Contributions from Pilot Projects in Quantum Technology Education as Support Action to Quantum Flagship

Sergej FALETIČ (1)

(1) University of Ljubljana, Faculty for Mathematics and Physics, Jadranska 19, 1000 Ljubljana, Slovenia

Abstract. The GIREP community on teaching and learning quantum physics and the Education section of the Quantum flagship project of the European Union have brought together different stakeholders in the field of teaching quantum physics. From university staff involved in quantum technology and research and with a long history of teaching the topic at university level to researchers and practitioners wanting to bring quantum physics to pre-university level and the general public. Within the initiatives several projects have been initiated. This symposium brings together four of them to discuss challenges, solutions and synergies between them.

Introduction

The teaching and learning of quantum mechanics at pre-university level has long been a topic of physics education research, but it has been given new emphasis with the creation of the GIREP community on teaching and learning quantum physics [1] and the Education section of the Quantum flagship project (QTEdu) [2]. Several researchers and developers of materials have come together to address the challenges of pre-university quantum mechanics. The Coordination and support action (CSA) within QTEdu gave the possibility to organize several pilot projects, each with its own aims. Many of the aims have been identified during previous GIREP meetings in 2019, 2020 and 2021 and through the Delphi study conducted by the CSA.

Aims of the symposium

The symposium brings together representatives of the various pilots within the QTEdu CSA and other large initiatives to present the goals of their projects and the preliminary results at this stage and to discuss the synergies between them.

The Development of quantum concepts via different two-state approaches (DQC-2stap) pilot aims at identifying differences between various two-state approaches such as polarization and double well, and also different methods used in instruction. To this aim a questionnaire has been developed to test student reasoning on the topic of measurement. Moreover, a teacher training program has been developed to support teachers in implementing the chosen approaches in school.

The Quantum concept inventory (QCI) pilot aims at developing a modular assessment tool that could be used to compare various approaches. Different approaches address different topics and in different contexts, but those that do address the same topics should be somehow comparable, and the tool should help in this comparison. The community-based development will insure content validity and the pilot implementations will help with other measures. To include as many experts as possible, a Delphi study is underway and some preliminary results from it are available to report.

The Quantum Technologies Education for Everyone (QUTE4E) pilot addresses the function of outreach in developing the modern scientific mind in the modern society of rapid technological development within a Responsible Research Innovation approach. It has been identified that a suitable outreach framework can be conceived by combining together the concept of the discipline-culture and the cycle of scientific thinking. This framework fosters a sustainable, practical implementation, supporting existing interactive tools and addressing a more effective development

of new ones. This provides a transformative and engaging storytelling of quantum science and technologies, which is in the course of being tested in selected outreach activities of the pilot.

The Italian quantum weeks (IQW) is a three-years project born from the desire to take the opportunity of the World Quantum Day (April 14) to try to spread the knowledge of quantum mechanics and quantum technologies in schools and, more generally, to the entire citizenry. IQWs involves more than 130 researchers, technicians, disseminators, communicators, teachers, belonging to more than 40 research institutions, universities, scientific societies, in 17 Italian cities.

All the perspectives discussed in the contributions come together when addressing the quantum literacy of the general population. From the formal settings and its assessment at pre-university level where a large audience can be reached to effectiveness of outreach in informal settings where an diverse population can be reached and a more organic approach is needed. The symposium will highlight the commonalities, challenges and especially good practices in and synergies between the projects and thus provide a holistic overview of current efforts to bring the quantum world to the public.

List of contributions

- Development of quantum concepts via different two-state approaches. *Gesche Pospiech, TU Dresden, Dresden, Germany* et al.
- Community-based development of the Quantum Concept Inventory *Kim Krijtenburg-Lewerissa, Freudenthal Institute, Utrecht University, Utrecht, the Netherlands* and *Philipp Bitzenbauer, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany* et al.
- Cultural Storytellings in Quantum Science and Technology Education *Marilù Chiofalo, Department of Physics "Enrico Fermi", University of Pisa, Italy and QPlayLearn* et al.
- Italian Quantum Weeks outreach activities to enhance quantum awareness *Maria Bondani, CNR – Institute for Photonics and Nanotechnologies, Como, Italy*

Discussants:
Oxana Mishina, National Institute of Optics - CNR, Trieste, Italy and *Rainer Müller, Technical University Braunschweig, Institute for Didactics of the Natural Sciences, Braunschweig, Germany*

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Development of quantum concepts via different two-state approaches

Gesche POSPIECH[1] , Philipp BITZENBAUER[2], Marisa MICHELINI[3], Lorenzo SANTI[3], Alberto STEFANEL[3], Kristof TÓTH[4],

(1) TU Dresden, Dresden, Germany, (2) Friedrich-Alexander-Universität, Erlangen-Nürnberg, Erlangen, Germany, (3) University of Udine, Udine, Italy, (4) Physics Education PhD Programme, Eötvös Loránd University, Budapest, Hungary.

