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Games for Quantum Physics Education

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Symposium
Games for Quantum Physics Education
Responsible
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Introduction
Educating to quantum physics is becoming a priority as an extraordinary opportunity to educate physics intuition and innovate physics teaching, and to build up awareness on quantum technologies while they revolutionize our lives. We have no direct experience of the microscopic phenomena underlying the world we have experience of, and so beautifully explained by quantum mechanics with its advanced formal machinery. Thus, we cannot easily rely on experience nor math to educate our quantum-physics intuition. In this Symposium, we propose that games may provide a playground with engaging forms of experimental and symbolic literacy at everyone's reach. We explore the extent which this idea can be effective to, with scientists who pioneered it.
According to estimates, by the age of 21 the average US citizen has spent playing videogames the equivalent of a 40 hours/week full-time job for five years [1]. People have started to wonder if this enormous amount of human brainpower can be harnessed for tasks beyond the grasp of current computer machines. One answer is by designing games with a purpose (GWAPs). Citizen science has become a powerful approach in research, educational, and decision-making contexts [2,3]: games have goals focused on in epic, emotions activating, adventures, a set of rules that are constraints but also opportunities unleashing creative thinking to cross skill limits, a feedback reinforcing motivations, a voluntary participation allowing to leave or keep up while not dreading failures. In fact, games are extraordinary tools in pedagogy [4] to develop competences [5] and foster community building: in fact, a non-perishable and yet untapped source of extremely valuable goods in terms of problem solving.
Despite these ideas might sound extravagant, there are many successful examples of GWAPs for research problems [6] starting from the seminal Foldit experience down to proposals to integrate human and machine minds to solve otherwise intractable quantum problems [7], and for education in classical and quantum physics pioneered by the contributors to this Symposium within ScienceAtHome, QPlayLearn, QWorld, and Quantum Game Jams [8], leading also to creating a GTG on the topic within GIREP, coordinated by the Symposium responsible. "Creating the learning ecosystem necessary to inform and educate society about quantum technologies" enabling "the emergence of a quantum-ready workforce" [9] has more recently been growing as a goal, cross-disciplinary boosted within the European Quantum Flagship Coordination and Support Action for Quantum Technology Education, which all the Symposium contributors are involved in, with Jacob Sherson the QTEdu coordinator, and Marilù Chiofalo and Zeki Seskir coordinating the pilot QuTE4E on outreach and education.
We believe that WCPE represents a timely spacetime to dig into the topic in a systematic, critical, and rigorous manner, unveil opportunities and criticalities, elaborate under theoretical and practical perspective the specific physics-education research tools.
The Symposium addresses a number of fundamental questions. Sabrina Maniscalco first elaborates on the delicate question of whether and how the use of quantum games as educational tools can be framed into a global and strategic vision to root a durable educational and societal change. What is a quantum game, what makes any game 'quantum', and how quantum games effectiveness for education can be assessed are the questions posited by Zeki Seskir. How humans think about quantum mechanics regardless of their educational level and used game form is the dimension explored by Jacob Sherson, also illuminating potential and practical implications in increasing players knowledge of quantum research and technology in society. Down to which age one can design effective games for quantum physics education, is the dimension explored by Cristina Lazzeroni with her class-workshop experience of proven impact record, incorporating arts and crafts and creativity to convey a scientific and inspirational message on particle physics in primary schools. With her renowned expertise, our Discussant Marisa Michelini, GIREP's President, can lead the discussion, bridging the panelists

diverse stories and channelling them into crucial methodological and practical aspects.
Given the leading roles of the participants to this field, the Symposium will also offer a wide-open vision of status and perspectives, discussing in depth and width the challenge of building up an ecosystem on quantum science and technology education.

