Symposium on Teaching and Learning Quantum Physics

Responsibles

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# Goal and Content of Symposium

Quantum physics and its implications for future science and technology is becoming culturally important and more attention is being given to its introduction before university level.

There is a rich literature about different approaches and strategies [2]: 1) historico-philosophical, 2) matter-wave, 3) two-state systems, 4) Feynman path integrals, 5) quantum field theory, 6) quantum technology, which have been all adapted for pre-university level. Further differences are in: a) contextual aspects: e. g. choosing a spin, polarization or double well two-state system, and b) methodological aspects, using frontal traditional presentation or active engagement methods. All approaches show learning gains among students.

Given the diversity of approaches, there are growing efforts [3] to identify key concepts to be taught and key competences to be learned hinting that all approaches might not be equally suitable to introduce different concepts. The symposium gathers experts who have experience in teaching quantum physics with some of these approaches in different settings and with different populations to share their experience and insights into the advantages and potential limitations of the various presented approaches.

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3. See pilot projects at <https://qt.eu/about-quantum-flagship/projects/education-coordination-support-actions/>

What are the key concepts and key competences for teaching quantum physics we should focus on at pre-university level?

Abstract for the Symposium on Teaching and Learning Quantum Physics, WCPE in Hanoi 2021

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In recent time, in view of the increasing importance of the emerging field of quantum technologies, a large variety of experiments, models, animations and simulations has been developed from various groups in Europe and beyond, aiming at teaching different key concepts of quantum physics at various levels of education [1].

In the first part of my talk, I will highlight some of these approaches at pre-university level by using explicit examples. Concerning experiments, e.g. a modular system based on 3D-printed optic cubes allows for a cheap and flexible realization of many relevant optic experiments in the physics classroom [2]. While single-photon experiments are still beyond reach at pre-university level, I will discuss possible future developments in this field and their impact for education. In particular, miniaturization of optical devices on chips are a promising field of technology [3]. A coupled system of two waveguides can be considered as a two-level system. I will discuss how by using the simulation tool QuantumComposer [4] pupils can easily model the emerging superposition state and its time dynamics.

The superposition of product states – in other words, entanglement – immediately follows from this approach. However, the concept of entanglement is particularly challenging. I will give a short overview on different approaches on how to teach entanglement [5, 6]. Then, I will focus on the increasing importance of topology in various fields in physics. I will present a simple haptic model revealing entanglement as the counterpart of distinguishability from a topological point of view [7, 8].

In the second part of my talk, I will discuss key competencies in teaching quantum physics from the point of view of different stakeholders: While the emerging industry in the field of quantum technology is in need of a sharp spectrum of competencies and training for future workforce in this field [9], school education is much broader in its aims compared to industrial training. Here, I will argue that empirical research in physics education should start from this more general and fundamental point of view towards the impact of quantum physics on society.

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9. European Competence Framework for Quantum Technologies, QTEdu consortium (2021)

Prior knowledge needed for quantum mechanics

Abstract for the Symposium on Teaching and Learning Quantum Physics, WCPE in Hanoi 2021

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**Abstract**. In the last years, quantum mechanics has become part of many secondary school curricula. Teaching quantum mechanics at a conceptual level is a challenge, because of its counterintuitive nature: research shows that students mix up concepts, and overgeneralize prior classical knowledge. In order to prevent this, it is important to show students how quantum mechanics relates to their prior knowledge. This contribution will give an example of how focus on prior knowledge of potential energy contributes to the understanding of quantum mechanics within the Dutch curriculum. This example illustrates the importance of a coherent physics curriculum for understanding quantum mechanics.

# Introduction

Because of its impact on society, quantum mechanics (QM) has become part of many secondary school curricula [1]. The approaches, contexts, and methods of introducing QM differ [2]. In the Netherlands QM was introduced during a curriculum renewal in 2013. The current QM topics in the Dutch secondary school curriculum are: (1) the wave character of light, (2) wave-particle duality, (3) the photoelectric effect, (4) Heisenberg’s uncertainty principle, (5) the 1D infinite potential well, (6) the hydrogen atom, and (7) tunneling. As many secondary school curricula, the Dutch curriculum does not include the mathematical tools for a mathematical approach to QM. Therefore, QM needs to be taught at a more conceptual level.