Abstract. In the last decades two-state approaches were increasingly considered useful for introducing quantum physics to students on all levels. Some promising results were reached. However, a thorough evaluation with reliable and validated instruments is still missing. In addition, it could be possible that some two-state approaches are more suitable to some quantum concepts than to others. In order to be able to evaluate and compare different approaches instruments are developed. In the project "DQC-2stap" first steps towards this goal are taken. We describe the development of a questionnaire on the measuring process and a corresponding activity for in-servicer teacher education.

Introduction

A two-state approach to quantum physics seems to be a suitable and flexible means for teaching quantum physics. As two-state systems are the simplest possible quantum systems they may serve as an easy-to-handle mathematical framework to explore some of the fundamentals of quantum physics. The basic quantum concepts are not only clearly visible but also discoverable by students itself while a comprehensible mathematical formalism is used. Such an approach can be taught in different contexts, e. g. with polarization, with spin, with a double-well system or with still other systems with two basis states. However, the question arises if all these approaches are equivalent in the sense that they are all equally well suited to teach the most important quantum concepts such as quantum state, superposition, uncertainty, entanglement and measuring process with similar success with respect to understanding by high school students. It could be thought that different approaches have different strengths and weaknesses. In order to find hints in this direction in the project DQC-2stap *"Development of quantum concepts via different two-state approaches"* a questionnaire should be developed that sheds light onto this question. This process is accompanied by corresponding teacher education activities.

Project objectives

The ultimate goal of the project DQC-2stap *"Development of quantum concepts via different two-state approaches"* is to give recommendations for teachers or educators at university on how two-state approaches and appropriate teaching material can be optimized in the sense that students understand best the quantum concepts.

First, it should be identified which of the two-state contexts mentioned above is most suitable for teaching which quantum physics concept at the secondary school level. Especially specific learning difficulties of students should be identified. To this end a questionnaire is developed.

Secondly, the gained insights into students' learning difficulties in two-state approaches will be used to develop or improve secondary school teaching proposals and material based on the two-state approach within a design based research process. This research goal needs longer time and will profit from cooperation with other projects in the Quantum Flagship education initiative.

Development of questionnaire

In order to limit the complexity of the questionnaire development, we initially restricted ourselves to the concept "quantum physical measurement process". This concept was also chosen because the measurement process lies at the core of the peculiarity of quantum physics. So the research question is:

Which understanding and learning difficulties do students show with respect to the measuring process?

In a first step, we work on the development of a first version of a questionnaire to evaluate our teaching materials with secondary school students. Herewith we focused on the understanding of the measuring process. Based on own teaching experiences, on existing questionnaires and on a classification of aspects of the measuring process sample items were developed. These were graded with respect to their suitability independently by all the members of the group and the item with highest grades were taken. The items were mostly closed single choice items with required justification and some open items.

In the next step the questionnaire was tried with selected students, adapted and refined. Then a pilot with teacher students was made. The resulting final version is now being tested with school students in Hungary, Slovenia and Italy, whereof first results will be presented.

Activity of teacher education

Since it is an overarching aim of this project to derive recommendations for teachers or educators at university on how two-state-approaches can be optimized towards student learning of quantum physics, teacher education courses are developed and conducted within this project. In this talk, we will describe one of these teacher education courses developed by the project partners from Udine (Italy): A teacher training consisting of 5 meetings (4 hours each, once a week) has been completed in March 2022 preparing teachers for the implementation of a field study into teaching/learning quantum physics via a polarization-approach (one of the two-state- approaches comprised in our pilot project). The teachers attending the course filled in four tutorials on the different topics such as the phenomenology of polarization. In this GIREP presentation, we report on the teacher training course in more detail. Furthermore, we give insights into the analysis of the four tutorials and the discussions during the training.

Outlook

Using the questionnaire, we will conduct field studies in order to compare learning outcomes from students who are introduced into Quantum Measurement via different two-state-approaches. We will use the outcomes of the questionnaire for a) a refinement of the different teaching sequences, and b) for answering the question about the suitability of different two-state-approaches to introduce students to Quantum Measurement.