Description of presenters:
1) Professor Sabrina MANISCALCO, QTF Centre of Excellence, Department of Physics, Faculty of Science, University of Helsinki (Finland), CEO of Algorithmiq Oy, Creator of QPlayLearn
2) Professor Zeki SESKIR, METU Physics Department, Ankara (Turkey), Co-founder of QWorld, Co-coordinator of the pilot QuTE4E within QuTEdu of the European Quantum Flagship
3) Professor Jacob SHERSON, School of Business and Social Sciences, Aarhus University (Denmark), Director and founder www.ScienceAtHome.org, Coordinator of QuTEdu CSA
4) Professor Cristina LAZZERONI, University of Birmingham Edgbaston, Birmingham B15 2TT (UK), Spokesperson of NA62 at CERN, Creator of Particle Physics for Primary Schools Education

Discussant
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Quantum Games as Tools in a Strategic Educational Vision: the experience of QPlayLearn
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Abstract. Educating to quantum physics is an inevitable must, while quantum technologies revolutionize our lives. But quantum mechanics is one most counterintuitive theory, manifesting in a reality we have no direct experience of, and represented by tough formalisms. Games can provide a playground for engaging forms of experimental and symbolic literacy at everyone's reach. Here we present the global educational strategy and vision that we have implemented in QPlayLearn, to provide multilevel education on quantum science and technologies for anyone, where serious games are essential toolbox items. We report on the ongoing assessment of its potential and effectiveness, performed by physics education tools.

1 The context
Teaching quantum physics to school students and the general public represents an inevitable must, while quantum technologies revolutionize our lives. Quantum literacy is a formidable challenge and opportunity for a

massive cultural uplift, where citizens learn how to engender creativity and practice a new way of thinking, essential for smart community building. Scientific thinking hinges on analysing facts and creating understanding, then formulating these with dense mathematical language for later fact checking. Within classical physics, learners' intuition can be educated via classroom demonstrations of everyday life phenomena. Their understanding can even be framed with the mathematics suited to their instruction degree. For quantum physics instead, we have no experience of quantum phenomena, and the required mathematics is beyond non-expert reach. In fact, quantum mechanics is known as one the most counterintuitive and bizarre physical theories, involves imagination and diverse thinking, and a change in paradigm perhaps more radical than any other in the history of human thought: quoting Niels Bohr "Anyone who is not shocked by quantum theory has not understood it". Therefore, educating everyone's intuition in quantum physics needs alternative forms of experimental and mathematical literacy: educators would otherwise face the risk of providing only evanescent tales, often misled, while resorting to familiar analogies.
In this context, games designed with a purpose can be effective tools for the general goal of innovating educational processes and the specific (here crucial) goal of providing a playground for physics concepts that cannot be easily experimented with everyday-life experience. Games are exceedingly more challenged than reality: players are engaged to overcome their limits and rewarded by skill challenges, which implies to amplify motivations and unleash creative thinking as ever-lasting resources for community development [1,2]. But hinging on games as educational tools without a global vision of the educational frame, may easily fail to produce a real cultural change we aim at, and root it into a durable educational and societal transformation.

2 The QPlayLearn vision

Here, we report on the global strategic vision that we have implemented in QPlayLearn [3,4], an online platform conceived to explicitly address challenges and opportunities of massive quantum literacy. QPlayLearn was born from a group of scientists passionated about quantum science and firmly believing that everyone can learn about quantum physics and its applications. QPlayLearn's mission is to provide multilevel education on quantum science and technologies to anyone, regardless of age and background. To this aim, interactive tools enhance the learning process effectiveness, fun, and accessibility, while remaining grounded with scientific rigour. As a strategy for massive cultural change, QPlayLearn offers diversified content for different target groups, from primary school all the way to university physics students, to quantum science enthusiasts. It is also addressed to companies interested in the emergent quantum industry, journalists, and policy makers needing to grasp what quantum technologies are about.
Inspiring to the theory of multiple intelligences [5], QPlayLearn's holistic perspective stems from the recognition that different types of intelligence dominate the learning process of each person. Therefore, the platform is conceived to accompany users in the travel through Alice's rabbit's hole via different paths aimed at: 1) building intuition and engagement through games and videos; 2) understanding physical concepts through accessible and scientifically accurate descriptions, graphics, animations and experiments; 3) acquiring formal understanding through the mathematics. For each concept in the dictionary, each user can begin from the approach that feels easier to him/her, and then possibly explore the others. Eventually, it is the combination of the different manners that shifts and expands the understanding of quantum physics.
In this context, games are one of the tools, embodied in the section Play, to stimulate the interactive participation of the users to grasp the counterintuitive features of quantum physics. Besides games, short animations (Quantum Pills) explain concepts at different understanding depths, useful for experts and not. In the Discover section, experts explain concepts with short videos, using metaphors, experiments or deductive examples. The Learn section enters the formal core of the quantum theory, devoted to a more expert audience. In the Apply section, concepts can be practiced by running code samples on real-world quantum devices. Finally, the Imagine section offers an environment totally free from restrictions, where learning proceeds via the preferred user's artistic language, in fact involving creativity at its most.
After presenting QPlayLearn, we will report on ongoing investigation of its potential by means physics education research tools, to assess how to fully exploit its opportunities and transform its possible limitations in learning and teaching processes.

