene are 12: the identity E, five rotations about the z-axis, $C_{\pm 6}$, $C_{\pm 3}$, and C_2 and six vertical reflection planes; three of them (σ_v) bisect two opposite faces, the others (σ_d) connect two opposite vertices. Figure 3 shows how a generic point X_0 is moved into another position by the symmetry operations.

5 Third Week: Calculation of the Lower Electron Energy States According to Free Electron Model

We first show how to calculate the lower electron energy states in the context of the free electron model. According to this model, the effects of the crystal potential are ignored and the electrons possess only kinetic energy; successively we treat the same argument in the framework of band theory, that takes into account the potential energy of the electrons, consequence of their interaction with the lattice.

Before discussing the effects of the symmetry properties of the lattice on a function of the coordinates, the wave function ψ in the present case, we recall some basic formulae about rotations and reflections in a Cartesian plane xy (Nussbaum 1966). They allow us to write down the effects of the 12 symmetry operations characteristic of the hexagonal lattice or those of a subgroup on a wave function $\psi_{\mathbf{K}}[r]$ representing a plane wave (a free electron) propagating in a two-dimensional lattice. The range of variability of the wave vector **K** is very large. It is customary to consider the range inside the first Brillouin zone characterized by the vector **k** and add to it a vector **h** when **K** is outside the first zone.

[1]A definition of the projection operator belonging to the one-dimensional representation Γ_j is $P_{\Gamma j} = \Sigma_{Ri} \chi_{\Gamma j,Ri} R_i \psi_{\Gamma j}$, where R_i is an operation of the group.

The Schrodinger equation for a free electron is

$$-(\hbar^2/2m)\nabla^2\psi_K[r] = \varepsilon_K\psi_K[r]$$

and the energy eigenvalues are given by

$$\varepsilon_K = (\hbar^2/2ma^2)K^2 = (\hbar^2/2ma^2)[(h_x + k_x)^2 + (h_y + k_y)^2]$$

To be able to carry out the computation, we need to introduce some notation about the range of variability of the various quantities being considered. This is a consequence of the features of the vectors $\mathbf{t}_1$ and $\mathbf{t}_2$ in the real lattice, $\mathbf{b}_1$ and $\mathbf{b}_2$ in the reciprocal lattice.

In the calculation of the energy levels and degenerations, we pay most attention to some points and lines (high symmetry points/lines) of relevant importance. They are:

(1) The center of the Brillouin zone, denoted Γ-point.
(2) The centers of face of the hexagon (M_j-points). The magnitude of a vector connecting one of them to the Γ-point is $1/3^{1/2}a$.
(3) The line Γ–M_j known as line Σ. The k_1-component of the line Σ_1 varies in the range $0 \leq k_1 \leq 1/2$, whereas k_2 is zero.
(4) The vertexes of face (K_j points). The magnitude of a vector connecting K_1 to Γ is 2/3a, since the values of k_1 and k_2 are −1/3 and 2/3, respectively. It follows: $k_x = 0$, $k_y = 2/3$.
(5) The line Γ–K_j known as line T. Concerning the line Γ–K_1, k_1 and k_2 are related by the relationships $k_1 = -k_2/2$ with $0 \leq k_2 \leq 2/3$, consequently $k_x = 0$, $0 \leq k_y \leq 2/3$.

Figure 4 shows the high-symmetry points and lines of graphene reciprocal lattice.

The tutorial will be dedicated to the calculation of the degeneracies along the lines of symmetry Γ–M, Γ–K and at the points Γ, M and K using the group theory. In the study of the electronic properties of crystals, it is of fundamental importance to locate the degenerations in the k-space since in the proximity of them there is an accumulation of energy states available to the charge carrier.

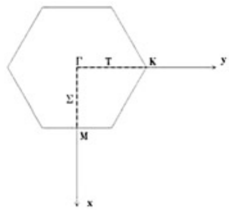

Fig. 4 High-symmetry points and lines in graphene

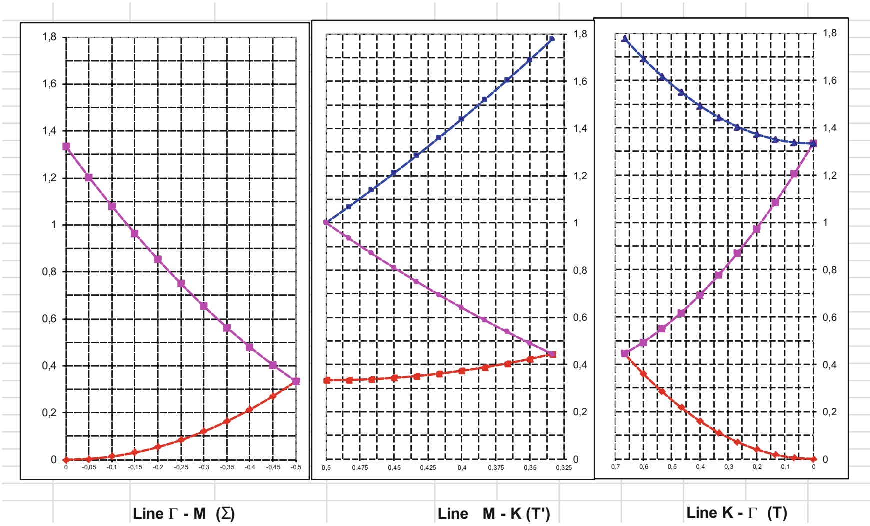

Fig. 5 Lowest energy values along the symmetry lines: Σ, T and M–K (line T′) and at their edge points, calculated by only taking into account the electron kinetic energy