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Community-based development of the Quantum Concept Inventory

Kim KRIJTENBURG-LEWERISSA[1], Erica ANDREOTTI[2], Daria ANTILLA[3], Maria BONDANI[4], Marilù CHIOFALO[5], Mieke DE COCK[6], Caterina FOTI[8], Renaat FRANS[2], Aurél GÁBRIS[9], Simon GOORNEY[10], Franziska GREINERT[11], Leon JURČIĆ[7], Zdeňka KOUPILOVÁ[12], Massimiliano MALGIERI[13], Avraham MERZEL[14], Rainer MÜLLER[11], Pasquale ONORATO[15], Henk POL[16], Gesche POSPIECH[17], Kirsten STADERMANN[16], Malte UBBEN[18], Andreas WOITZIK[19], Philipp BITZENBAUER[20]

(1) Freudenthal Institute, Utrecht University, Utrecht, the Netherlands, (2) University College Leuven-Limburg, Diepenbeek, Belgium, (3) University of Turku, Turku, Finland, (4) University of Insubria, Como, Italy, (5) University of Pisa, Pisa, Italy, (6) KU Leuven, Leuven, Belgium, (7) University of Ljubljana, Ljubljana, Slovenia, (8) Aalto University, Helsinki, Finland, (9) QWorld Association, Tallinn, Estonia, (10) Aarhus University, Aarhus, Denmark, (11) Technische Universität Braunschweig, Germany, (12) Charles University, Prague, Czech Republic, (13) University of Pavia Pavia, Italy, (14) The Hebrew University of Jerusalem, Jerusalem, Israel, (15) University of Trento, Trentino, Italy, (16) University of Twente, Enschede, the Netherlands, (17) TU Dresden, Dresden, Germany, (18) Westfälische Wilhelms-Universität, Münster, Germany, (19) Albert-Ludwigs-Universität Freiburg, Freiburg im Breisgau, Germany, (20) Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany.

Abstract. For the improvement of quantum physics education at the secondary level, it is important to develop a flexible assessment tool, which is suitable for evaluating the numerous existing teaching concepts that have emerged from physics education research over the last decades. We therefore give an overview of the plans of the QTEdu pilot project 'Community-based development of the Quantum Concept Inventory' to create such an assessment tool. Additionally, we will present the results of a Delphi study aiming to identify the community's perspective on key topics for teaching quantum physics at the secondary school level.

Introduction

In the last years, teaching proposals for quantum physics have been developed in order to make quantum physics (QP) accessible at the secondary school level, and to promote conceptual understanding of quantum physics among learners. Quantum physics can be taught in different contexts (e.g., historical approach, experiment-based approach, two-state approach) and by using different key topics [1]. This makes the evaluation and comparison of the different developed approaches difficult. In order to be able to evaluate the developed teaching proposals, it is important to have instruments available which can be used to assess students' conceptual understanding within the framework of the individual teaching proposal. Since there is no such an instrument available at present, the authors of this paper have started the QTEdu pilot project *"Community-based development of the Quantum Concept Inventory (QCI)"*. In this project a modular concept inventory will be developed based on community input which allows for the assessment of students' understanding of quantum physics' key concepts within different contexts and for different key topics. Thus, we aim to create a concept inventory that is found useful for evaluating the numerous teaching concepts despite their different emphasis.

Project objectives

To create a concept inventory that is based on the communities' perspectives and that is applicable for different contexts and key topics, in this project we aim to:

1. Identify quantum physics' key concepts to be taught to secondary school students from a community perspective,
2. collect existing test instruments (published or unpublished) from the literature and from our research groups to create a platform of existing test items on the central concepts of quantum physics,
3. create additional test items in various task formats (e.g., multiple choice, likert scale items, open-ended questions, concept cartoons), and
4. evaluate the existing and additional test items qualitatively (e.g. think-aloud interviews) and quantitatively in a later stage of the project.

At present, the project members have collected existing test instruments, and distributed a Delphi study to identify the key concepts. This procedure ensures content validity of our instrument in an early stage of its development.

Results of the Delphi study

A Delphi study was conducted in order to identify key concepts that represents a community-based view. In the first round of this Delphi study, physicists, physics teachers, and physics education researchers where asked why secondary school students should learn quantum physics and what topics should be addressed in classroom teaching. Currently, a second questionnaire is distributed, in which the QP community is asked to select which of these topics (including various specifications considering QTEdu's Competence Framework [2]) should be part of the secondary school curriculum.