3 Conclusions and perspectives

QPlayLearn is a free platform for wide and diverse use, intended to tailor education processes on quantum science on the many talents of different users, operate a diffuse and massive cultural change, build up literacy and awareness. Because of this flexibility, QPlayLearn can be adopted by educators as largely as one can imagine at first.
While we proceed in the goal of assessing the effectiveness of our approach, we are working to different perspectives, such as completing the quest environments, adding a multiple language version, and extending the class of beneficiaries to 0-99 years old users together with pedagogy experts. This is, we believe, an authentic priority and in fact also a unprecedented challenge.

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Theorizing Quantum Games for Education

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Abstract. Quantum technologies have been becoming increasingly an important topic for education research. Quantum games possess the potential to become a general tool for increasing both awareness and literacy in quantum technologies and to attract new audiences to the field. In this work, we would like to explore the existing landscape of quantum games and posit certain questions that we believe can help researchers who wish to study them on both conceptual and practical levels.

Quantum technologies have been becoming increasingly an important topic for education research, especially as new M.Sc. and B.Sc. level education programs for Quantum Information Science and Quantum Engineering are coming to life in the US, the EU, and China.
Although, the topic of how to best present quantum phenomena related to the second quantum revolution in the context of education has been discussed previously in the literature [1,2] more recent discussions heavily focus on quantum technologies, computing in particular [3,4,5]. This is not surprising considering that the literature in quantum technologies has grown nearly three orders of magnitude in the last two decades [6], and quantum computing has been receiving particular attention with developments like the demonstration of 'quantum supremacy'[7], a term used for denoting the point where a quantum computer performs much better at a task than the best available classical computer, regardless of whether that task is useful or not.
In this context, quantum games have been proposed as a medium where people can learn quantum computing without many previous requirements [8], and an experimental environment for introducing learners to quantum mechanics [9]. It has been noted that allowing scientific experimentation is an important part of fostering scientific inquiry [10], and in the quantum realm, such experimentation opportunities are not readily available for the majority of the population. Hence, properly designed games [11] can be used to close this gap to some extent.
We believe that quantum games allow the easiest approximation of experimentation in a quantum regime. Players interacting with games constructed upon 'classical' game engines reinforce their intuitions on how the 'classical' world operates, a similar approach can be adopted for quantum games and the quantum world. Therefore, it is important to explore which aspects, actions, engine properties, and integration methods are most effective for building up players' intuitions.
We have found that there are more than 100 'quantum games' that have been developed around the globe, and most of them are freely accessible. Existence of such games, with the increased presence of global online communities (due to COVID-19), we believe that this is an opportune moment to explore the possibilities provided by utilizing quantum games for education and outreach purposes within the second quantum revolution.
The phenomenon of the digital divide [12,13] is expected to translate into the quantum era, where similar to the severe inequalities in access and utilization of digital technologies, there will be even further inequalities in access and utilization of quantum technologies. There are several initiatives trying to gap this divide early on, however, developing high-quality quantum games that foster scientific inquiry, and raise quantum literacy would bolster these efforts significantly.
In this context, we would like to posit and try to develop the following questions:
- What is a quantum game, what makes any game 'quantum'?
- Can there be a 'quantization method' of classical games, which turns regular games into quantum games?
- Can we assess the effectiveness of different quantum games with the same assessment tools, and if so, how can these assessment tools be developed?