In order to calculate the degenerations, the steps are: (1) Determine the symmetry group of the line or point taken into account. It is a sub-group of the crystal full point group; (2) determine the range of variability of k if a line is considered or its values if a point is considered; (3) write the explicit wave function $\psi_{kh}[r]$; (4) apply to $\psi_{kh}[r]$ the projection operator (Slater 1963).

The results regarding the lowest energy values along the symmetry lines: Σ, T and M–K (line T′) are shown in Fig. 5.

6 Fourth Week: Energy Bands and Anomalies Near the K-Points

The comprehensive calculation of the electron energy states and degenerations must take into account that the electron motion is affected by the crystal potential, that has the same symmetry properties of the lattice. The presence of the potential determines a rearrangements of the E-k curves both in value and shape. In particular, in the proximity of the K point of the Brillouin zone, as a consequence of the primitive cell, the dispersion curve E-k has an approximately linear shape that yields in the two dimensional k-space an energy spectrum represented by a set of modes constituting a pair of cones (see Fig. 6). The upper cone represents modes with positive energy with respect to the k-point energy, the lower cone represents negative energy modes. The cones in the limit $m \to 0$, touch, consequently, there is

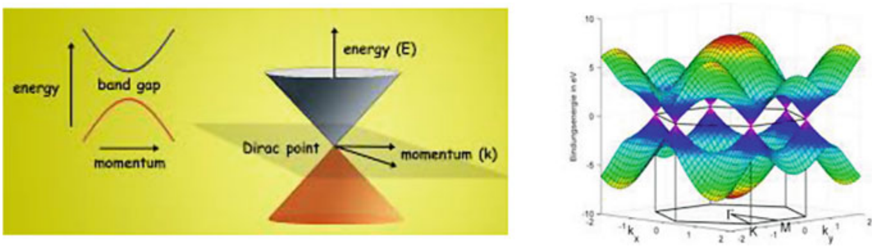

Fig. 6 Left: Dispersion curve E–k in graphene. In the 2-dimensional k-space the energy spectrum is represented by a set of modes constituting a pair of cones; Right: Graphene band structure over the complete Brillouin zone (in Dr. T. Haarlammert's Thesis, University of Münster, 2011; http://www.unimuenster.de/Physik.P1/Zacharias/en/research/graphene/graphene.html)

no gap. It follows that these quasiparticles (Dirac fermions) are characterized by a dispersion relation that depends on the magnitude of the wave vector; they behave differently from charge carriers in metals or semiconductors, where the energy spectrum has an approximate parabolic dispersion relation.

To deepen this aspect it is worth to recall and compare the equations governing a quantum free particle with those to be used for a relativistic one.

The wave equation governing a free particle in the former case, is the well-known Schrodinger equation. It has two main properties: (i) it is homogenous and linear in order to respect the property of superposition, (ii) it is a differential equation of the first order with respect to time specifying that the solution $\psi(r, t)$ at a given initial state uniquely defines the time evolution of the system. This equation does not satisfy the principle of relativity. Relativity treats space and time as a whole, in a relativistic generalization both space and time derivatives in the differential equation should enter symmetrically and must be of the same order. The momentum and the energy that are the derivatives of the space-time vector are related by the relativistic relation

$$E^2 = [p^2c^2 + m^2c^4] = [k^2\hbar^2c^2 + m^2c^4]$$

where mc^2 is the relativistic particle (the electron) rest energy. It follows

$$E = \pm[p^2c^2 + m^2c^4]^{1/2} = \pm[k^2\hbar^2c^2 + m^2c^4]^{1/2}$$

That implies positive as well as negative energy values for a relativistic free particle.

Dirac, who was interested to solve this puzzle, suggested the existence of anti-particles occupying the states with negative energy. If the states are completely occupied the exclusion principle forbids the transitions from other states. At $T > 0$ some lower energy states in the upper band (occupied by electrons) and upper energy states in the lower band (occupied by hole with opposite charge) are partially empty and transitions become possible. Proceeding in a similar way to that used to obtain the Schrodinger equation it is possible to deduce the equation

$$-\hbar^2\,\partial^2\psi(r,t)/\partial t^2 = -\hbar^2 c^2\,\nabla^2\psi(r,t) + m^2c^4\psi(r,t)$$

known as Klein-Gordon equation. It satisfies the criteria of homogeneity and linearity, but it does not satisfy criterion of being of the first order with respect to time. An interesting feature of these particles, denoted Dirac fermions, is their insensitivity, under some conditions, to external electrostatic potentials due to the so-called Klein paradox. According to it, Dirac fermions can be transmitted with probability close to unity through a classically forbidden region (Katsnelson et al. 2006; Robinson 2012).