Outlook

Based on the results of the Delphi study, the QP topics that should be addressed by the QCI will be determined, and the relation between profession, country, and proposed topics will be analysed. Subsequently, we will create a database of existing test items referring to the identified key concepts, and new test items will be developed. This will form the basis for a flexible and community-based QCI.

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Cultural Storytellings in Quantum Science and Technology Education

Marilù CHIOFALO (1), Aditya ANUPAM (2), Maria BONDANI (3), Ilke ERCAN (4), Simon GOORNEY (5), Marisa MICHELINI (6), Lorenzo SANTI (6), Zeki SESKIR (7), Jacob SHERSON (5), Alberto STEFANEL (6), Jorge YAGO MALO (1), Elif SURER (9), Carrie WEIDNER (10), Olga ZABELLO (11)

(1) Department of Physics "Enrico Fermi", University of Pisa, Italy and QPlayLearn, (2) Georgia Institute of Technology, (3) Istituto di Fotonica e Nanotecnologie - CNR-IFN, Como, Italia, (4) Department of Microelectronics, TU Delft, 2628 CD Delft, The Netherlands, (5) ScienceAtHome and Institute for Physics and Astronomy, Aarhus University, Ny Munkegade 120, 8000 Aarhus C, Denmark, (6) Unità di Ricerca in Didattica della Fisica, Università di Udine, Via delle Scienze 208, 33100 Udine, Italy, (7) ITAS, Karlsruhe Institute of Technology, Karlstraße 11, 76133 Karlsruhe, Germany, (9) Department of Modeling and Simulation, Graduate School of Informatics, Middle East Technical University, Ankara, 06800, Turkey, (10) University of Bristol, UK, (11) Offenburg University, Badstraße 24, 77652 Offenburg, Germany

Abstract. The field of Quantum Science and Technologies (QST) has the potential to generate significant changes in every citizen's lives, and so a carefully designed approach to its formal and informal education activities is essential. In this contribution, we reflect on the functions of outreach in developing the modern scientific mind, discuss its essential importance in the modern society of rapid technological development, and propose a novel framework, *Culturo-scientific storytelling*. In a manner consistent with Responsible Research Innovation, we propose tools to implement this narrative within the pilot project Quantum Technologies Education for Everyone (QUTE4E).

Introduction

The rapidly evolving field of Quantum Technologies (QT) requires the understanding of Quantum Science (QS) through a renovated mindset, posing important challenges to outreach experts to find engaging, rigorous, and effective narratives. QST offers a thriving opportunity to design an outreach framework able to support citizens of any age and cultural background to develop a modern scientific mind, and be able to navigate the "society of acceleration" [1,2]. These considerations have motivated the design of the Quantum Technologies Education for Everyone (QUTE4E) pilot project [3], part of the QTEdu Coordination and Support Action under the European Quantum Flagship Program. QUTE4E is centered on the idea of accessible quantum science to every citizen through shaping outreach as an accessible non-formal education framework, alongside existing formal activities. We present the general theoretical framework of culturo-scientific storytelling (CSS) [4], discuss its links to Responsible Research Innovation, and analyse the available interactive tools [5] that can be exploited to implement the CSS idea into practical outreach context.

The theoretical framework of Culturo-scientific storytelling and research questions

As discussed in Ref. [4] disciplinary structure exists in the fundamental sciences which is firmly respected to this day [6]. Tseitlin et al. [6] highlighted that the rigid, disciplinary description does not incorporate their temporal evolution. To this end, they introduced a *discipline-culture* (DC) *framework* in which scientific knowledge is organized into a nucleus of core principles, a body of

working applications, and a periphery of alternative views and accounts. It is also understood that scientists process and develop knowledge in a narrative cycle, which proceeds from observation, to creative understanding, formalization, and refinement [7]. To do so demands creative, formal and experimental literacies and the awareness that scientific knowledge is an ongoing dialogue of interacting discipline-cultures. However, what of the modern scientist? What skills are needed to contribute to the rapidly emerging fields such as QTs, those with an enormous impending impact on society? QTs indeed offer an opportunity in which a narrative can be presented that may enable students to develop skills of *future-scaffolding*, including recognition of causality, scenario-thinking, and multi-perspective problem-solving [8]. The emphasis on education for "everyone" naturally calls for another question, of how to design generalizable guidelines which educators can exploit and the essential concepts of physics on which they rely, in a captivating and language-accessible manner.