For students that are used to classical reasoning, quantum mechanics is counterintuitive, and often seen as strange and incomprehensible. Because of that, students can relate the new knowledge to unrelated prior learning, mix up concepts, or interpret concepts intuitively [3,4]. In order to prevent these incorrect interpretations it is good to focus on connecting prior knowledge to quantum mechanics [5]. We have therefore designed and evaluated a module aiming to reduce the gap between students’ prior knowledge of potential energy (PE) and QM [6].

# Method & Results

In order to investigate the influence of knowledge of PE on the understanding of QM, a module was developed in which students’ prior knowledge on PE, kinetic energy and energy conservation was activated. The module addressed PE in the classical contexts of gravitation, mass-spring systems, and electric fields. To increase students’ understanding needed to understand the 1D potential well and tunneling, the teaching materials focused on interpreting *E,x*-diagrams. An example diagram from the module can be found in Figure 1.

To determine whether the knowledge of PE diagrams provided a better understanding of tunneling and the potential well, a quasi-experimental intervention was conducted at ten different schools (see Figure 2); the experimental groups (*N*=234, 13 classes) worked with the module, and the control groups (*N*=157, 11 classes) did not. Two tests were used to evaluate students’ understanding. A PE test addressed students’ understanding of energy in relation to force, position and velocity before QM instruction. The QM test was used as pre- and post-test, and focused on understanding in terms of energy and probability.

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| Fig. 1 An example E,x-diagram from the module. | Fig. 2 The quasi-experimental procedure. |

The test results showed that the experimental group ultimately had a significantly better understanding of the potential well and tunneling (Cohen’s *d*=0,29). In addition, this study showed that there was a small, but significant correlation between the understanding of potential energy and the understanding of the potential well and tunneling (Pearson’s *r*=0,21).

# Conclusions

Based on these results we can conclude that there is an relation between PE and QM that can be used to strengthen the coherence of the curriculum and deepen students’ understanding of QM. In order to improve students’ understanding of QM, it is important to give students the possibility to relate QM to concepts that they have learned previously. Therefore, it is important to rethink the topics that are taught before introducing QM. Central topics in classical physics that also play a role in QM need to be addressed thoroughly, in order to create deep understanding of relevant prior knowledge before teaching QM. This is not only the case for energy, but also for other topics such as momentum, forces, fields, interference, superposition, and probability distribution.

The needed prior knowledge depends on the approach, method or context with which QM is introduced. Therefore, the further development of QM education should not only focus on learning effects and learning outcomes of the different ways to introduce QM, but also on the coherence between QM and the complete physics curriculum.

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Pedagogical Considerations for Quantum Instruction

Abstract for the Symposium on Teaching and Learning Quantum Physics, WCPE in Hanoi 2021

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**Abstract**. We discuss developmental considerations for two quantum mechanics curricula: Paradigms in Physics (from Oregon State University) and Tutorials in Physics: Quantum Mechanics (from University of Washington).

# Details

The considerations include theoretical commitments about pedagogy and practical structures shaped by the instructional constraints [1]. We compare the considerations themselves along with how instructors are typically prepared to implement each curriculum in the classroom. In the case of the Paradigms [2-3], the theoretical commitments drove changes to the practical structures. However, the Tutorials [4] were shaped in a way that the theoretical commitments had to be incorporated into a course with a relatively fixed structure. This difference contributed substantially to the fact that the two curricula prioritize different commitments and consequentially promote student understanding in different ways. We explore example activities from each curriculum to highlight some of these differences, focusing on the same topic (angular momentum in quantum mechanics) for both.