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Playing Games with Quantum Physics

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Abstract. Amidst the second quantum revolution, there is an increasing need to educate people, both students and the general public. Games provide a unique platform for this, as they can engage these populations and allow them to learn about quantum mechanics in a playful setting. Citizen science games are also extremely interesting in that they can combine the educational efforts with research efforts. Here, we describe some of our efforts in gamifying quantum citizen science, especially as they relate to the use of human common sense in finding solutions to quantum problems.

1 Introduction

Amidst the second quantum revolution, where quantum technologies and solutions are being developed for sensing, simulation, computing, and networking purposes, there is the potential for incredible economic development, but this also comes with potential societal impacts. As such, there is an incredible need to educate students and the general public about quantum technologies, their benefits, and their potential drawbacks. That is, there is a need for an increased quantum literacy among the public.

Games are a unique way to approach this problem. A game can be interesting and engaging for people across a wide range of backgrounds and disciplines, and educational material can then be developed about the topics considered in the game, helping to build the desired competences. In addition, citizen science efforts are useful in that they engage the general public in research projects, fostering interest and a desire to help further scientific knowledge.

At ScienceAtHome, we have developed a number of quantum games and initiatives aimed at building quantum awareness and quantum literacy, and some of these games include citizen-science-based tasks where players contribute to cutting-edge quantum research. In particular, we are interested in understanding how amateurs and experts approach and solve quantum problems, tapping, in some sense, into human intuition about a very unintuitive subject. In this proposal, we outline briefly some of our games and their relevance for quantum education and research. We conclude by discussing the potential for such games in the future.

Fig. 1 Screenshots of Quantum Moves 2 (left) and the Quantum Mønster (right)

2 Quantum games and initiatives

In this section, we will describe some of the quantum games and initiatives developed by ScienceAtHome; all games and surrounding educational material can be found online [1]. In Quantum Moves 2 (QM2, Fig. 1 left), the player is tasked with solving relevant problems in the control of a quantum state consisting of one or many atoms, and the quantum state is represented as a liquid-like object that sloshes around as the player manipulates the system in which it resides. We have found that player solutions can provide valuable information to researchers [2], even in the face of the unintuitive nature of quantum mechanics, and QM2 has been used in numerous educational scenarios, including a randomized control trial on research games in Danish schools [3], where students play QM2 and learn about physics.

The Quantum Mønster (Fig 1 right, Danish for "pattern") is being developed to help physicists understand the theories underlying the behavior of electrons in ordered potentials, which is useful for the study of high-temperature superconductivity. As with QM2, the Quantum Mønster is aimed at understanding how amateurs and experts think about the problem at-hand, with the goal of helping neural networks to better classify these theories.

The same is true of the Netty game, where players are tasked with helping to solve problems regarding the organization of quantum spins in networks; the minimization of the energy of the system is an NP-hard task for classical computers. We also developed the Rydbergator, a gamified tool used for understanding how interacting atoms organize themselves in the presence of highly-excited Rydberg states. Finally, in 2018, we opened up our laboratory to the general public for the Alice challenge, wherein citizen scientists used a gami-

fied interface to optimise the cooling of atom clouds used for quantum simulation experiments; the amateurs were able to make larger clouds than the experimental experts had previously [4].
Thus, games like these are useful for scaffolding both self-reflection and quantum knowledge—in each case, we have developed a unique visual interface and means of interacting with the system. This allows us to both tap into what makes human thinking unique and educate the public via their participation in scientific projects.

3 Conclusion

While quantum games can take many forms, from games developed using quantum computers to purely educational games aimed at teaching the player something about quantum mechanics, the suite of games developed by ScienceAtHome are aimed at exploring how humans think about quantum mechanics regardless of their educational level in physics. In addition, we seek to educate our players on the relevant aspects of quantum mechanics applied in the games they play, increasing knowledge of quantum research and technology in society.