Methods and findings

Guidelines would be evanescent without a theorization which they can ground into, and abstract without a reasoned toolbox at hand. To answer the above questions, we have thus first conceived the theoretical framework of *Culturo-scientific thinking* , representing the ability to embrace scientific thinking with an appreciation of the past, present, and future of the field and society. We found that an engaging narrative, *culture-scientific storytelling (CSS)* can be conceived by drawing in participants with unexplainable knowledge from the periphery of the field. In interpreting a paradigm by which this can be understood, curiosity is engaged and participants are able to access the working applications of the field. Finally, with the dual entry and exit through the periphery, where knowledge cannot be fully explained, participants are directly exposed to the reality of being a scientist: there is always more to learn. CSS echoes the conclusions of Levrini et al. [9] that skills, not just disciplinary knowledge, should be the goals of science education and must be considered in activity design and educational policies. CSS is also deeply connected to the RRI dimensions. Here, we report on a specific QST characterization of the RRI dimensions, by means of a participatory process involving PhD students of the University of Pisa [10]. We now address the suitability of available tools. As compared to formal education, outreach activities have a distinct advantage in not being limited to any formal curriculum, so that a focus on activities which are deeply engaging, such as gamified and creative experiences, can overcome some of the challenges educators are faced with in teaching quantum concepts with traditional means of instruction. To implement the CSS should not necessarily require the production of new tools, as many exist already which can support it. Indeed we classify [5] the existing interactive tools and quantum game creation events supporting the CSS approach, that are being validated in outreach activities of the QUTE4E pilot.

Conclusions

The QUTE4E pilot project is a fertile opportunity to reflect on the importance of designing suitable outreach frameworks for rapidly evolving scientific fields of research, such as QST. We found that an engaging storytelling, with high educational content, can be conceived by combining the concepts of discipline-culture and the cycle of scientific thinking. Our theorization fosters sustainable, practical implementations, as it uses existing interactive tools to support creative, formal, and experimental literacies, besides properly addressing the development of new ones. With this theoretical and practical toolbox, we have sown a fertile ground for a transformative and RRI-coherent QST storytelling, which is now in testing through selected outreach activities of the pilot.

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Italian Quantum Weeks outreach activities to enhance quantum awareness

Maria BONDANI

CNR – Institute for Photonics and Nanotechnologies, via Valleggio 11, 22100, Como, Italy

Abstract. The three-year project Italian Quantum Weeks was born from the desire to take the opportunity of the World Quantum Day (April 14) to try to spread the knowledge of quantum mechanics and quantum technologies in schools and, more generally, to the entire citizenry. IQWs involves more than 130 researchers, technicians, disseminators, communicators, teachers, belonging to more than 40 research institutions, universities, scientific societies, in 17 Italian cities.

Introduction

With the advent of Quantum Technologies that exploit the quantum properties of matter, the Second Quantum Revolution is officially started: Quantum Mechanics with all its peculiar features is no longer just a very effective theory to describe the microscopic world but has become a tool for the design of new devices. The control and manipulation of quantum properties (superposition and entanglement) of light and matter actually allow to realize quantum computers, secure communication protocols, simulations of complex quantum systems and new ultra-precise sensors.

The European funding plan "Quantum Technology Flagship" [1], started in 2016, aims to bring Quantum Technologies to maturity and at the same time to raise awareness of the change in cultural perspective that the Second Quantum Revolution requires from all of us.

In the framework of the Flagship, on the occasion of the first World Quantum Day (April 14, 2022) [2] we propose the Italian Quantum Weeks [3], several weeks from March 26 to May 31 dedicated to the exploration of the foundations and applications of Quantum Mechanics.

We have organized a network of researchers in different universities and research institutes in order to set up a didactic/dissemination exhibition, educational games, activities and interactive workshops, to be proposed to students and general public, as well as lectures and guided tours to research laboratories. We aim at offering school students and citizens an interactive experience of the peculiar behaviour of the quantum world and of its immense application potential.

We have directly involved researchers active in Quantum Mechanics and Quantum Technologies in a common work of dissemination, to elaborate contents and communication strategies so that the conveyed message is scientifically precise and effective at the same time.

Till now more than 130 researchers, technicians, disseminators, communicators, teachers, belonging to more than 40 research institutions, universities, scientific societies, in 17 Italian cities are involved in the project.

Evaluation activities of the events will be carried out in the different locations.

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