We also discuss how the alignment and tension between the theoretical commitments for each curriculum has resulted in different needs for instruction preparation. In particular, the Paradigms requires a much more intensive involvement on the part of the instructor in terms of preparing, sequencing, and adapting to what happens in the classroom. On the other hand, preparation for the Tutorials is more focused and requires less adjustment on the part of the instructor. For both curricula, however, direct preparation of the instructional team (especially if it involves multiple teaching assistants) to address student ideas in the classroom is essential. Lastly, we note some deep similarities between the two curricula: the importance of social interactions and multiple representations and the ways in which students build their own ideas.

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The Second Quantum Revolution at school:

teaching and learning Quantum Physics in the context of Quantum Technologies

Abstract for the Symposium on Teaching and Learning Quantum Physics, WCPE in Hanoi 2021

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**Abstract**. The context of the Second Quantum Revolution, in which basic results of Quantum Physics are generating new technological applications, is exploited to devise teaching-learning paths for high-school teachers and students. The concepts of quantum state, superposition, entanglement and measurement are addressed introducing the qubit and the quantum logic gates.

# Context

Since about twenty years we have entered the Second Quantum Revolution [1] where applications and technologies based on the principles of Quantum Mechanics are becoming increasingly available thanks to the capability of preparing, controlling and manipulating single quantum states and exploiting their nonclassical properties, such as superposition and entanglement. Among these technologies, the European Flagship on Quantum Technologies [2] focuses on quantum information and communication, quantum computing and simulations, and quantum metrology. Such newly developed quantum technologies will not only have fundamental social and economic implications in the next future [3,4] but also require changes in our epistemic perspective. The reason is that the properties of the physical systems underlying quantum technologies have no classical analogues and require a different logical approach: the classical propositional binary logic must be replaced by a new one to deal with the evolution of quantum systems.

On such basis, it would be important to familiarise new generations with these technologies so they be part, in the near future, of the workforce needed to fully implement the second quantum revolution [4]. However, usual teaching approaches of Quantum Physics at secondary school level does not empahsize current findings of in advanced quantum research [5-6] [6]. To bridge this gap, it is necessary to create new learning environments to support both teachers and students in tackling the conceptual difficulties related to quantum physics [7]. This can be achieved through the exploration of quantum technologies as a significant context to show how quantum superposition, entanglement, and other quantum core concepts can be used in the developoment of new technologies.

# Activities

Introducing the qubit, the basic building block of quantum information, and approaching physical transformations from a computational point of view, as quantum logic gates, help reducing the level of the mathematical formalism required to describe the essential features of quantum physics. Moreover, relevant properties of physical systems, such as electron spin or single-photon polarization, can be seen as physical realizations of qubits and discussed keeping the argumentation rigorous enough to avoid distorting hyper-simplifications [8].

To address the above issues, during the past three years, we designed and implemented Continuous Professional Development (CPD) programs to support the development of teachers’ pedagogical content knowledge in quantum physics. Combining the exploration of quantum concepts (i.e., quantum superposition, entanglement) and the development of physical models to interpret the result of electrons spin and single-photons experiments, teachers had the opportunity to reflect on the nature of quantum objects using an elemental and rigorous mathematical formalism.

We also organized extracurricular activities (Summer Schools and PCTO - Transversal Competencies and Orientation Program) to introduce students to quantum technologies. Using an interdisciplinary approach, we designed and implemented a teaching learning sequence for high school students about the core concepts of quantum physics and the tenets of quantum computation. The intertwining between logic and physics enables students to understand the way quantum computers manipulate information and how this could be used to develop cryptographic protocols and perform quantum teleportation. Extensive use of interactive simulations [9] and processing of quantum algorithms on real quantum computers [10], together with analytical calculations, supported students’ learning process.

# Conclusion

All the activities are the result of the joint efforts of the communities of researchers active in Italy the fields of Quantum Technologies and Physical Education.

Preliminary results of the evalutaton of activities carried out with small groups of students during the Summer Schools, show that using the quantum technologies, and quantum computing in particular, was effective in introducing foumding concepts of quantum physics: quantum superposition and entanglement, evolution of quantum states, quantum measurement and quantum probabilities.

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