7 Fifth Week: Massless Fermions, Dirac Equation and the Klein Paradox

In order to visualize the Klein paradox, one must consider that the behavior of a moving particle when it meets a step potential V_0, greater than its kinetic energy, depends critically on its nature. If the particle is classical it is reflected. A quantum particle can tunnel though the barrier although the tunneling probability decreases exponentially with the thickness and the height of the barrier. For relativistic particles, governed by the Dirac equation, the situation is more articulate. In fact, consider an electron in the upper state of Fig. 7 traveling in the direction of increasing values of x with a positive value of k in absence of potential. When it encounters a potential step V_0, one must consider whether the quantity $E - V_0$, is greater than zero or not. In the first case, the electron will continue to propagate with a new value of k satisfying the relation

$$E - V_0 = [\hbar^2 k^2 c^2 + \ m^2 c^4]^{1/2}$$

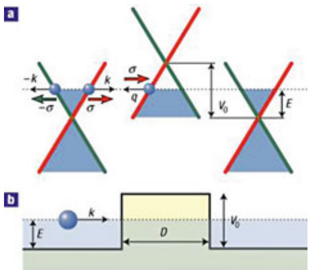

Fig. 7 Tunneling through a potential barrier in graphene. **a** Schematic diagrams of the spectrum of quasiparticles in single-layer graphene. The three diagrams illustrate schematically the values of the Fermi energy E across the potential barrier of height V_0 and width D shown in **b**. The Fermi level (*dotted lines*) lies in the conduction band outside the barrier and the valence band inside it. The *blue* filling indicates occupied states (Katsnelson et al. 2006)

In the second case, one must distinguish two cases: (i) if $E - V_0 < mc^2$ it must be $k^2 < 0$, the momentum inside the potential barrier is imaginary and the wave function decays exponentially, (ii) if V_0 is sufficiently high so that $E - V_0 < -mc^2$, it can be $E{-}V_0 = -\left[\hbar^2k^2c^2 + m^2c^4\right]^{1/2}$ and again $k^2 > 0$. In this case, the propagation of an electron becomes possible for states in the lower branch since the electron is turned into a hole inside the barrier and changed back to electron outside the barrier. Therefore the propagation is possible only for low energy electrons and high values of the potential step V_0. The transmission probability approaches the value one for very high potential barriers and weak electron energies in stark contrast with non-relativistic particle tunneling. The group velocity dk/dx is positive for particles of the upper branch with positive values of k as well as for particles of the lower branch with negative values of k. Consequently, an electron continues to propagate with a negative momentum.

As a consequence of the linear dispersion near the K-point, assuming as zero the energy at a this point and denoting with v_F, the Fermi velocity ($v_F \approx c/300$), we have $E = \pm\hbar v_F|k|$ that indicates that the dispersion relation depends only on the magnitude of k and represents a set of modes forming the surface of a pair of cones in energy-momentum space. Two particles, one in the upper band and one in the lower band, behave as an electron and a hole (or a positron in nuclear physics) since they have identical properties, except for the fact that their charges are opposite (Wilson 2006). This property is called chiral behavior[2] (Katsnelson et al. 2006). This behavior does not occur in semiconductors in which the Schrödinger equations as well as their solutions are different for electrons and holes, due to the different effective masses.

8 Conclusion

This work is the preliminary portion of a more comprehensive research devoted to the setup of a learning path aimed to guide the students to deepen their understanding of the fundamental concepts underlying the electronic properties of graphene. The present learning environment is based on the knowledge and use of basic concepts of Solid State Physics, as the symmetry properties of the crystal lattice, the group theory for the calculation of the degenerations of the wave functions and essential relativistic notions. We have here presented the main steps of this learning path with the final goal of making graphene more accessible to non-specialists and, in particular, to encourage its inclusion in undergraduate courses.

[2]An object is said chiral if it is not identical to its mirror image; the human hands are a simple example of chiral objects, in fact the mirror image of the right hand is the left hand.

Consequently, we have focused on some basic properties and introductory concepts concerning: (i) the lattice structure of graphene; (ii) the symmetry properties; (iii) the electronic energy levels, both in the free electron model and in the band theory of quantum mechanics; (iv) relativistic behavior of the electrons in the case of energy proportional to k and their chiral properties.

This learning path may be twofold useful for physics/engineering students: first because it guides them to expand their theoretical knowledge about graphene and similar problems related to the structure of new materials and, second, to learn and apply the reasoning sequence beneath the present investigation so that, they may surmount eventual epistemological problems. By providing a learning environment focused on active engagement and conceptual understanding, in conjunction with the traditional lecture setting, we would help the students to manage the physics of materials more effectively. We will deepen these ideas, by extending concepts presented here in a preliminary form and carrying out demonstrative calculations in a forthcoming paper with the aim of furnishing a general tool toward the understanding of similar problems.

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