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Particle Physics for Primary Schools Education

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Abstract. Particle Physics for Primary Schools (PPPS) is a project born in UK in 2016 to bring the excitement of modern physics and the particle world to primary school children. PPPS was devised as a pioneering collaboration between University of Birmingham researchers, a local school teacher and the Odgen Trust. Originally developed as an iterative process involving testing sessions in local schools, after many years PPPS has reached a large national audience and a proven record of impact. A class workshop is the main element, incorporating arts and crafts and creativity, to convey a message that is both scientific and inspirational.

The rapid change in science and technology witnessed in the last decades have significantly increased the awareness in decision makers and education stakeholders of the need to strengthen the connection between outreach and research and education. he accent has rapidly moved from “outreach” to “engagement”, in order to reflect the need of a two-ways-processes where contributions and benefits are present for all parties. In this context, the project to divulge particle physics research concepts to primary school children represents a fruitful example of a collaboration between academia, school teachers and professional outreach officers.
The project stems from the mounting evidence that early school years are critical for children education, and are influential for the later development, including personal attitude towards science and its perception. The project finds its rationale in the compelling need to modernise the science content of both primary and secondary schools, taking modern 20th-century physics to the classroom, with its fundamental questions, its fascination and inspiring wonder.
The common perception of 18th century classical physics as a set of well-established concepts doesn’t help to raise the interest of young minds towards science; most importantly it doesn’t foster or promote the message that science is a dynamic process to which individual children can directly contribute once adults. This message is however essential to establish a personal connection between children and science and a sense of ownership of the subject, and ultimately to increase the society science capital.
The project was developed as part of a school activity. The main aspect of the project is a workshop, led by researchers and/or teachers, to be performed during class lessons or as an after-school club. The workshop is complemented by enrichment and feedback activities. The project also includes an aspect of teachers training and continuous development.
The workshop starts with an introduction to the world of elementary particles, with practical demonstrations of key concepts to promote children active participation. The introduction is followed by a range of creative enjoyable activities, with an increasing degree of complexity and physics content. The activities range from making models of elementary particles inspired by their characteristics (such as mass, electric charge, and particle families), to card games to facilitate the assimilation and consolidation of notions and concepts. The games explore more challenging concept relating to the quantum world, such as particle interactions, matter-antimatter annihilation, and the beauty of Feynman diagrams. The gaming aspect has been identified as key to facilitate the learning process of young children.
The workshop includes both single and group activities. The workshop concludes with a group activity that sees children explaining and demonstrating their work and creations to fellow students and teachers; this part facilitates and promotes the communication aspect of the project, while allowing checks of the learnt concepts and ideas.
The project has been recently extended to schools in Greece and in Italy. The art-and-craft aspects of the

workshop are crucial to transmit the message there isn't a rigid dichotomy between art and science, and that creativity is in fact an essential part of the scientific process. Particular emphasis has been placed on the need to divulge a correct and detailed scientific message, albeit simplified and tailored to the audience using metaphors and similitudes. Finally special care has been taken to avoid limiting the freedom of creative expression, allowing children to use their favorite art media (that being drama, dance, poetry, narrative, illustration etc.) for most of the activities.
The follow-up enrichment activities have been left to the teachers with suggestions from the researchers, to explore connections between physics and other sciences, and between science and other disciplines. As an example, the aspect of citizenship in science can be addressed when speaking of international science collaborations that are natural in experimental particle physics research.
The aspect of teachers and ambassadors training have been developed over the years, to make the project scalable and sustainable, with the help and collaboration of several scientific institutions such as the Institute of Physics, the Ogden Trust and the STEM Ambassadors. Resources have been developed to this end, consisting of a teacher manual and educational material to assist the delivery of the workshop. As a result, a sizeable number (in the hundreds) of primary teachers have been successfully trained to deliver the workshop in England.
The impact of the project has been verified collecting feedback from students and teachers before, during and one month after the project. As well as measures of how enjoyable the project was, indicators of specific impact, such as quantity and quality of scientific content assimilated and remembered, and changes in behaviour, attitude and perception towards science have been recorded. The results are positive, indicating a clear evidence of a positive impact on students.

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